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Assessing climate change and climate variability impacts in the coastal savannah agroecological zone of Ghana

Ankrah Johnson

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Thesis carried out as part of the Doctorate in Geography, supervised by Prof. Dr. Ana Maria Rodrigues Monteiro Sousa and by Prof. Dr. Helena Cristina Fernandes Ferreira Madureira.

Faculty of Arts and Humanities, University of Porto

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To my parents, who selflessly sacrificed all their resources for my education

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Declaration of honour

I declare that this thesis is my own and has not been used previously in another course or curricular unit, at this or any other institution. References to other authors (statements, ideas, thoughts) scrupulously respect the rules of attribution, and are duly indicated in the text and bibliographical references, in accordance with the rules of referencing. I am aware that the practice of plagiarism and self-plagiarism constitutes an academic offence.

I also declare that I did not use generative artificial intelligence tools (chatbots based on large language models) to carry out this thesis.

Porto, 31st July 2024

Ankrah Johnson

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Abstract

Climate change and climate variability have substantial adverse impacts on various sectors of the global economy, threatening the sustainability of these economies and the livelihoods of millions of people, particularly in developing countries with limited adaptation measures. Regular assessment is necessary to enhance our understanding of the adverse impacts and improve policy decisions on the appropriate adaptation strategies. Therefore, the aim of this study is to assess climate change and climate variability impacts in the coastal savannah agroecological zone of Ghana, where there is currently a dearth of knowledge on these impacts from a socio-ecological perspective. This study contributes to the scientific literature by offering a conceptual understanding of the impacts of climate change and variability, as well as making a significant methodological contribution by adapting existing research methods in a multimethod and interdisciplinary manner to enhance our understanding of climate change and variability impacts on socio-ecological systems. The study employed an interdisciplinary and multimethod approach and data sources, including climatological data and community participatory approaches. Results show that drought and wetness event incidences have increased in the zone over the past four decades. Again, the results show that the zone has an orderly climate, with higher levels of variability in the day-to-day maximum temperature than the day-to-day minimum temperature. Additionally, results indicate that smallholder farmers perceive extreme temperatures, droughts, pests, and diseases as the major climate risks that adversely impact their agricultural activities. Smallholder farmers have employed various adaptation strategies, including crop diversification, cultivating improved seed varieties, using fertilisers, and using irrigation. The results predict an increase in the zone's future warming and rainfall variability. Results indicate that the different El Niño-Southern Oscillation phases explained only a small variation in total annual rainfall in the zone, ranging from 1% to 12%. Moreover, results indicate that sea surface temperature and salinity account for 39% of the variability in the decrease in the total annual fish catch in the zone. Small-scale fishermen face several obstacles that limit their activities, with high premix fuel prices and high-sea transhipment activities being the most significant. The small-scale fishermen do not have satisfactory livelihood opportunities. Results from the shoreline change analysis show that Ghana's central and eastern coasts have eroded at rates faster than they are accreting. Improved policy decisions are necessary, including regular monitoring of drought and wetness

event incidences in the zone, the implementation of targeted policies to support and address the unequal power dynamics faced by women smallholder farmers in accessing resources, and the development of additional employment opportunities such as agriculture (crops, livestock, and poultry), small business, and occasional wage labour for small-scale fishermen in the zone.

Keywords: climate change, climate variability, risk perception, adaptation, coastal livelihoods

Resumo

As alterações climáticas e a variabilidade climática têm impactos adversos substantivos em vários sectores da economia mundial, ameaçando a sustentabilidade e os meios de subsistência de milhões de pessoas, sobretudo nos países em desenvolvimento onde as medidas de mitigação e de adaptação são ainda muito limitadas. Por isso, nestes países é necessário uma avaliação muito mais atenta, frequente e regular para melhorar a nossa compreensão dos impactos adversos e tornar as decisões políticas sobre as estratégias de adaptação mais eficazes e mais adequadas.

Daí, o objetivo deste estudo é avaliar os impactos das alterações climáticas e da variabilidade intrínseca ao sistema climático na zona agroecológica da savana costeira do Gana, onde ainda existe atualmente uma considerável escassez de conhecimento sobre estes impactos numa perspetiva socioecológica. Este estudo pretende contribuir para acrescentar conhecimento científico dedicado a este contexto geográfico e propiciar uma melhor compreensão da complexidade de causas envolvidas nos impactos frequentemente atribuídos às alterações climáticas, bem como dar um contributo metodológico significativo adaptando os métodos de investigação existentes de uma forma multimétodo e interdisciplinar para melhorar a nossa compreensão deste tipo de impactos nos sistemas socioecológicos.

O estudo utilizou uma abordagem interdisciplinar e metodologicamente diversificada que aproveite todas as fontes de dados disponíveis, incluindo tanto os dados climatológicos como as abordagens participativas da comunidade. Os resultados parecem mostrar que as ocorrências de eventos extremos de seca e de chuva aumentaram na nossa área de estudo ao longo das últimas quatro décadas.

A evidência científica ilustra, com clareza, que área agroecológica da savana costeira do Gana tem assistido a uma maior variabilidade na temperatura máxima diária do que na temperatura mínima diária assim como uma maior variabilidade na precipitação ao longo das últimas quatro décadas.

Esta constatação a partir da análise dos registos climatológicos coincide com a perceção dos pequenos agricultores que consideram as temperaturas extremas, as secas, as pragas e as doenças como os riscos climáticos que mais afetam negativamente as suas atividades agrícolas.

Para diminuir as perdas e danos causadas por estes riscos, os pequenos agricultores têm vindo a implementar várias estratégias de adaptação, incluindo a diversificação de culturas, o cultivo de variedades de sementes melhoradas, a utilização de fertilizantes e a irrigação.

Estes resultados parecem ser particularmente relevantes uma vez que os cenários preveem um aumento do aquecimento e da variabilidade da precipitação na área agroecológica da savana costeira do Gana.

As projeções climáticas sugerem que as diferentes fases do El Niño-Oscilação Sul explicam apenas uma pequena variação na precipitação total anual na zona, entre 1% e 12%. Todavia, a temperatura da superfície do mar e a salinidade parecem poder ser responsáveis por 39% da variabilidade na diminuição do total anual de capturas de peixe na zona, o que é, na área agroecológica da savana costeira do Gana, um impacte negativo de elevada magnitude.

De facto, os pescadores de pequena escala enfrentam já vários obstáculos que limitam as suas atividades, dentre as quais se destacam, a título de exemplo, os preços elevados da pré-mistura de combustível e as atividades de transbordo no mar. E, por isso, os pescadores de pequena escala não têm condições suficientes de subsistência.

Os impactes das alterações climáticas expressam-se já numa grande alteração da linha costeira, especialmente nas costas central e oriental do Gana onde há testemunhos de uma erosão muito mais rápida e uma diminuição substantiva da acumulação de sedimentos.

Por tudo isto parece claro que são necessárias decisões políticas mais eficazes, incluindo a monitorização regular das ocorrências de eventos extremos de seca e chuva na área agroecológica da savana costeira do Gana que combinem a implementação de medidas específicas para apoiar e resolver simultaneamente a dinâmica de poder desigual enfrentada pelas mulheres pequenas agricultoras no acesso aos recursos, o desenvolvimento de oportunidades adicionais de emprego como a agricultura (culturas, gado e aves), os pequenos negócios e o trabalho assalariado ocasional para os pescadores de pequena escala na zona.

Palavras-chave: alterações climáticas, variabilidade climática, perceção do risco, adaptação, meios de subsistência costeiros

Statement of Co-authorship

Chapters 1 to 6 of this thesis include standalone manuscripts published and/or under review in peer-reviewed journals. Chapter 1 integrates four journal-published review papers. Three distinct original papers, all published in peer-reviewed journals, comprise Chapter 2. Chapter 3 contains one original published paper in a journal. Chapter 4 has one original paper being reviewed in a journal. Two original papers published in peer-reviewed journals make up Chapter 5. Chapter 6 contains one original paper published in a peer-reviewed journal. There are a total of 12 papers in this thesis, with their citations listed below. I conceptualised and executed all 12 papers in this thesis. As a result, I formulated the methodology, devised the design, conducted data collection and analysis, carried out the investigation, engaged in formal writing, and performed review and editing. My supervisors, Prof. Dr. Ana Maria Rodrigues Monteiro Sousa and Prof. Dr. Helena Cristina Fernandes Ferreira Madureira, provided oversight and editorial input on the papers. Below, I outline the specific contributions each individual made to the papers.

Chapter 1

Paper 1: Monteiro, A., Ankrah, J., Madureira, H., & Pacheco, M. O. (2022). Climate risk mitigation and adaptation concerns in urban areas: A systematic review of the impact of IPCC assessment reports. *Climate, 10*(8), 115. https://doi.org/10.3390/cli10080115. **(Published)**.

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Paper 2: Ankrah, J., Monteiro, A., & Madureira, H. (2023). Geospatiality of sea level rise impacts and communities' adaptation: a bibliometric analysis and systematic review. *Nat Hazards,* 116, 1–31. https://doi.org/10.1007/s11069-022-05675-3. **(Published)**.

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Chapter 2

Paper 5: Ankrah, J., Monteiro, A., & Madureira, H. (2023). Spatiotemporal characteristics of meteorological drought and wetness events across the coastal savannah

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Paper 7: Ankrah, J. (2024). Climate risks and adaptation strategies: the perspectives of farmers in coastal Ghana. *Journal of Environmental Studies and Sciences*, *2024*. https://doi.org/10.1007/s13412-024-00970-w. **(Published) (Sole author)**.

Chapter 3

Paper 8: Ankrah, J., Monteiro, A., & Madureira, H. (2023). Extreme temperature and rainfall events and future climate change projections in the coastal savannah agroecological zone of Ghana. *Atmosphere*, *14*(2), 386. https://doi.org/10.3390/atmos14020386. **(Published)**.

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Paper 9: Ankrah, J., Monteiro, A., & Madureira, H. (2023). Analysis of the influence of ENSO on rainfall variability in the coastal savannah agroecological zone of Ghana. *Theor Appl Climatol*. **(Under Review)**.

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Paper 10: Ankrah, J., Monteiro, A., & Madureira, H. (2024). Climate variability, coastal livelihoods, and the influence of ocean change on fish catch in the coastal savannah zone of Ghana. *Water, 16*(9), 1201. https://doi.org/10.3390/w16091201. **(Published)**.

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Paper 11: Ankrah, J., Monteiro, A., & Madureira, H. (2024). Using qualitative research methods to understand how climate variability impacts the livelihoods of fishermen in coastal Ghana. *Maritime Studies,* 23, 40. https://doi.org/10.1007/s40152-024-00382-0. **(Published)**.

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Chapter 6

Paper 12: Ankrah, J. (2024). Shoreline change and coastal erosion: an analysis of long-term change and adaptation strategies in coastal Ghana. *Geo-Marine Letters, 44*, 12. https://doi.org/10.1007/s00367-024-00774-5 **(Published) (Sole author)**.

List of Abbreviations

AOGCMs	Atmospheric-Ocean General Circulation Models
CanESM2	Canadian Earth System Model version 2
CMIP5	Coupled Model Intercomparison Project
DSAS	Digital Shoreline Analysis System
ENSO	El Niño-Southern Oscillation
EPA	Environment Protection Agency
ETCCDI	Expert Team on Climate Change Detection and Indices
FAO	Food and Agricultural Organisation
GCMs	General Circulation Models
GMet	Ghana Meteorological Agency
GSS	Ghana Statistical Service
HadCM3	Hadley Centre Coupled Model version 3
IPCC	Intergovernmental Panel on Climate Change
IPCC AR	Intergovernmental Panel on Climate Change Assessment Report
ITCZ	Inter Tropical Convergence Zone
MESTI	Ministry of Environment Science, Technology, and Innovation
MICE	Multiple Imputation by Chained Equation
MMDAs	Metropolitan Municipal and District Assemblies
NCAR	National Centre for Atmospheric Research
NCEP	National Centre for Environmental Prediction
RCM	Regional Climate Model
RCPs	Representative Concentration Pathways
SDSM	Statistical Downscaling Model
SPSS	Statistical Package for Social Sciences
SSA	Sub-Saharan Africa
UNEP	United Nations Environment Programme
WAM	West African Monsoon
WMO	World Meteorological Organisation

CHAPTER 1: Introduction

1.1. Introduction

The global climate is changing, and this has significant consequences for all forms of life (Solomon et al., 2007). This change prompted the Intergovernmental Panel on Climate Change (IPCC) to emphasise the unequivocal warming of the global climate system in its fourth assessment report (AR4) (Solomon et al., 2007; Stott et al., 2010). Climate change, therefore, remains one of the greatest challenges of the twenty-first century (Easterling, 2007) and has become an issue of life and death because of its negative impacts on socio-economic development (Food and Agriculture Organisation [FAO], 2017; IPCC, 2018). The causes of global climate change are clear and well recognised (McMichael et al., 2004). Several research studies and bodies of literature have attributed the observed global warming over the past 50 years to harmful anthropogenic activities (Anderegg et al., 2010; Bindoff et al., 2013; Broecker, 1975; Cook et al., 2013; Doran & Zimmerman, 2009; Feng & Li, 2023; IPCC, 2023; IPCC, 2001a; Karl & Trenberth, 2003; McMichael et al., 2004; Padrón et al., 2020; Stott et al., 2010). Karl and Trenberth (2003) reiterated that anthropogenic pressures control the changes in the present global climate, surpassing the limits of natural variability.

The IPCC estimates that anthropogenic activities have caused a global warming of about 1.0 °C higher than the preindustrial level (IPCC, 2018). The IPCC states with high confidence that if negative anthropogenic activities continue at their current rate, a 1.5 °C warming is likely between 2030 and 2052 (IPCC, 2018). The IPCC sixth assessment report (AR6) further states with a high level of confidence that the global surface temperature has experienced a more rapid increase since 1970 compared to any other 50-year period in the past 2000 years (IPCC, 2023). Moreover, Seneviratne et al. (2021) highlight that even if the 1.5 °C stabilisation limit is reached, global warming will persist. The negative anthropogenic activities that alter the atmospheric composition and cause global warming include the emission of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), among others (Bruhwiler et al., 2021; Forster et al., 2007; Hansen & Lacis, 1990; Karl & Trenberth, 2003; Ruddiman, 2003). For instance, Karl and Trenberth (2003) highlighted that since preindustrial times, CO_2 has increased by 31% from 280 parts per million (ppm) to more than 370 ppm, with almost half of the increase occurring since 1965. Greenhouse gases absorb and reflect long-wave terrestrial radiation from the earth, warming the planet (Hansen & Lacis, 1990; Karl & Trenberth, 2003).

Undoubtedly, the accumulation of these greenhouse gases directly influences alterations in the global climate system and associated elements like temperature and precipitation (Stott et al., 2010). The IPCC AR6 presents compelling evidence of anthropogenic influence on the amplification of heavy precipitation, particularly in Asia, Europe, and North America, due to increased greenhouse gas emissions (Seneviratne et al., 2021).

Climate influences global temperature, precipitation, and other critical variables like humidity and wind speed (Célestin et al., 2019; Karl et al., 2009). Findings from Brohan et al. (2006) revealed a global increase in mean surface air temperature by about 0.74 °C ± 0.18 °C during the twentieth century. The researchers further indicate a projected increase of 1.8 °C to 4.0 °C in the twenty-first century (Brohan et al., 2006). The IPCC also states in its fifth assessment report (AR5) that the global mean surface air temperature increased by 0.85 °C (0.65 °C to 1.06 °C) between 1880 and 2012, with a further projected increase in the range of 0.3 °C to 4.8 °C between 2081–2100 in comparison to 1986–2005 (Bindoff et al., 2013). Similarly, the IPCC reported in its special report on 1.5 °C global warming (SR1.5) a 0.87 °C (0.0 °C to 1.2 °C) increase in global mean surface temperature for the decade 2006–2015, which is higher than the 1850–1990 average (IPCC, 2018). The IPCC (2018) attributes a current estimate of a 0.2 °C increase to anthropogenic global warming. Célestin et al. (2019) argue that global temperatures will increase, along with increases in both precipitation and wind speed. The changes in global precipitation follow a pattern where wetter regions will continue to be wetter and vice versa for drier regions (Donat et al., 2016; IPCC, 2007; Trenberth, 2011). Researchers project that global warming will cause an increase in wind speed in many regions of the Northern Hemisphere, as well as in the tropics and sub-tropics (Akinsanola et al., 2021; Mcinnes et al., 2011; Vecchi & Soden, 2007; Zha et al., 2021). Furthermore, the combination of temperature, precipitation, and humidity changes is expected to increase the frequency of extreme weather and climate events, including droughts, floods, and heat waves in various regions (Chen et al., 2019; Coffel et al., 2018; Cook et al., 2018; Do et al., 2020; Fischer et al., 2012; Kennedy-Asser et al., 2021; Li et al., 2020; Zhao & Dai, 2017).

Changes occurring in the abovementioned climatic parameters pose threats to all sectors of the global economy. For instance, on agriculture and food security (Ahmed et al., 2022; Aydinalp & Cresser, 2008; Kogo et al., 2021; Lee et al., 2024; Malhi et al., 2021; Nelson et al., 2014), water resources (Aliyari et al., 2021; Arnell, 1999; Haddeland et al., 2014; Konapala et al., 2020; Mengistu et al., 2021; Papa et al., 2023; Pokhrel et al., 2021), health (Haines and Patz, 2004; McMichael et al., 2006; Rocque et al., 2021), human

security (Barnett & Adger, 2007; Taylor, 2013; von Uexkull & Buhaug, 2021), and livelihoods (Connolly-Boutin & Smit, 2016; Gentle & Maraseni, 2012; Mohammed et al., 2021), among others. In emphasising climate change effects on agriculture, several research studies have indicated the consequences on a continental scale. Examples include Asia (Aryal et al., 2020; Mendelsohn, 2014), Australia (Anwar et al., 2015; Steffen et al., 2011), Europe (Olesen et al., 2011; Olesen et al., 2002), North America (Kukal & Irmak, 2018; Murdoch et al., 2000), South America (Fernández et al., 2019; Seo & Mendelsohn, 2008), and Africa (Kurukulasuriya et al., 2006; Schlenker & Lobell, 2010).

In recent decades, the West African climate has reacted to harmful anthropogenic greenhouse gas forcing (Sylla et al., 2016). In their study on climate change over West Africa, Sylla et al. (2016) reported a current decade-long warming of the region. The researchers further indicated a significant warming in the Gulf of Guinea and the West Sahel portions, with countries such as Ghana, Guinea, Cote d'Ivoire, and Senegal experiencing the greatest warming of between 0.2 and 0.5 °C (Sylla et al., 2016). Again, the IPCC's AR5 reported a current decade warming of 0.3 °C to 1.0 °C for the West African region (Bindoff et al., 2013). There is uncertainty regarding precipitation changes in the region. Literature reports increasing and decreasing trends in precipitation over the region. These uncertainties may be due to the greater interannual variability and the role of the West African monsoon (WAM) winds (Diallo et al., 2013; Odoulami & Akinsanola, 2018; Seth et al., 2013). For instance, research studies such as those of Sylla et al. (2016), Druyan (2011), Lebel and Ali (2009), and Nicholson (2005) found an increasing trend in precipitation in the Sahel area and a decreasing trend in the Gulf of Guinea section in the past decades. On the contrary, the IPCC AR5 reported a drying in precipitation over the West African region based on a time series that spanned from 1951 to 2012 (Bindoff et al., 2013). The recent studies of Akinsanola and Zhou (2019), Biasutti (2019), Bichet and Diedhiou (2018), and Diatta et al. (2020) have reported an increase in precipitation over West Africa, especially in the Sahel. However, Sylla et al. (2016) expect an increase in mean temperature over the region as mean precipitation variability increases. The present and expected climate changes will present difficulties for the already vulnerable West African region, which has limited capacity for adaptation (Boko et al., 2007; Sylla et al., 2016), particularly in its coastal areas. Climate change is expected to adversely affect the region's water resources (Rameshwaran et al., 2021), ecosystem services (van der Geest et al., 2019), and agriculture (Sultan & Gaetani, 2016). Climate change and rising sea levels will also lead to increased shoreline change and erosion, floods, inundation, and disruption

of aquatic ecosystems and resources, such as fish and fisheries, in most West African coastal regions (Boko et al., 2007; Lam et al., 2012; Nyadzi et al., 2021). The condition would limit the livelihood opportunities of many people in the sub-region, particularly smallholder farmers and small-scale fishermen, including those in coastal Ghana, whose activities are entirely dependent on the climate.

Ghana has several environmental problems, and the prevalence of climate change has exacerbated these problems (Neville & Mohammed, 2010). As indicated in the reports of Ghana's Ministry of Environment Science, Technology, and Innovation (MESTI), greenhouse gas emissions increased from 12.2 metric tonnes of CO_2 equivalent (Mt CO_2e) to 242 Mt CO_2e between the years 2000 and 2006 (MESTI, 2013). Findings from the study of Asante and Amuakwa-Mensah (2015) on climate variability and change in Ghana revealed about a 107% rise in anthropogenic greenhouse gas emissions in Ghana between 1990 and 2006. In its report, the MESTI noted a temperature increase of about 1.0 °C between 1960 and 2000, with a projected rise of about 1.7 °C to 2.0 °C (MESTI, 2013). As reiterated by Abbam et al. (2018), Ghana's rainfall has become irregular, with greater variability in distribution. These changes negatively impact the sectoral development of the country, especially the agricultural sector, considering the agrarian nature of Ghana (Asare-Nuamah & Botchway, 2019).

The coastal zones of Ghana, including industries such as fishing, agriculture, and tourism, continue to experience significant adverse impacts from climate change and rising sea levels (Freduah et al., 2017; Jonah et al., 2016; Nunoo et al., 2015; Seidu et al., 2022). The activity of fishing and the industry of fisheries are widely recognised as significant means of employment and a primary source of livelihood for around 2.6 million people, constituting 10% of the total population (Dovlo et al., 2016; Nunoo et al., 2015; Seidu et al., 2022). However, climate change, sea level rise, and harmful human activities have negatively impacted the sustainability of these resources. As a result, coastal communities that rely exclusively on fishing for their livelihoods are facing challenges (Ankrah, 2018; Ayilu et al., 2023; Okyere et al., 2023). Climate change and the resulting rise in sea levels pose substantial risks to the resources and historical sites along the coast of Ghana. These risks include shoreline changes and erosion, as highlighted by Boateng (2012) and Jonah et al. (2016).

Studies revealing the impacts of climate change have increased in Ghana (Adu-Prah et al., 2019; Boadi & Owusu, 2019; Cudjoe et al., 2021; Larbi et al., 2021; Larbi et al., 2018; Owusu et al., 2008). Additionally, there have been studies that emphasise the effects

of shoreline change and erosion on ecological and social systems along the coast. The research conducted by Abdul-Kareem et al. (2022), Angnuureng et al. (2022), Appeaning Addo et al. (2020), Appeaning Addo (2014), Appeaning Addo et al. (2011), Boye et al. (2018), Jayson-Quashigah et al. (2013), Jonah et al. (2016), Jonah (2015), and Mann et al. (2023) have also analysed the impacts of shoreline change and erosion on the coastal areas of Ghana.

Although there has been an increase in research, there is a dearth of information on the impacts of climate change and variability in coastal Ghana, particularly in the coastal Savannah agroecological zone. The complex interaction between the land and ocean in this area makes it particularly susceptible to the impacts of climate change and variability, which necessitates research. There is a critical need for an interdisciplinary approach to conduct a thorough assessment of the impact of climate change and variability in coastal Ghana. No study has assessed climate change and variability in coastal Ghana, particularly in the coastal Savannah agroecological zone, using an interdisciplinary approach. Research studies such as those conducted by Bhaskar et al. (2010) and Simonovic and Davis (2006) have supported the idea of interdisciplinary approaches in climate change research. Schipper et al. (2021) explain interdisciplinarity as the collaborative attempt to address a problem, such as the implications of climate change and variability, by considering several disciplines. According to Castree et al. (2014), employing interdisciplinary research methodologies facilitates the exploration of the interconnections between various disciplines and offers solutions to climate change problems. The impacts of climate change on humans and their strategies for responding to it are interdisciplinary, resulting from the interaction of a variety of disciplines (Balzter et al., 2023; Molina et al., 2020). The research in this thesis incorporated various disciplines, such as climatology, agroecology, hydrology, oceanography, fisheries, and geomorphology, to assess climate change and variability impacts, which were applicable to coastal Ghana and the coastal savannah agroecological zone in particular.

The main objective of this thesis was to assess climate change and variability impacts in the coastal savannah agroecological zone of Ghana. An assessment was conducted to evaluate the impacts of climate change and variability on the coastal ecosystems, resources, and livelihoods of people, including farmers and small-scale fishermen, in the coastal savannah agroecological zone of Ghana. The subsequent sections present a review of the literature that outlines the problems related to climate change and variability by identifying knowledge gaps and justification for research in the coastal savannah agroecological zone

of Ghana, as well as the climate change and variability impacts in coastal areas. Following that, the thesis presents the research objectives, the applied societal, academic (science), and methodological contributions of the research, and the organisation of chapters.

1.2. Literature review

This chapter presents a comprehensive analysis of the existing literature on the impacts of climate change and climate variability in coastal areas. The aim is to build a theoretical foundation for the thesis. The chapter commences by analysing the existing body of literature pertaining to climate change, variability, and extreme event incidences at the global level. The chapter then proceeds to examine the impacts of climate change, variability, and extreme events on global agriculture and water resources. The chapter once again presents an overview of the impacts of climate change, variability, and extreme events, with a particular focus on their implications on agriculture and food security in Sub-Saharan Africa (SSA). In addition, it offers an assessment of climate change projections, emphasising the uncertainties, models, scenarios, and related applications. The chapter further presents related information on climate change and coastal zones. Moreover, the chapter presents the climate change and variability problems in Ghana. The chapter also features systematic review papers, published in relevant scientific journals, that explore the impacts of climate change and climate variability on coastal zones.

1.2.1. Global climate change, variability, and extreme events

The global climate has changed due to increased negative anthropogenic influence (Campbell-Lendrum et al., 2007; Daramola & Xu, 2022; Donat et al., 2016; Dore, 2005; IPCC, 2014). The change is evident through increased global surface temperatures (Arnell et al., 2019; Hansen et al., 2006; Jiang et al., 2016; Vose et al., 2005) and greater global precipitation variability (Adler et al., 2017; Gu & Adler, 2015, 2023; Gherardi & Sala, 2019; Zhang & Wang, 2023). Between 1880 and 2012, the global average surface temperature changed by 0.65 °C–1.06 °C, based on the IPCC report (IPCC, 2013). From 2081 to 2100, the IPCC expects an increase of 0.3–4.8 °C in comparison to the period from 1986 to 2005 (IPCC, 2013). This projection is based on different Representative Concentration Pathways (RCP2.6 to RCP8.5) scenarios. Arias et al. (2021) also state that the global temperature increased by 1.09 °C from 1850–1900 to 2011–2020. As reiterated by the IPCC (2021), the global surface temperature increase over land was 1.59 °C (with a

range of 1.34 to 1.83 °C) and is larger than the increase over the ocean, which was 0.88 °C (with a range of 0.68 to 1.01 °C). The IPCC (2021) again asserts that greenhouse gases caused an increase in global surface temperature by 1.0 °C to 2.0 °C; other anthropogenic forcings, particularly aerosols, caused a cooling of 0.0 °C to 0.8 °C; natural drivers caused a change by –0.1 °C to +0.1 °C; and internal variability by –0.2 °C to +0.2 °C.

The IPCC (2014a) states with high confidence that anthropogenic forcings contributed substantially to the increase in global surface temperature since the mid-20th century, except for Antarctica, even though Swanson et al. (2009) believe that the increase has not been monotonic as there is a possible long-term natural variability due to changes in ocean circulation. The IPCC (2021) further states that there has been a rise in world average precipitation over land since 1950, with a more rapid rate of increase since the 1980s. The El Niño-Southern Oscillation (ENSO) phenomena for instance, is recognised as a dominant cause of the interannual and decadal variability of the global climate system (Lin & Qian, 2019) with increased impacts across many land regions (Cook et al., 2024; Cowan et al, 2023; de Souza et al., 2021; King et al., 2020; Lin et al., 2023; Lüdecke et al., 2021).

Climate change through global surface temperatures and precipitation variability has a strong link with the increased and frequent extreme weather and climate events such as droughts, floods, heat waves, and heavier storms (Bindoff et al., 2013; Campbell-Lendrum et al., 2007; Hu et al., 2023; Tripathy et al., 2023). Ahsan et al. (2022) recognise that extreme weather and climate events as the most evident impacts of climate change due to their greater adverse impacts on socio-ecological systems. Fischer et al. (2013) assert that climate change has increased the likelihood of extreme temperature and precipitation event incidences. Seneviratne et al. (2021) reported that there has been an increase in the occurrence and intensity of hot extremes, whereas cold extremes have declined globally since 1950.

Several studies, such as those conducted by Abbasnia and Toros (2019), Coronato et al. (2024), Cowan et al. (2014), Dasio (2017), Graczyk et al. (2017), Imran et al. (2023), New et al. (2006), Sulikowska and Wypych (2020), Yavaşlı and Erlat (2024), and Yeh et al. (2021), have underscored the frequent incidences of extreme events such as hot days, hot nights, warm spells, and heatwaves. Abbasnia and Toros (2019) found that the Marmara region of Turkey experienced an increase in the duration of warm spells, the frequency of summer days, tropical nights, and warm days and nights. Conversely, there was a decline in cold spells as well as cool days and nights over the above-mentioned region (Abbasnia and Toros, 2019). Yavaşlı and Erlat (2024) found a notable increase in

the occurrence of tropical nights across the entire Mediterranean region, particularly in urban areas. Furthermore, New et al. (2006) revealed an average increase and decrease in the duration of warm and cold periods, respectively, across southern and western Africa. Seneviratne et al. (2021) assert that there has been a global-scale increase in both the frequency and intensity of heavy precipitation events, particularly on the continents of Asia, Europe, and North America. Seneviratne et al. (2021) predict that extreme precipitation will intensify, leading to an increase in the frequency and severity of flooding, including both pluvial and river floods. Seneviratne et al. (2021) emphasise once again the increasing incidence of droughts, including agricultural, ecological, and hydrological aspects, in some land areas as a result of climate change caused by human activities.

The frequent occurrence of drought and flooding has become a significant issue across many land regions due to climate change and variability (Bolan et al., 2024; Dai, 2011; Seneviratne et al., 2021; Verhoeven et al., 2022; Zhang et al., 2023; Zhou et al., 2023). Tellman et al. (2021) discovered that floods affected a larger proportion of the global population, ranging from 20 to 24% more, based on their analysis of satellite images depicting flood extent and population exposure between 2000 and 2018. Nevertheless, Do et al. (2020) argue that this percentage will increase in conjunction with ongoing global climate warming. The scientific consensus on the adverse impacts of drought on agriculture and food security, water resources, environmental systems, health, and livelihoods have been widely established in the literature (Abadi et al., 2022; Ahmad et al., 2022; Asmall et al., 2021; Gwon et al., 2024; Musolino et al., 2018; Muthuvel et al., 2023; Qiu et al., 2023; Tofu et al., 2023). In the review on drought of the last millennium, Dai (2011) reported that drought lasting for years to decades have occurred several times in North America, East Asia, and West Africa. The researcher went further to highlight the substantial increase in global aridity since the 1970s over Africa, southern Europe, East and South Asia, and eastern Australia due to drought (Dai, 2011). According to Thiaw and Kumar (2015), droughts in West Africa are a natural characteristic of the climate and are recognised as significant factors that contribute to economic challenges, migration, and mortality.

The IPCC (2014a) projects that global warming will increase the occurrence of extreme events, such as droughts and floods, in many parts of the world. Researchers have made considerable efforts to comprehend the dynamics of drought and its associated consequences in order to devise strategies for mitigation (IPCC, 2014a; Sheffield et al., 2012). Despite these attempts, understanding and accurately assessing the evolution,

duration, frequency, and intensity of droughts continue to be challenging due to their complex nature, which sets them apart from other natural disasters (Wilhite, 2000). Therefore, it is crucial to conduct frequent assessments and regular monitoring of extreme weather and climate events in various regions worldwide (Real-Rangel et al., 2020) to mitigate their impacts on socio-ecological systems (Collier et al., 2009) and reduce their global economic costs (Newman & Noy, 2023). Newman and Noy (2023) estimated that the annual cost of climate change-induced extreme events amounts to 143 billion United States dollars, with the largest portion (63%) attributed to human fatalities.

1.2.2. Impacts of climate change, variability, and extreme events

The impacts of climate change and climate variability are evident in all areas of the world's economies (Baarsch et al., 2020; Rawat et al., 2024). As reiterated by Rawat et al. (2024), climate change and climate variability pose substantial negative impacts. The impacts include those that stem from rising temperatures, fluctuations in precipitation, increased and frequent incidences of disastrous events, rising sea levels, and related oceanic changes. Climate change and variability have posed a challenge to the sustainability of various sectors globally (Abbass et al., 2022), impacting substantially on agriculture, health, water resources, energy production, and biodiversity (Rawat et al., 2024). Researchers have investigated the increasing impact of climate change and variability on the tourism industry in various studies (Amelung and Nicholls, 2014; Dogru et al., 2019; Dube & Nhamo, 2018; Muñoz et al., 2023; Scott et al., 2012). Scott et al. (2019) found that countries in Africa, South Asia, the Middle East, and the Small Island Developing States are most vulnerable in the tourism industry, while Canada, western and northern Europe, Central Asia, and New Zealand are the least vulnerable. In Indonesia, Susanto et al. (2020) revealed that a 1% increase in temperature and relative humidity led to a decline in foreign tourist numbers by 1.3% and 0.59%, respectively.

Various studies, such as those by Adger et al. (2014), Ani et al. (2022), Barnett and Adger (2007), Ehiane and Moyo (2022), Theisen et al. (2013), and von Uexkull and Buhaug (2021), have demonstrated the effects of climate change and variability on human security. Adger et al. (2014) informed us about the adverse effects of climate change on human security and related consequences on people's livelihoods, which result in migration. Ani et al. (2022) pointed out the human security issues in Nigeria due to climate change. Natural disasters have become prevalent due to climate change and variability and

are impacting the lives of millions of people worldwide (Banholzer et al., 2014; Rawat et al., 2024). Loayza et al. (2012) and Fomby et al. (2013) discovered that natural disasters had a greater effect on economic growth in developing countries compared to developed countries.

1.2.3. Impacts on global agriculture

The agricultural sector, despite its substantial greenhouse gas emissions, remains one of the sectors negatively affected by climate change and climate variability impacts (Abbass et al., 2022; Adegbeye et al., 2020). Extreme weather and climate events, such as droughts and floods, greatly impact the world's agricultural output (Lesk et al., 2016). Asseng et al. (2015) emphasised that a 1 °C increase in global temperatures would result in a 6% decrease in global wheat yield. Liu et al. (2016) anticipated a global reduction of 4.1% to 6.4%. Leng and Hall (2019) discovered that rice production in Vietnam and Thailand is particularly vulnerable to drought. In a previous study, Challinor et al. (2014) stressed the expected losses in overall production of rice, maize, and wheat in tropical and temperate countries due to a 2 °C increase in local temperatures without any adaptation measures.

Researchers have conducted studies on climate change impacts in various regions: Asia (Aryal et al., 2020), Australia (Steffen et al., 2011), Europe (Olesen et al., 2002), North America (Kukal & Irmak, 2018; Murdoch et al., 2000), South America (Fernández et al., 2019; Seo & Mendelsohn, 2008), and Africa (Kurukulasuriya et al., 2006; Schlenker & Lobell, 2010). For example, Mendelsohn (2014) utilised the Ricardian model to estimate little cumulative damage to crops in Asia with a 1.5 °C temperature increase due to carbon fertilisation. Estimates project damages exceeding 84 billion United States dollars with a 3 °C temperature rise (Mendelsohn, 2014). The researcher predicts that India will be more vulnerable (Mendelsohn, 2014). Researchers, including Anderson et al. (2020) and Godfray et al. (2010), have warned us about food insecurity issues as agriculture continues to face challenges from the changing global climate. The situation will be worse for countries with low adaptation efforts (Seaman et al., 2014). In their modelling study, Dawson et al. (2016) predicted that without significant adaptation and enhanced agricultural innovation by 2050, 2.5 billion people, representing 31% of the global population, will be undernourished. The researchers stated that climate change will lead to

an additional increase of 1.7 billion people, or 21% of the global population, experiencing undernourishment by 2050 (Dawson et al., 2016).

1.2.4. Impacts on global water resources

Water is recognised as a vital resource for all living organisms (Douville et al., 2021; D'Odorico et al., 2020; Lal, 2015) and plays a significant role in sustainable development (Smol et al., 2020). Douville et al. (2021) emphasised that 71% of the earth's surface is covered by water. Saline ocean water accounts for about 97% of the total, while terrestrial freshwater makes up less than 2%, and saline groundwater and lakes combined account for about 1 to 2% (Abbott et al., 2019; Douville et al., 2021). About 96% of all freshwaters is made up of glaciers, ice sheets, and snowpacks (Abbott et al., 2019; Durak, 2015; Douville et al., 2021). Less than 4% of the total percentage is freshwater that is accessible for human needs and ecosystem functions (Abbott et al., 2019; Durak, 2015; Douville et al., 2021). Abbott et al. (2019) emphasise that a small portion of freshwater is mostly preserved as groundwater, while the remainder is found in rivers, lakes, soils, and wetlands. Abbott et al. (2019) acknowledge that the natural freshwater cycle meets socio-ecological needs but argue that its distribution is uneven geographically and varies seasonally, impacting regional demand. Lal (2015) states that freshwater resources are poorly distributed geographically and vulnerable to pollution and eutrophication.

Several studies, including those by Abbott et al. (2019), Haddeland et al. (2014), Senbeta and Romanowicz (2021), Veldkam et al. (2017), and Wada et al. (2016), have demonstrated the increasing impact of human activities on global water resources along with climate change. Haddeland et al. (2014) stressed that human activities directly alter the water cycle dynamics by constructing dams for water storage and extracting water for industrial, agricultural, and domestic use. Researchers expect climate change to affect water supply and demand (Haddeland et al., 2014). Haddeland et al. (2014) utilised the multimodel method to analyse the impacts of climate change and human activities on the terrestrial water cycle. They identified direct human impacts on the water cycle in locations like the western United States and parts of Asia (Haddeland et al., 2014). Haddeland et al. (2014) projected an increase in irrigation water use with higher global mean temperatures, leading to water scarcity in many parts of southern and eastern Asia, with the situation worsening in the future. In their compiled synthesis of the global water cycle diagrams around the world, Abbott et al. (2019) contended that human freshwater usage accounts for

half of the worldwide water output, while only 15% of water cycle diagrams depict human interaction with water. Senbeta and Romanowicz (2021) identified substantial changes in the runoff of the Kamienna watershed in central Poland starting in 1982 as a result of human interventions. According to Senbeta and Romanowicz (2021), a 23.9% reduction in the runoff occurred due to a combination of climate change and human activities during the disturbance area.

Anthropogenic climate change has altered every aspect of the global water cycle in the past few decades (Arnell, 1999; Douville et al., 2021; IPCC, 2022). Arnell (1999) stressed the intensification of the hydrological cycle due to increased evaporation and precipitation, along with an unequal global distribution of extra rainfall. According to Arnell (1999), numerous areas worldwide would encounter reduced precipitation or significant changes in the timing of wet and dry periods. Notwithstanding, the IPCC (2022) asserts with high confidence that there has been an increase in the intensity of heavy precipitation in many regions of the world since the 1950s. According to the IPCC (2022), more people live in regions with an increase in annual maximum one-day precipitation compared to those with a decrease. With high confidence, the IPCC (2022) states that changes to the hydrological cycle have impacted water security, leading to increasing water vulnerabilities. Several studies have demonstrated the impacts of climate change and variability on water security (e.g., Eekhout et al., 2018; Gesualdo et al., 2019; Stringer et al., 2021) and scarcity (e.g., Dinar et al., 2019; Filho et al., 2022; Gampe et al., 2016; Gosling & Arnell, 2016; Karimi et al., 2024; Liu et al., 2023; Qureshi et al., 2013; Schewe et al., 2014). Gampe et al. (2016) emphasised the growing water scarcity issues in the Ebro, Evrotas, Adige, and Sava river basins in the Mediterranean region caused by a significant reduction in precipitation, runoff, and evaporation. Liu et al. (2023) discovered that variations in precipitation considerably endanger the agricultural water scarcity index in mainland China. Future climate change is projected to significantly increase changes in the agricultural water scarcity index by more than 200%, particularly in Inner Mongolia, as indicated by the researchers (Liu et al., 2023).

Extreme weather and climate events, such as drought and flood, also substantially impact water availability and quality (Ascott et al., 2016; Faramarzi et al., 2013; Geris et al., 2022; Hui-Mean et al., 2018; IPCC, 2022; Pervez & Henebry, 2015; Sun et al., 2016; Zuo et al., 2023). The IPCC (2022) indicates that climate change has possibly increased the severity of agricultural and hydrological drought impacts in many land regions. From 1970 to 2019, 7% of worldwide disaster events were drought-related, resulting in 34% of

disaster-related deaths, mostly in Africa, according to the IPCC (IPCC, 2022). Pervez and Henebry (2015) reported increased positive trends in the total water output, streamflow, and groundwater recharge in the Brahmaputra River basin, suggesting a potential for floods from August to October. Nevertheless, the researchers observed a greater decreasing trend in the likelihood of drought, particularly throughout the period from May to July (Pervez & Henebry, 2015). Faramarzi et al. (2013) state that the average total amount of accessible freshwater resources is projected to increase over the whole African continent; however, there will be substantial variations in the individual subbasins and countries. Van Vliet et al. (2016) reported that hydropower usage decreased by 5.2% and thermoelectric power decreased by 3.8% during major drought years, specifically in 2003 in Europe and 2007 in Eastern North America. Meteorological drought can lead to hydrological, agricultural, and other types of drought, resulting in significant harm to agricultural output, ecosystem functions, watershed systems, and drinking water availability (Ahn et al., 2016; Qiu et al., 2023; Zhou et al., 2021). Sun et al. (2016) analysed water quality issues following the 2012 Beijing flood and found that all samples tested were not fit for consumption. Geris et al. (2022) discovered that the water quality in the catchment upstream of Gaborone Dam on the Notwane River in southeast Botswana and northern South Africa was impacted by severe rainfall and major flooding in 2016 and 2017. Zou et al. (2023) highlighted in their review that floods had more negative effects on water quality compared to droughts. The researchers indicated that water quality difficulties during extreme events are more common in low-income countries with limited water resource technologies than in high-income ones (Zou et al., 2023).

Climate change, variability, and extreme events have significant impacts on people, agriculture, and ecosystems, as highlighted by several studies (Giordano et al., 2019; Grimm et al., 2013; IPCC, 2022; Lesk et al., 2016; Mancosu et al., 2015; Waseem et al., 2022). Changes in the hydrological cycle significantly affect agriculture and energy production, as stated by the IPCC (2022) with high confidence. Between 1983 and 2009, the IPCC (2022) reported that almost 75% of global harvested areas had yield reductions due to meteorological drought, resulting in a total financial loss of 166 billion United States dollars. Waseem et al. (2022) reported that a meteorological drought has a negative impact on maize production in south Punjab, Pakistan. The researchers further claimed that meteorological drought was responsible for 27% of the total yield variations (Waseem et al., 2022). The impacts pose substantial challenges for the African continent, particularly

the Sub-Saharan African region (Calzadilla et al., 2013a; Emediegwu et al., 2022; Tesfaye et al., 2015).

1.2.5. Implication for agriculture and food security in SSA

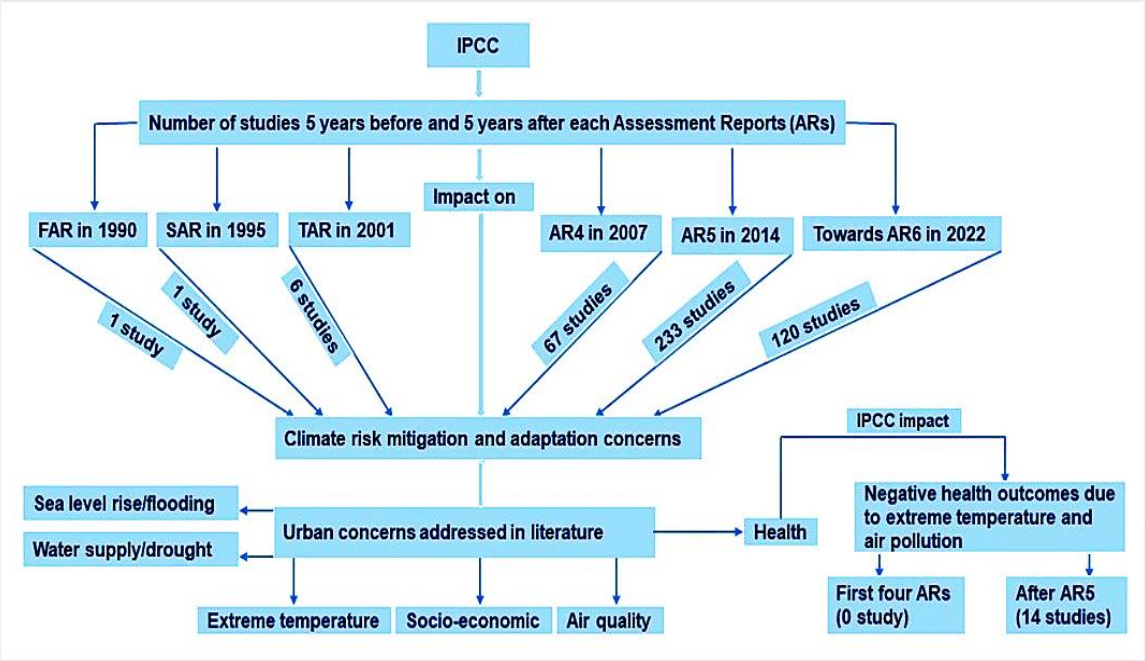
Several studies, including those by Cairns et al. (2013), Connolly-Boutin and Smith (2016), Niang et al. (2014), and Serdeczny et al. (2017), have demonstrated Africa's climate challenges, with more emphasis on the changing climate in SSA. Studies such as those of Adesete et al. (2023), Boko et al. (2007), and Thompson et al. (2010) have estimated a warming trend of 3 °C to 4 °C, which is above the global annual average. In SSA, studies such as those of Chapman et al. (2020) and Serdeczny et al. (2017) have projected increased temperatures, heavy rainfall, and frequent incidences of disastrous events like droughts and flooding. Cairns et al. (2013) and the IPCC (2007) stated that the forecasted distribution patterns of rainfall across SSA show increased uncertainty despite the expected rise in rainfall intensity. Climate models forecasting future precipitation in SSA show conflicting trends in change direction, as indicated by Cairns et al. (2013) and IPCC (2007). The IPCC (2007) projects increased and decreased rainfall amounts in East Africa and Southern Africa, respectively. Rainfall projections for West Africa exhibit significant variability, posing challenges in predicting potential climatic scenarios (Cooper et al., 2008; IPCC, 2007). Literature documents variable precipitation patterns in West Africa as reported by Druyan (2011), Lebel and Ali (2009), and Nicholson (2005). Collier et al. (2008) emphasise the significant global factors, such as the Inter Tropical Convergence Zone (ITCZ), WAM, and ENSO, that influence the African climate.

According to Niang et al. (2014), climate change and variability will negatively impact the planting seasons and agricultural output in SSA. Studies by Ahmed (2020), Kamali et al. (2022), Ojara et al. (2022), and Stuch et al. (2021) have demonstrated how climate change affects crop yield in SSA. For example, Kamali et al. (2022) emphasised the significant reduction in agricultural output of rain-dependent maize, millet, and sorghum in SSA due to drought. Declining crop yields in SSA pose food security challenges, according to several studies (Adesete et al., 2023; Affoh et al., 2022; Ahmed, 2020). SSA stands out as the world's most food-insecure region due to its heavy reliance on cereal imports, rapid population growth, and poor agricultural productivity (Giller, 2020). Adesete et al. (2023) emphasised the increasing occurrence of greenhouse gases and their effects on malnutrition and food security in SSA. In SSA, studies such as those conducted

by Antwi-Agyei et al. (2014), Aschinger et al. (2023), Connolly-Boutin and Smit (2016), and Fadairo et al. (2020) have evaluated food security issues and livelihoods, especially those of smallholder farmers and their relations with climate change.

1.2.6. Climate risk mitigation and adaptation concerns in urban areas: A systematic review of the impacts of IPCC assessment reports

Paper 1



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Review

Climate Risk Mitigation and Adaptation Concerns in Urban Areas: A Systematic Review of the Impact of IPCC Assessment Reports

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Abstract: Urban areas continue to be the center of action for many countries due to their contribution to economic development. Many urban areas, through the urbanization process, have become vulnerable to climate risk, thereby making risk mitigation and adaptation essential components in urban planning. The study assessed the impacts of IPCC Assessment Reports (ARs) on academic research on risk mitigation and adaptation concerns in urban areas. The study systematically reviewed literature through searches of the Web of Science and Scopus databases; 852 papers were retrieved and 370 were deemed eligible. The results showed that the East Asia and Pacific, and Europe and Central Asia regions were most interested in IPCC ARs, while Sub-Saharan Africa showed little interest. Several urban concerns, including socio-economic, air quality, extreme temperature, sea level rise/flooding, health, and water supply/drought, were identified. Additionally, studies on negative health outcomes due to extreme temperatures and air pollution did not appear in the first four IPCC ARs. However, significant studies appeared after the launch of the AR5. Here, we must state that climate-related problems of urbanization were known and discussed in scientific papers well before the formation of the IPCC. For instance, the works of Clarke on urban structure and heat mortality and Oke on climatic impacts of urbanization. Though the IPCC ARs show impact, their emphasis on combined mitigation and adaptation policies is limited. This study advocates more combined risk mitigation and adaptation policies in urban areas for increased resilience to climate risk.

Keywords: urban areas; climate change; mitigation; adaptation; risk; IPCC

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1. Introduction

Urban areas have long been the preferred place for human settlement [1]. This is due to the benefits and functions that serve and enable culture, learning, information, and industry [2,3]. Urban centers or cities in general go beyond human and resource concentration. People continue to settle in urban centers, and today, about half (54%) of the world's population lives in urban areas [4,5]. This is projected to increase to about 70% by the middle of the century [4]. Urban centers are articulate and facilitate greater functions of socio-economic activities that attract a lot of people [6].

The increasing concentration of people in urban areas has resulted in the transformation of agricultural lands into residential and industrial purposes [7,8]. There is, thus, unequal development of trade, housing, and tourism [9,10]. People's willingness to live in urban areas has resulted in migration and the continuous expansion of urban areas [5,11–13].

Through urbanization, many urban areas of the world have experienced massive growth with respect to population and economic development [13,14]. Urbanization is, thus, considered an essential process that offers numerous opportunities and serves as a catalyst for economic growth in urban areas [14]. Despite the numerous opportunities associated with urbanization, it results in some negative impacts and has received criticism in many studies (e.g., Wang et al. [15], Zhang et al. [16]). As people continue to live in urban centers, urban spaces expand, resulting in many socio-economic and environmental problems [15,17].

As urban areas continue to battle with the problems of urbanization, they are also challenged by the negative impacts of climate change [18,19]. This has made many urban areas of the world vulnerable [18,20,21]. For example, rising climate risks and atmospheric pollution negatively affect urban areas and increase urban vulnerabilities [22,23]. While several threats arise from the climate–atmosphere interactions, it is crucial to stress the negative impacts posed to human health, especially considering the critical role of health in socio-economic transformation [24]. Several studies have stressed the negative human health impacts and related vulnerabilities. For instance, Knol et al. [25] reported a medium to high relationship among short-term ultrafine particle exposure, mortality and morbidity, and increased cardiac and lung disease in Europe. Baccini et al. [26] highlighted the dire effects of increasing summer temperatures on people's health in fifteen European cities. Kan et al. [22] informed us about the mounting effects of extreme weather events and air pollution on mortality, infectious diseases, and water quality in China. Petkova et al. [27] also highlighted how heat-related death (deaths per one thousand population) increased in Philadelphia, New York City, and Boston between 1985–2006. Additionally, Lehtomäki et al. [28] showed that the death rate caused by particulate matter ($PM_{2.5}$) and ozone (O_3) was highest in Denmark and lowest in Iceland among the Nordic countries. Similarly, Peters and Schneider [29] explained how the combined consequences of heat, air pollution, age, and socio-economic and health conditions cause cardiovascular diseases and the need to consider disease prevention. The rise in the negative impacts of climate change and the potential health effects and vulnerabilities, especially in urban areas, needs attention [30–32]. Attention in this regard is on the right path considering the already existing negative impacts associated with the urbanization process and climate change [15].

Recent climate change is highly attributed to anthropogenic activities, and this makes population growth in urban areas a factor of global warming [14,33]. The numerous problems and vulnerabilities associated with the urbanization process place urban areas at the center of climate adaptation and mitigation [18,34]. Massive efforts have been made by urban areas and cities in general to mitigate and adapt to climate change [35,36]. As reported by Mi et al. [34], many of the world's urbanized areas have agreed on protocols that address climate change and push for urban actions that reduce greenhouse gas emissions and climate risks. Urban areas and cities' mitigation and adaptation actions to climate risks are, thus, essential towards the reduction of vulnerabilities [37].

Several studies have revealed the complementary and interrelated nature of adaptation and mitigation [38,39]. As reiterated by Landauer et al. [38], whereas adaptation reduces urban areas' sensitivity to climate risks, mitigation lessens their exposure. Conversely, Jones et al. [40] indicated differing views on the interrelatedness of adaptation and mitigation and, thus, suggested their separate treatment, especially considering the diversity of urban scale and policy design. Notwithstanding, adaptation and mitigation policies are essential to the continuous development of urban areas, and their combination offers enormous benefits, increases synergies, and minimizes conflicts [41]. As emphasized by Grafakos et al. [42], urban areas and cities recently have given attention to both adaptation and mitigation policies in planning. Several research studies (e.g., Seto et al. [13], de Oliveira and Doll [43], Gao et al. [44]) have stressed the co-benefits of adaptation and mitigation plans for urban areas.

Climate risks in urban areas were initially given less attention by climate change researchers and institutions as much attention was given to ecosystems and agriculture [45].

However, in recent times, urban areas have become the center of climate risk mitigation and adaptation, considering the socio-economic and human health vulnerabilities [13,18,34,35]. With urbanization and population growth recognized as a greater driver of global warming [14,33], it is imperative to understand how urban areas and urbanization have been treated by the climate change community, especially by the Intergovernmental Panel on Climate Change (IPCC) in their Assessment Reports (henceforth ARs).

The IPCC, established in 1988 under the auspices of the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO), is responsible for providing consistent scientific assessment on climate change, its consequences and potential future hazards, as well as adaptation and mitigation options (https://www.ipcc.ch/ accessed on 2 January 2022). The IPCC has delivered six ARs since 1988: the First (FAR) in 1990, which stressed the essence of climate change as a challenge with global effects and the need for world collaboration; the Second (SAR) in 1995, delivered essential materials for policymakers close to the approval of the 1997 Kyoto Protocol; the Third (TAR) in 2001, also drew attention to the impacts of climate change and the need for adaptation; the Fourth (AR4) in 2007, further based on the approval of the Kyoto Protocol and aimed at limiting warming at 2 °C above the late 19th century temperatures, and the Fifth (AR5) completed between 2013 and 2014, offered scientific contributions to the Paris Agreement. The Sixth (AR6), which is the current report, is expected to be completed by the second half of 2022 (although some sections are already released) and seeks to deliver three special reports: Global Warming of 1.5 °C (SR1.5), Special Report on Climate Change and Land (SRCCL), and Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (https://www.ipcc.ch/about/history/ accessed on 2 January 2022).

As policymakers, academic and scientific communities, and other stakeholders await the release of the full and complete AR6, it is worthwhile to understand the impact of the first five ARs on academic concerns. With urban areas at the forefront of climate change adaptation and mitigation [13,18,34], and urbanization regarded as a major contributor to global warming [14,33], it is critical to comprehend the implications of IPCC ARs on the issue of climate risk mitigation and adaptation in urban areas. It is interesting to note that amongst the five IPCC ARs, only the AR5 dedicated a chapter to urbanization (captured under chapter 8: Urban Areas) [46]. The AR6 also recognizes climate-related problems of urbanization. It is, thus, important to understand how research advances after the delivery of each of the IPCC's ARs. The geographical distribution and prominence of this research and the main topics reached will help understand which regions of the world are represented and cared for by IPCC ARs.

Although there exist several research studies on urbanization [33,47–49], especially on urbanized areas [14,50,51], there exists a dearth of information about how it is represented and treated after the release of each of the IPCC's ARs. Again, there is a dearth of information on how IPCC ARs impact climate risk mitigation and adaptation concerns in urban areas. A comprehensive systematic review of literature, looking at how urban areas and urbanization have been treated before and after the release of each of the IPCC's ARs is, therefore, necessary. This will help to understand the impact of IPCC ARs on climate risk mitigation and adaptation in urban areas. Such an understanding will be helpful in advising future academic research and development projects. In this regard, this study presents results of a systematic review undertaken to extract and synthesize existing knowledge on the number and type of papers 5 years before and 5 years after each of the IPCC's five ARs, their geographical distribution and prominence, and the main topics reached by placing emphasis on climate risk mitigation and adaptation in urban areas in each of these ARs. Following this, the key question that drives this review is: What impacts have IPCC ARs had on academic research on risk mitigation and adaptation concerns in urban areas?

2. Materials and Methods

This section describes the approach that was utilized to extract relevant papers that aided the understanding of the impacts of IPCC's ARs on academic research on risk mitigation and adaptation concerns in urban areas. This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) procedures [52]. The PRISMA procedure guides systematic reviews of the scientific literature to ensure that a clear research question and inclusion and exclusion criteria for studies are defined [53].

2.1. Resources and Search Procedure

The study systematically searched for documents that showed evidence of how IPCC's ARs have impacted academic research on climate risk mitigation and adaptation concerns in urban areas. The search process was conducted on 14 January 2022, in the Web of Science (WoS) and Scopus databases. The WoS, established by Clarivate Analytics, is a strong database containing more than 33,000 journals and covering more than 256 disciplines such as social sciences, environmental studies, interdisciplinary, development, and planning, among others [54,55]. Thus, WoS has more than a century of comprehensive backfile and citation data [54,55]. The Scopus database also contains more than 22,800 journals with peer-reviewed literature from five thousand publishers globally. Scopus is considered one of the largest abstract and citation databases, and has varied subject areas such as social sciences, environmental sciences, and agriculture, among others [55].

After several tests and deliberations on keywords, the authors established a range of terminologies associated with the concepts of climate change, urbanization, and risk mitigation and adaptation (Table 1). To understand the impact of IPCC ARs, the terms "ipcc" and "intergovernmental panel on climate change" were included.

Table 1. Keywords used in the document search. Note: the asterisk (*) function of truncation was used where applicable to ensure variant endings of keywords.

Climate Change	Urbanization	Risk Mitigation and Adaptation	IPCC Reports
climate change	cities	adapt *	ipcc
global warming	city	mitigate *	intergovernmental panel on climate change
greenhouse	Urban *	polic *	
CO_2			

Keywords were blended with Boolean operators (e.g., OR, AND) to find relevant concepts about climate change, urbanization, and risk mitigation and adaptation. The usage of the Boolean operator "AND" indicates that the review included studies that were based on these concepts. The full search plan with strings and Boolean operators for each database is presented in Supplementary Materials Table S1.

2.2. Eligibility and Exclusion Criteria

The literature search was restricted to research articles, books, book chapters, conferences, and conference proceedings. While many systematic review studies employ only the English language, our study expanded to include Portuguese and Spanish in addition to the English language. Publication years between January 1985 and December 2021 were deemed eligible. This was done to place the study findings in the context of current research and to conform to the IPCC's FAR published in 1990 [56]. The study excluded document types such as reviews, editorials, comments, and letters. Again, the study excluded papers that failed to treat all the three topics of interest (i.e., climate change, urbanization, and risk mitigation and adaptation). Additionally, the study excluded documents that were not related to the subject and those without direct access. The present study accepts that the exclusion of other document types might have led to the missing of vital information. How-

ever, the study believes the literature sample is broad enough to obtain a fair representation of the present literature. We must state that our study is limited to academic concerns.

2.3. Search and Selection Process

Searches from both WoS and Scopus produced 411 and 441 documents, respectively. We must state that the document search from WoS was conducted in the Web of Science Core Collection. Resulting literature citations were imported to the EndNote reference management software for organization of references (https://endnote.com/ accessed on 2 January 2022). At this stage, authors first eliminated duplicate records, a total of 268. After this, 584 documents were exported to Microsoft Excel where authors independently screened the documents to check for their eligibility. Through an independent review, the authors employed selection criteria to titles and abstract. The authors first selected a large array of articles based on titles and abstracts. From this point, the criteria were restricted to incorporate only studies that centered on climate risk mitigation and adaptation in urban areas. The study established its exclusion criteria on the proof of inclusion of climate change, urbanization, and risk mitigation and adaptation. Therefore, only studies that tackled these elements were included in this review. During this process, authors met regularly to resolve and discuss all conflicting issues with respect to the selected articles for review. In the instances where it was difficult for authors to reach a consensus on a selected document, a third researcher was contacted. The final stage of this process resulted in a total of 370 documents (Figure 1).

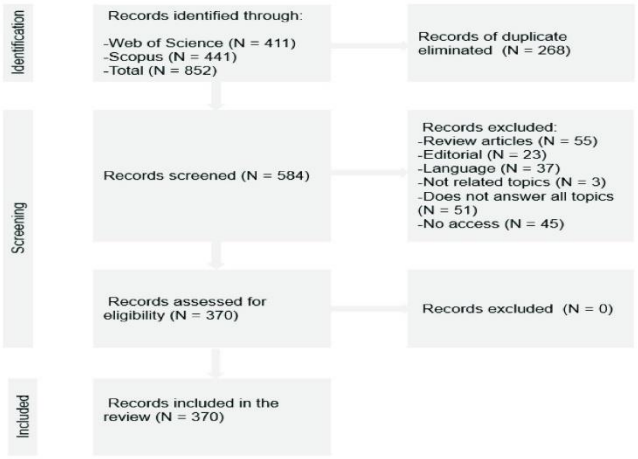


Figure 1. Flow diagram of the search and selection process of documents. Note: N indicates number of records.

2.4. Data Extraction and Analysis

Here, the data extraction procedure used by Madureira and Monteiro [57] was followed. In this regard, the authors first extracted publication characteristics such as title of the study, authors, and year of publication. Additionally, the study area, geographical distribution, and prominence were examined and extracted from each document. Additionally, the number and type of papers 5 years before and 5 years after each of the IPCC's AR were analyzed. Moreover, the topics and concerns raised in each of these documents were also extracted and analyzed. At the end of this process, documents were grouped into recurring topics, which enabled comparison across studies. Inductive qualitative analysis was used to identify the main topics covered in the IPCC ARs.

3. Results

3.1. Trends in Publication, Study Locations, Regional Groupings, and Spatial Dimension

Figure 2a–d shows the number of studies published by year, their locations, regional groupings, and the spatial dimensions applied. From Figure 2a, the majority (51) of the studies were published in the year 2019 and the least (0) in the years (e.g., 1985–1989) among others. From Figure 2a, it can be said that the IPCC paid little or no attention to climate-related urbanization problems in the earlier ARs, even though these issues were well known and discussed in scientific papers. The variations in studies between periods AR4, AR5, and AR6 could be attributed to the introduction and recognition of climate-related urbanization problems in AR5. For instance, the AR4 did not highlight the urbanization problems, and this could be a reason for the low number of studies as compared to the AR5 and AR6. FAR, as shown in Figure 2a, refers to the First Assessment Report of the IPCC which was released in 1990. The FAR stressed the essence of climate change as a challenge with global effects and the need for world collaboration. SAR is the Second Assessment Report released in 1995. Here, the IPCC delivered essential materials for policymakers close to the approval of the 1997 Kyoto Protocol. The Third Assessment Report (TAR) was launched in 2001 and in this report, the IPCC underlined the impacts of climate change and the need for adaptation. The Fourth Assessment Report (AR4), which was released in 2007, emphasized the approval from the Kyoto Protocol and aimed at limiting warming at 2 °C. Between 2013 and 2014, the Fifth Assessment Report (AR5) was also released and presented scientific contributions to the Paris Agreement. The Sixth Assessment Report (AR6), which is the current IPCC report and is expected to be completed by the second half of 2022, will seek to provide three special reports: Global Warming of 1.5 °C (SR1.5), Special Report on Climate Change and Land (SRCCL), and Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) (https://www.ipcc.ch/about/history/ accessed on 2 January 2022).

In Figure 2b, most (74) of the studies were undertaken in China, the U.S.A (50), and the least (1) were undertaken in countries such as Barbados, Algeria, and Madagascar, among others. The diversities in study locations reveal the wide-ranging regional groupings as shown in Figure 2c. Here, the majority (134) of the studies were in the East Asia and the Pacific region, followed by Europe and Central Asia (89) with the least (15) in Sub-Saharan Africa. Here, the study adapted the regional groupings of the World Bank (https://www.worldbank.org/en/about/unit accessed on 2 January 2022). In furtherance to this, a greater part (188) of the studies were conducted at the local scale, followed by national (103), and the least (6) being without scale (Figure 2d). It must be noted that local scale in this review indicates studies undertaken in specific urban areas of a country. The national scale consists of two or more cities/countries. International scale comprises two or more countries whereas global scale contains studies that were general in nature with no interest in a specific city or country but have their outcome applicable to the global sense. Studies without scale were those that did not indicate any specific scale of applicability. These studies occurred due to the document types (e.g., books and book chapters) used in the review. A summary of all the studies (370) used in the review is displayed in Supplementary Materials Table S2.

3.2. Number of Studies 5 Years before and 5 Years after the Release of Each of the IPCC ARs

Figure 3 shows the number of studies 5 years before and 5 years after the release of each of the IPCC ARs. On the FAR, the 5 years before begins from 1985–1989 and the 5 years after, which included the actual year of release (1990), starts from 1990–1994. That of the SAR in 1995 starts from 1990–1994 (5 years before) and 1995–1999 (5 years after), in that order. From Figure 3, 5 years before and 5 years after the release of the FAR (in 1990) produced (0 study) and (1), respectively. Following this and in a consistent manner, 5 years before and 5 years after the release of the SAR (in 1995) produced (1) and (0), respectively. Likewise, TAR (in 2001) recorded (0) and (6), correspondingly. It is interesting to note that more studies were produced towards the release of the AR4 (in 2007). For

instance, 5 years before and 5 years after the release of the AR4 produced (7) and (60), in that order while 5 years before and 5 years after the release of the AR5 (in 2014) recorded (77) and (156), respectively. The AR6 has produced a total of 120 studies even though it has not been fully launched. This analysis gives an idea of the research behavior of the studies that follow the IPCC ARs. It also helps to understand why the IPCC paid little attention to climate-related urbanization problems, despite the fact the issues were known and discussed in scientific papers.

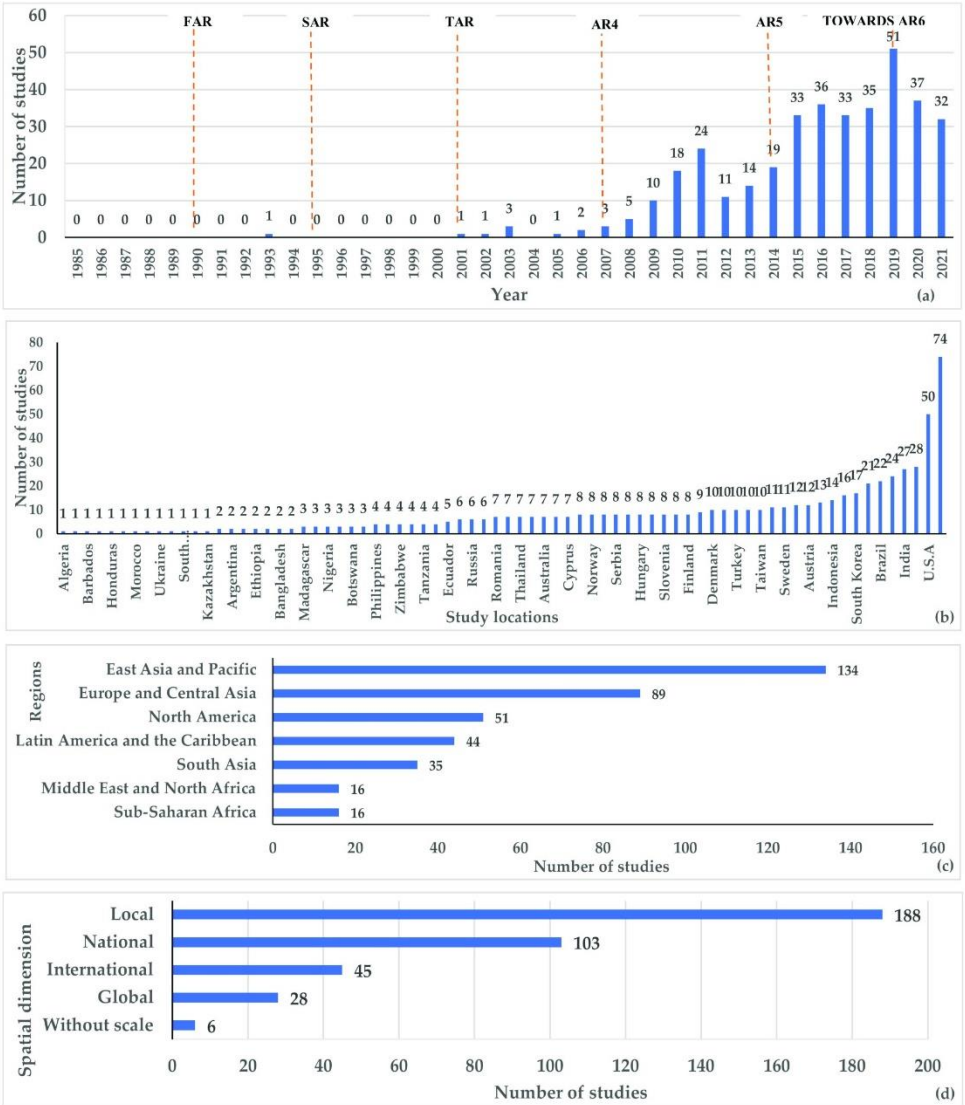


Figure 2. Study characteristics based on number of publications by year (**a**), study locations (**b**), regional distribution (**c**), and spatial dimension (**d**) of the literature used in the review.

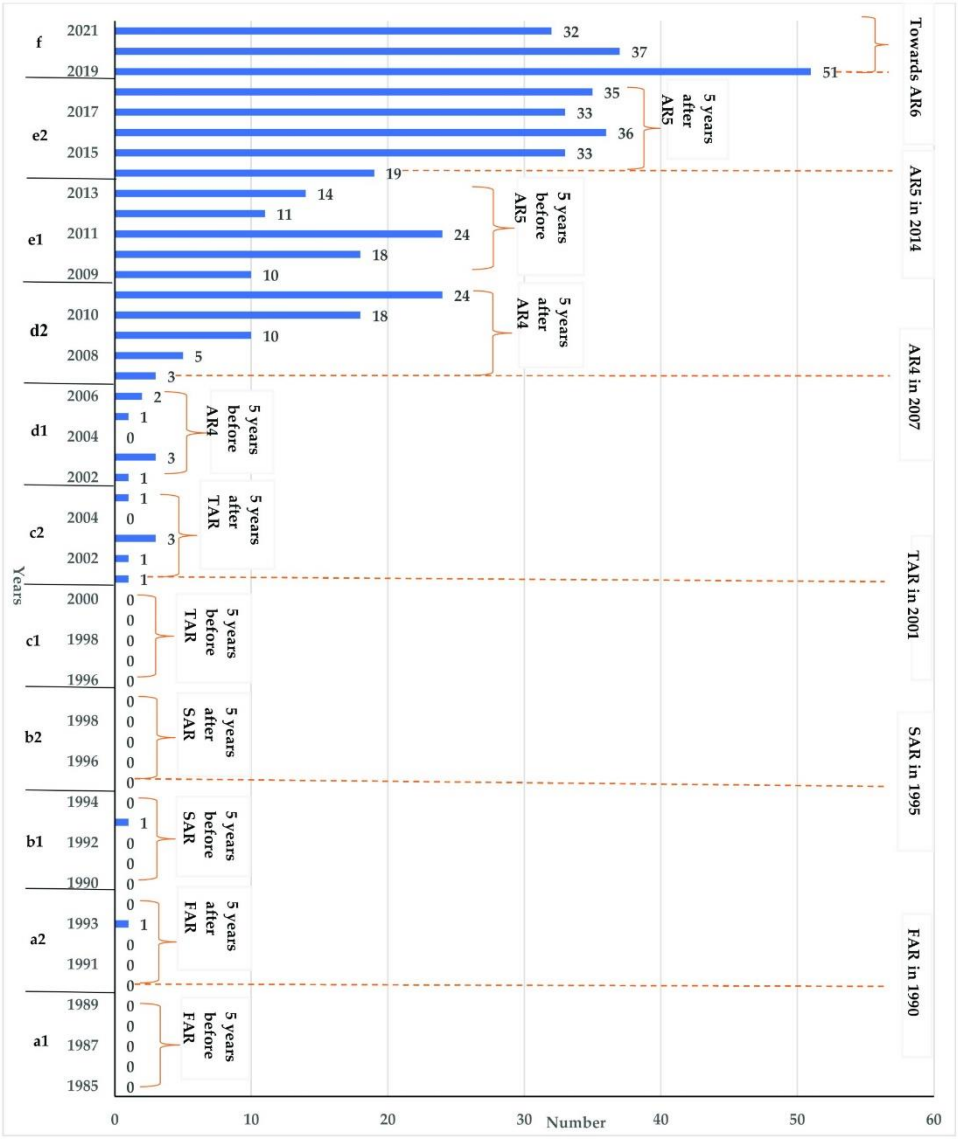


Figure 3. Number of studies 5 years before and 5 years after the release of FAR (**a1**,**a2**), SAR (**b1**,**b2**), TAR (**c1**,**c2**), AR4 (**d1**,**d2**), AR5 (**e1**,**e2**), and towards AR6 (**f**). Note: The 5 years after analysis include the year of release of the IPCC ARs.

3.3. Data Sources, Approaches to Data, and Methods

The study considered the data sources, approaches to data analysis, and methodologies utilized in the studies problematizing the subject in question. From Figure 4a, the majority (70%) of data were obtained from secondary sources and the least (5%) from both primary and secondary sources. Here, secondary sources were those studies where researchers employed already collected data. For instance, from government departments, nongovernmental organizations, etc. Primary sources reveal studies where researchers

utilized their own data, either through field surveys, experiments, or interviews, among others. In Figure 4b, a greater proportion (80%) of the studies used quantitative approach to data analysis while the qualitative approach was the least utilized (2%). In furtherance to this, most of the studies (28%) in Figure 4c used a model as the methodology, followed by the IPCC methodology (23%), while the life cycle assessment methodology, and machine learning/algorithms, among others, were the least (1%) methodology utilized. Additionally, in Figure 4d, the majority (24%) of the data type employed were from weather/climate and health data, followed by emission/activity/energy consumption (21%), while field data was the minimum (1%). The results presented here reflect the complex nature of climate-related problems of urbanization. For improved risk mitigation and adaptation plans to these problems, researchers employ diverse data sources and techniques in their analyses to understand the present and potential climate dynamics in urban areas.



Figure 4. Data sources (**a**), approach to data analysis (**b**), methodology (**c**), and data types (**d**) of the literature used in the review. Note: *NR indicates studies that did not report any data source, approach to data analysis, methodology, and data type.

3.4. Study Focus, Outcome, and Main Concerns

Figure 5a–c reveals the focus, outcome, and main concerns addressed by researchers following the release of each of the IPCC ARs and taking into consideration the concerns of risk mitigation and adaptation in urban areas. In Figure 5a, a greater proportion (53%) of research studies concentrated on risk mitigation measures, followed by adaptation (42%), while few studies (5%) placed emphasis on both risk mitigation and adaptation. Here, topics that focused on reducing the impact of climate change or reducing greenhouse gas emissions in a particular urban area were defined as "risk mitigation". Those that

focused on adjusting to present and potential impacts of climate change in a particular urban area were classified as "adaptation". Studies that employed both of the aforesaid were categorized as both (mitigation and adaptation). Again, in Figure 5b, outcomes from most research studies (98%) were general recommendations rather than specific evidence (2%) of risk mitigation and adaptation measures in urban areas. A general recommendation is used here to denote research studies that did not indicate any individual mitigation or adaptation measure in the area of application but made an overall conclusion of the need for such measures in the respective urban areas of application. Specific evidence is also used to signify research studies that show proof of the existence or new application of mitigation and adaptation measures in their study in the respective area of application. Additionally, socio-economic issues were the most (50%) concerns raised, followed by air quality (17%), while health (5%) and water supply/drought (5%) were the minimum concern highlighted (Figure 5c).

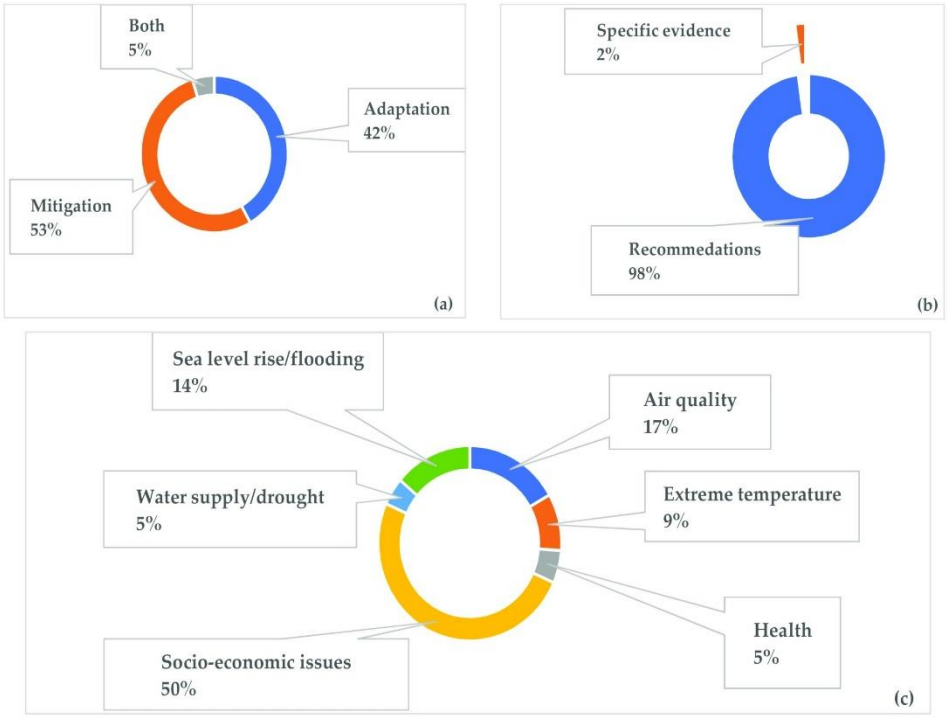


Figure 5. Study focus (**a**), outcome (**b**), and main concerns (**c**) raised in the literature used in the review.

4. Systematic Review: Qualitative Synthesis of Literature

The studies presenting the impacts of IPCC ARs on academic research on risk mitigation and adaptation in urban areas raised several concerns, including socio-economic, air quality, sea level/flooding, extreme temperature, health, and water supply/drought.

4.1. Socio-Economic

The studies revealing the socio-economic impacts of climate issues in urban areas showed varied outcomes. Most studies raised problems relating to climate impacts on agriculture, food security, poverty, and the adaptive capacity of urban areas. For instance, Salleh [58] stressed the impacts of climate change on agriculture and urban commerce in

Malaysia and the developing countries of Southeast Asia, and its effects on poverty and food security. Salleh [58] suggested the need for better adaptation plans to prevent national and international conflicts in the region. Similarly, Ruiz-Alvarez et al. [59] underlined the variations in monthly and annual precipitation and their negative effects on agriculture in Aguascalientes, Mexico. To better adapt to this situation, Ruiz-Alvarez et al. [59] advocated the need to store water during high humid precipitation months for use in the dry season. Likewise, Singh et al. [60] stated that decreased freshwater access will have a surging effect on worldwide food security, livelihood, and widespread migration. Singh et al. [60] recommended increased measures for water preservation and wastewater recycling for improved adaptation. On the contrary, Ye et al. [61] projected an increase in food crop yield from 2030−2050 in China and indicated an increase in food supply in China. Nonetheless, Ye et al. [61] warned of the growing Chinese population as a counter-element to the projected increase in food supply and called for significant policy alternatives to address this issue. Again, Zhao et al. [62] found low and high adaptive capacity to climate problems in the inland and eastern coastal urban agglomerations, respectively, in China. Zhao et al. [62] proposed both adaptation and mitigation measures such as the expansion of infrastructure and funding for improved adaptive capacity in the underdeveloped regions and the regular monitoring of climate change impacts in the developed areas of China. Additionally, Wilder et al. [63] noted that climate change adaptation at international (U.S.A.–Mexico) borders is conservatively seen as difficult, despite the possible improved resilience in regionalization of adaptive responses. The researchers suggested specific adaptation plans such as improved social learning and co-creation of climate knowledge [63]. Additionally, Khan et al. [64] reported the vulnerable conditions of farmers in urban Punjab, Pakistan. To adapt to this situation, Khan et al. [64] suggested the enabling of climate-smart adaptation initiatives for urban farmers through the execution of useful policies and investment strategies.

Other studies emphasized the concerns about the impact of urbanization, urban housing, and city planning. Norman [65] saw the challenges associated with urbanization in Australia and proposed seven principles (see Norman [65] for more details), that should support intergovernmental accord on urban coastal planning. Moreover, Xie et al. [66] emphasized that the Shanghai metropolitan areas in China have the highest rates of increase in annual and seasonal average surface air temperature, ranging from 0.23 °C to 0.50 °C per decade due to urbanization. Likewise, Marelle et al. [67] stressed that urbanization increased the frequency and intensity of extreme urban precipitation in the megacities of Paris, Tokyo, Shanghai, and New York. To mitigate this, Marelle et al. [67] advocated the recognition of urbanization effects in urban planning assessments to make cities more resilient to extreme precipitation. In furtherance to this, Wilkinson [68] found changes in environmental building elements in Melbourne, Australia, and emphasized the need for policymakers to monitor building owners' integration of environmental elements into their stock to enhance sustainability. Moreover, Rosatto et al. [69] informed us about the usefulness of green roofs in regulating the thermal change of buildings in the autonomous city of Buenos Aires, Argentina, and specifically advocated for their use in controlling thermal change of buildings. Equally, Kousis et al. [70] established the potency of resin-based pavement binder made with waste bio-oils in urban noise reduction and explicitly suggested its global exploration in the urban pavement market.

4.2. Air Quality

The studies on air quality reflecting the impacts of IPCC ARs on the concerns of risk mitigation and adaptation in urban areas focused on pollution from both outdoor and indoor sources in cities. For instance, Garg et al. [71] found the electric power generation division of India to be the highest contributor of sulfur dioxide (SO_2) emissions, while the power and transport divisions likewise lead in nitrogen oxide (NO_x) emissions. Garg et al. [71] suggested mitigation elasticity to officials for efficient mitigation in India. Sthel et al. [72], in their laboratory experiment, found that ethanol production in Brazil

generates pollutant gases like N_2O, SO_2, and NO_x, and advised better mitigation measures in that regard. Again, Campbell et al. [73], in their analysis on the impacts of transport sector emissions on future U.S. air quality under climate change reported widespread decreases in future concentrations of NO_X, SO_2, volatile organic compounds (VOCs), carbon monoxide (CO), ammonia (NH_3), and particulate matter with a diameter of microns (μm) less than or equal to 2.5 ($PM_{2.5}$) due to decreasing on-road vehicle emissions in urban areas. Notwithstanding, Campbell et al. [73] indicated an increase in 8 h ozone (O_3) in the U.S.A. and advised on the appropriate mitigation measures. Additionally, at the European level, San José et al. [74] found that by the year 2100, O_3 concentrations will decrease over most parts of Europe due to changes in temperature and precipitation, except Greece, Bulgaria, and Romania, and in the city of Milan, Italy, and advised on the need for the right mitigation measures. Moreover, Xie et al. [75] established that biogenic VOC and soil NO_X emissions over the Yangtze River Delta (YRD) area of China in 2008 were 657 Gigagrams (Gg) of carbon and 19.1 Gg of nitrogen, correspondingly. Xie et al. [75] indicated a potential increase in these emissions by 25% and 11.5% in 2050, in that order. In the same study, the researchers found an increase in surface O_3 of 5 to 15 parts per billion (ppb) in the northern areas and a decrease of −5 to −15 ppb in the southern areas of the YRD. Similarly, Lam [76] highlighted the potential increase in P.$M_{2.5}$ and O_3 in the Pearl River Delta region of China in 2050 under the representative concentration pathway (RCP 8.5). In their analysis on the impact of urban growth on air quality in Indian cities, Misra et al. [77] found that above the central portion of a city, concentrations of $PM_{2.5}$ emissions are mostly contributed by residential areas, brick kilns, and industries.

4.3. Sea Level Rise/Flooding

Several other studies confirmed sea level rise and flood risks in urban areas. On sea level rise, Bhuiyan and Dutta [78] informed us about increased salinity intrusion into the Gorai River in Bangladesh and advocated for the appropriate adaptation plans. Wong et al. [79] stressed that regionally, megacities in Africa, South, Southeast, and East Asia, and the Small Island States have the highest vulnerabilities to sea level rise, which requires adaptation. Wang et al. [80] revealed the potential impacts of rising tides on residential buildings in Australia and informed the need for adaptation. In Abadie's analysis of sea level damage risk in the world's 120 major coastal megacities, the researcher reported potential greater damage for Guangzhou, China and New Orleans, U.S.A., and emphasized the need for potential huge adaptation assets in these countries [81]. Additionally, Mycoo et al. [82] emphasized the vulnerable state of Greater Bridgetown, Barbados, due to sea level rise and revealed the significance of human adaptation and the safety of precious coastal assets.

On flood risk, Moeslund et al. [83] talked about the possible flooding in Aarhus, Denmark, in the event of extreme weather phenomena and suggested the incorporation of appropriate flood models equally to those in their study on potential city planning. Mortsch [84] revealed the flooding challenges in downtown London, Ontario, Canada, and recommended increased adaptation in that regard. Le Cozannet et al. [85] reported the probabilistic marine flooding in the urban Mediterranean basin in Lyon, France, and recommended the consideration of a change-centered global sensitivity analysis of potential marine flooding. Additionally, Cheng et al. [86] showed the effectiveness of the detention of increasing flood hazards in the Charles River watershed in Boston, U.S.A., and suggested the importance of creating more detention areas integrated with soil preservation in watershed development. Further, Samu and Kentel [87] stated that the greater part of Zimbabwe has low to medium (2.3% likelihood) flood incidence and highlighted the need for the execution of proper mitigation measures. Martínez-Gomariz et al. [88] highlighted the effects of pluvial flood risk in Badalona, Spain, and stressed the need for a comprehensive adaptation plan. Moreover, Abadie et al. [89] analyzed potential coastal flood risk damage in 136 cities and found the highest potential damage in Guangzhou, China; Mumbai, India, and New Orleans, U.S.A. Abadie et al. [89] recommended the need to encompass the

likelihood of high-end scenarios into coastal urban adaptation development for potential sea level rise and flood risk.

4.4. Extreme Temperatures

In extreme temperatures, many studies emphasize heat stress and thermal comfort. For instance, Lee and Levermore [90] reported an increase in mean surface temperature and its effect on heat and cold in the cities of Seoul and Ulsan, South Korea, and indicated the need for improved mitigation. Similarly, O'Neill et al. [91] stressed the excessive heat events in 285 communities in the U.S.A. Although mitigation measures are in place, O'Neill et al. [91] suggested the need for more collaboration and economic resources to assist widespread mitigation actions. Again, Adachi et al. [92] revealed the present and potential increased urban heat island (UHI) in Tokyo, Japan, and called for increased mitigation measures against UHI for the city. Additionally, Tromeur et al. [93] described the energy needs for residential buildings and comfort (heat) in 10 French cities and indicated their susceptibility. For improved mitigation, Tromeur et al. [93] suggested the need for city managers to think about green space spots, push polluting actions beyond the city, and lower car traffic for riders. McPhee et al. [94] informed us about the potential heat events in Santiago, Chile, due to increasing temperatures and decreasing precipitation and recommended the need for effective adaptation plans. Additionally, Shevchenko et al. [95] underlined the heat wave episodes in Lugansk and Henichesk, Ukraine, and highlighted the need for adaptation. Further, Cinar [96] revealed the increased UHI in Fethiye, Turkey, due to a rise in night-time temperatures. The researcher suggested the need to consider street alignment of buildings and the dimensions of public and green areas in city management and design [96]. Hamdi et al. [97] found no significant change and increased warming in annual mean UHI intensity and nocturnal UHI, respectively, in the cities of Brussels (Belgium) and Paris (France), and advised appropriate adaptation plans. In furtherance to this, Alves et al. [98] showed the residential thermal discomfort situation in São Paulo, Brazil, and recommended an improved adaptation plan in that regard. Equally, Invidiata and Ghisi [99] indicated the potential increase in residential energy demand of buildings in the cities of Curitiba, Florianópolis, and Belém, Brazil, and recommended the utilization of passive design plans in buildings. Li et al. [100] emphasized the potential for higher temperatures and severe heat waves in Toronto, Ontario, Canada, and showed how their study can help policymakers realize potential temperature changes in Ontario. In proposing specific mitigation measures against heat due to increasing urban temperatures in Bari, Italy, Lassandro et al. [101] specifically suggested the use of green roofs, water jects, and cooling resources. Furthermore, Kotharkar et al. [102] discovered significant variation in temperature regime and heat stress within Nagpur, India, and demonstrated how their research can provide heat response planning and mitigation plans to the area.

4.5. Health

Several studies stressed the negative health impacts (mortality, morbidity, and general human health) in urban areas due to increasing temperatures and air pollution. For instance, Knol et al. [25] reported that 14 European technocrats ranked a medium-to-high association between increased short-term ultrafine particle exposure and mortality, and morbidity for cardiac and lung diseases. The researchers recommended the need to consider ultrafine particles in potential health risk assessment [25]. Muthers et al. [103] informed us about the potential rise in heat-associated mortality of about 129% in the city of Vienna, Austria, if no adaptation plan is taken. In the analysis of the effect of heat on mortality in 15 European cities, Baccini et al. [26] found that heat-related mortality for summer went from zero (0) in Dublin, Ireland to 423 in Paris, France. Baccini et al. [26] further indicated the potential increase in summer temperatures and their effect on the health of the people in Europe, and emphasized the need for improved mitigation. Similarly, Ostro et al. [104] reported increased premature deaths in California, U.S.A., and recommended the increased use of air conditioners as a mitigation measure for heat risk. Likewise, Petkova et al. [27] showed

that heat-associated mortality per thousand population increased in Philadelphia, New York City, and Boston, respectively, from 1985 to 2006. Petkova et al. [27] highlighted the significant contributions of their study in developing measures that can reduce potential heat effects. Again, Kim et al. [105] revealed the projected increased mortalities in Seoul, Daegu, Gwangju, Busan, Incheon, and Daejeon, South Korea, and stressed effective measures that can cause significant health improvement and decrease heat-associated mortality. Additionally, Rasmussen et al. [106] highlighted the increased ragweed species in the European countries of Denmark, France, Germany, and Russia by the year 2100, and showed how this intersects with heavily inhabited cities like Paris and St. Petersburg. Rasmussen et al. [106] suggested the need for preventive measures to limit ragweed seed spread and the application of inter-country management measures for increased mitigation of potential health risk. Chen et al. [107] further informed us about the potential increase in surface O_3 and associated mortality in China and underlined the need for mitigation measures. Additionally, Estoque et al. [108] assessed heat health risk in 139 cities in the Philippines and reported high heat health risk in the Manila metropolitan area. The researchers indicated how their research can assist in risk reporting and improve knowledge of city-scale health risks.

4.6. Water Supply/Drought

Most studies raised concerns about the impact of climate issues relating to water supply and demand, water use and management, and drought. For example, Gober et al. [109] reported that current per capita water use in Phoenix, Arizona, can be maintained in the absence of unmanageable groundwater use. For improved mitigation against drought disasters, Galvão et al. [110] stated that rainwater catchment structures are used in the urban areas in Brazil and Japan to increase water source and use. Again, Wilson and Weng [111] reported water quality (phosphorus concentration) issues in the Des Plaines River watershed in Chicago, Illinois, U.S.A. during late winter and early spring. The researchers underlined the importance of their study in contributing to the reduction of negative effect on surface water quality and improved mitigation [111]. Moreover, Jacinto et al. [112] informed us about the potential reduction in water use in Portugal until 2100 and recommended a proper adaptation plan. Additionally, Huang et al. [113] found variations in water resources and potential drying trends and their effects on water resources in Chinese cities. Huang et al. [113] suggested the need to address water resource challenges and adapt to the impacts of climate change. Ougougdal et al. [114] reported increased water demand and related water scarcity problems in Ourika, Morocco, and called for an appropriate adaptation plan. Alike, Alkhawaga et al. [115] underlined the potential water security condition in Kafr El Sheikh city, Egypt, and recommended the need for frequent evaluation of water security features for Egyptian cities.

Table 2 shows a summary of the key findings, recommendations, and specific evidence from the main concerns reviewed.

Table 2. Summary of the key findings, recommendation and specific evidence of main concerns. Note: - shows no recommendation or specific evidence.

Author	Key Findings	Recommendations	Specific Evidence
	Socio-economic concerns		
Salleh [58]	The impacts of climate change on agriculture and urban commerce in Malaysia and the developing countries of Southeast Asia, and its effects on poverty and food security	The need for better adaptation plans to prevent national and international conflicts in the region	-
Ruiz-Alvarez et al. [59]	The variations in monthly and annual precipitation and their negative effects on agriculture in Aguascalientes, Mexico	Advocated the need to store water during high humid precipitation months for use in the dry season	-

Table 2. *Cont.*

Author	Key Findings	Recommendations	Specific Evidence
	Socio-economic concerns		
Singh et al. [60]	Decreased freshwater access will have a surging effect on worldwide food security, livelihood, and widespread migration	Increased measures for water preservation and wastewater recycling for improved adaptation	-
Ye et al. [61]	projected an increase in food crop yield from 2030−2050 in China and indicated an increase in food supply in China	Called for significant policy alternatives to address the growing Chinese population	-
Zhao et al. [62]	Low and high adaptive capacity to climate problems in the inland and eastern coastal urban agglomerations, respectively, in China	Expansion of infrastructure and funding for improved adaptive capacity in the underdeveloped regions and the regular monitoring of climate change impacts in the developed areas of China	-
Wilder et al. [63]	Climate change adaptation at international (U.S.A.-Mexico) borders is conservatively seen as difficult, despite the possible improved resilience in regionalization of adaptive responses	-	Improved social learning and co-creation of climate knowledge
Khan et al. [64]	Vulnerable conditions of farmers in urban Punjab, Pakistan	The enabling of climate-smart adaptation initiatives for urban farmers through the execution of useful policies and investment strategies	-
Norman [65]	Challenges associated with urbanization in Australia	Declaration of a buffer zone, capacity building for local communities, the recognition of the unique natural and cultural heritage and local interest in coastal planning, among others	-
Xie et al. [66]	Shanghai metropolitan areas in China have the highest rates of increase in annual and seasonal average surface air temperature, ranging from 0.23 °C to 0.50 °C per decade due to urbanization	Adaptation plan should be given the needed attention by policymakers	-
Marelle et al. [67]	Urbanization increased the frequency and intensity of extreme urban precipitation in the megacities of Paris, Tokyo, Shanghai, and New York	Advocated the recognition of urbanization effects in urban planning assessments	-
Wilkinson [68]	Changes in environmental building elements in Melbourne, Australia	The need for policymakers to monitor building owners' integration of environmental elements into their stock to enhance sustainability	-
Rosatto et al. [69]	The usefulness of green roofs in regulating the thermal change of buildings in the autonomous city of Buenos Aires, Argentina	-	Green roofs
Kousis et al. [70]	Resin-based pavement binder made with waste bio-oils reduce urban noise	-	The global exploration of bio-oils in the urban pavement market

Table 2. *Cont.*

Author	Key Findings	Recommendations	Specific Evidence
	Socio-economic concerns		
Singh et al. [60]	Decreased freshwater access will have a surging effect on worldwide food security, livelihood, and widespread migration	Increased measures for water preservation and wastewater recycling for improved adaptation	-
Ye et al. [61]	projected an increase in food crop yield from 2030−2050 in China and indicated an increase in food supply in China	Called for significant policy alternatives to address the growing Chinese population	-
Zhao et al. [62]	Low and high adaptive capacity to climate problems in the inland and eastern coastal urban agglomerations, respectively, in China	Expansion of infrastructure and funding for improved adaptive capacity in the underdeveloped regions and the regular monitoring of climate change impacts in the developed areas of China	-
Wilder et al. [63]	Climate change adaptation at international (U.S.A.-Mexico) borders is conservatively seen as difficult, despite the possible improved resilience in regionalization of adaptive responses	-	Improved social learning and co-creation of climate knowledge
Khan et al. [64]	Vulnerable conditions of farmers in urban Punjab, Pakistan	The enabling of climate-smart adaptation initiatives for urban farmers through the execution of useful policies and investment strategies	-
Norman [65]	Challenges associated with urbanization in Australia	Declaration of a buffer zone, capacity building for local communities, the recognition of the unique natural and cultural heritage and local interest in coastal planning, among others	-
Xie et al. [66]	Shanghai metropolitan areas in China have the highest rates of increase in annual and seasonal average surface air temperature, ranging from 0.23 °C to 0.50 °C per decade due to urbanization	Adaptation plan should be given the needed attention by policymakers	-
Marelle et al. [67]	Urbanization increased the frequency and intensity of extreme urban precipitation in the megacities of Paris, Tokyo, Shanghai, and New York	Advocated the recognition of urbanization effects in urban planning assessments	-
Wilkinson [68]	Changes in environmental building elements in Melbourne, Australia	The need for policymakers to monitor building owners' integration of environmental elements into their stock to enhance sustainability	-
Rosatto et al. [69]	The usefulness of green roofs in regulating the thermal change of buildings in the autonomous city of Buenos Aires, Argentina	-	Green roofs
Kousis et al. [70]	Resin-based pavement binder made with waste bio-oils reduce urban noise	-	The global exploration of bio-oils in the urban pavement market

Table 2. *Cont.*

Author	Key Findings	Recommendations	Specific Evidence
	Air quality concerns		
Garg et al. [71]	Electric power generation division of India is the highest contributor of Sulfur dioxide (SO_2) emissions, while the power and transport divisions likewise lead in nitrogen oxide (NO_x) emissions	Mitigation elasticity to officials for efficient mitigation in India	-
Sthel et al. [72]	Ethanol production in Brazil generates pollutant gases like N_2O, SO_2, and NO_x	The need for better mitigation measures	-
Campbell et al. [73]	Decrease in future concentrations of NO_X, SO_2, volatile organic compounds (VOCs), carbon monoxide (CO), ammonia (NH_3), and $PM_{2.5}$) due to decreasing on-road vehicle emissions in urban areas and increase in 8-hr ozone (O_3) in the U.S.A.	The need for appropriate mitigation measures	-
San José et al. [74]	By the year 2100, O_3 concentrations will decrease over most parts of Europe due to changes in temperature and precipitation, except Greece, Bulgaria, and Romania, and in the city of Milan, Italy	Advised on the need for the right mitigation measures	-
Xie et al. [75]	Biogenic VOC and soil NO_X emissions over the Yangtze River Delta (YRD) area of China in 2008 were 657 Gg of carbon and 19.1 Gg of nitrogen, correspondingly	The need for appropriate mitigation measures	-
Lam [76]	The potential increase in P.$M_{2.5}$ and O_3 in the Pearl River Delta region of China in 2050 under the RCP 8.5	The need for appropriate mitigation measures	-
Misra et al. [77]	Concentrations of $PM_{2.5}$ emissions are mostly contributed by residential areas, brick kilns, and industries in Indian cities	Right mitigation measures	-
	Sea level rise/flooding		
Bhuiyan and Dutta [78]	Increased salinity intrusion into the Gorai River in Bangladesh	Advocated for the appropriate adaptation plans	-
Wong et al. [79]	Regionally, megacities in Africa, South, Southeast, and East Asia, and the Small Islands States have the highest vulnerabilities to sea level rise	The need for adaptation plan	-
Wang et al. [80]	The potential impacts of rising tides on residential buildings in Australia	The need for adaptation	-
Abadie [81]	potential greater damage for Guangzhou, China and New Orleans, U.S.A. due to sea level rise risk	The need for potential huge adaptation assets in these countries	-
Mycoo et al. [82]	Vulnerable state of Greater Bridgetown, Barbados due to sea level rise	The significance of human adaptation and the safety of precious coastal assets	-
Moeslund et al. [83]	Potential flooding in Aarhus, Denmark in the event of extreme weather phenomena	The incorporation of appropriate flood models in potential city planning	-
Mortsch [84]	Flooding challenges in downtown London, Ontario, Canada	Increase adaptation	-
Le Cozannet et al. [85]	Probabilistic marine flooding in the urban Mediterranean basin in Lion, France	The consideration of a change-centered global sensitivity analysis of potential marine flooding	-

Table 2. *Cont.*

Author	Key Findings	Recommendations	Specific Evidence
	Sea level rise/flooding		
Cheng et al. [86]	the effectiveness of detention in decreasing flood hazards in the Charles River watershed in Boston, U.S.A.		The use of detention in controlling flood hazards
Samu and Kentel [87]	Greater part of Zimbabwe has low to medium (2.3% likelihood) flood incidence	The need for the execution of proper mitigation measures	-
Martínez-Gomariz et al. [88]	The effects of pluvial flood risk in Badalona, Spain	The need for a comprehensive adaptation plan	-
Abadie et al. [89]	Potential coastal flood damage in Guangzhou, China; Mumbai, India; and New Orleans, U.S.A.	The need to encompass the likelihood of high-end scenarios into coastal urban adaptation development	-
	Extreme temperatures		
Lee and Levermore [90]	An increase in mean surface temperature and its effect on heat and cold in the cities of Seoul and Ulsan, South Korea	The need for improved mitigation	-
O'Neill et al. [91]	Excessive heat events in 285 communities in the U.S.A	The need for more collaboration and economic resources to assist widespread mitigation actions	-
Adachi et al. [92]	Present and potential increased urban heat island (UHI) in Tokyo, Japan	Increase mitigation measures against UHI for the city	-
Tromeur et al. [93]	The energy needs for residential buildings and comfort (heat) in 10 French cities.	The need for city managers to think about green space spots, push polluting actions beyond the city, and lower car traffic for riders	-
McPhee et al. [94]	Potential heat events in Santiago, Chile due to increasing temperatures and decreasing precipitation	The need for effective adaptation plans	-
Shevchenko et al. [95]	Heat wave episodes in Lugansk and Henichesk, Ukraine	The need for adaptation	-
Cinar [96]	Increased UHI in Fethiye, Turkey due to a rise in night-time temperatures.	The need to consider street alignment of buildings and the dimensions of public and green areas in city management and design	-
Hamdi et al. [97]	Potential neutral and increased warming in annual mean UHI intensity and nocturnal UHI, respectively, in the cities of Brussels (Belgium) and Paris (France)	Appropriate adaptation plans	-
Alves et al. [98]	Residential thermal discomfort situation in São Paulo, Brazil	Improve adaptation plan	-
Invidiata and Ghisi [99]	Potential increase in residential energy demand of buildings in the cities of Curitiba, Florianópolis, and Belém, Brazil	The utilization of passive design plans in buildings	-
Li et al. [100]	Potential for higher temperatures and severe heat waves in Toronto, Ontario, Canada	The effectiveness of their research in helping policymakers realize potential temperature changes in Ontario	-
Lassandro et al. [101]	The effectiveness of green roofs, water jects, and cooling resources increasing temperatures	-	The use of green roofs, water jects, and cooling resources
Kotharkar et al. [102]	Significant variation in temperature regime and heat stress within Nagpur, India	Their research can provide heat response planning and mitigation plans to the area	-

Table 2. *Cont.*

Author	Key Findings	Recommendations	Specific Evidence
	Health		
Knol et al. [25]	14 European technocrats ranked a medium-to-high association between increased short-term ultrafine particle exposure and mortality and morbidity for cardiac and lung diseases	The need to consider ultrafine particles in potential health risk assessment	-
Baccini et al. [26]	Heat related mortality for summer went from zero (0) in Dublin, Ireland to 423 in Paris, France	The need for improved mitigation	-
Petkova et al. [27]	showed that heat-associated mortality per thousand population increased in Philadelphia, New York city and Boston, respectively, from 1985 to 2006	The effectiveness of their study in developing measures that can reduce potential heat effects	-
Muthers et al. [103]	Potential rise in heat-associated mortality of about 129% in the city of Vienna, Austria	The need for adaptation	-
Ostro et al. [104]	Increased premature deaths in California, U.S.A.	The increased use of air conditioners as a mitigation measure for heat risk	-
Kim et al. [105]	Projected increased mortalities in Seoul, Daegu, Gwangju, Busan, Incheon, and Daejeon, South Korea	The need for effective measures that can cause significant health improvement and decrease heat-associated mortality	-
Rasmussen et al. [106]	Increased ragweed species in the European countries of Denmark, France, Germany, and Russia by the year 2100	The need for preventive measures to limit ragweed seed spread and the application of inter-country management measures for increased mitigation of potential health risk	-
Chen et al. [107]	Potential increase in surface O_3 and associated mortality in China	The need for mitigation measures	-
Estoque et al. [108]	High heat health risk in the Manila metropolitan area, Philippines	The strength of their research can assist in risk reporting and improve knowledge of city-scale health risks	-
	Water supply/drought		
Gober et al. [109]	Current per capita water use in Phoenix, Arizona, can be maintained in the absence of unmanageable groundwater use	The need to monitor groundwater for improved adaptive plan	-
Galvão et al. [110]	Rainwater catchment structures are used in the urban areas in Brazil and Japan to increase water source and use	The need for improved mitigation	-
Wilson and Weng [111]	Water quality issues in the Des Plaines River watershed in Chicago, Illinois, U.S.A. during late winter and early spring	The effectiveness of their study in contributing to the reduction of negative effect on surface water quality and improved mitigation	-
Jacinto et al. [112]	Potential reduction in water use in Portugal until 2100	The need for proper adaptation plan	-
Huang et al. [113]	Variations in water resources and potential drying trends and their effects on water resources in Chinese cities	The need to address water resource challenges and adapt to the impacts of climate change	-

Table 2. *Cont.*

Author	Key Findings	Recommendations	Specific Evidence
	Water supply/drought		
Ougougdal et al. [114]	Increased water demand and related water scarcity problems in Ourika, Morocco,	Appropriate adaptation plan	-
Alkhawaga et al. [115]	Potential water security condition in Kafr El Sheikh city, Egypt	the need for frequent evaluation of water security features for Egyptian cities	-

5. Discussion

The study assessed the impacts of IPCC ARs on academic research on risk mitigation and adaptation concerns in urban areas. The study has shown how research advances before and after the release of each of the IPCC ARs. This review has revealed the little or no interest by the IPCC in their first three ARs (FAR, SAR, and TAR) in the concerns of risk mitigation and adaptation in urban areas, thereby showing few studies (only 2). This is also reflected in the 5 years before and 5 years after analyses of the IPCC ARs, where the combined total number of studies produced under FAR, SAR, and TAR was only 6 (see Figure 3). Notwithstanding, attention was given to risk mitigation and adaptation in urban areas 5 years after the release of the AR4, with increased attention from the AR5 in 2014. It is interesting to note that it was in this report (AR5) that the IPCC first recognized urban areas and the associated urbanization [46]. Since then, the IPCC's impact on risk mitigation and adaptation concerns in urban areas has increased. The impact in this regard influenced further investigations and the related increase in the number of studies by different researchers from different countries. For example, the highest number (74) comes from China, and 2019 was the year with the highest (51) number of publications on risk mitigation and adaptation in urban areas.

The studies problematizing the subject in question were conducted at a wide scale (from local to global scales) with the East Asia and Pacific, and Europe and Central Asia regions showing more interest in IPCC ARs. This is reflected in their increased number of studies and their attempt to address climate risk in urban areas through mitigation and adaptation measures. Little interest is observed in Sub-Saharan Africa, and this could be due to their low socio-economic and human capital. The study again revealed that data for urban risk mitigation and adaptation is obtained from secondary sources through governmental and non-governmental bodies and the academic community. For improved risk mitigation and adaptation, quantitative analysis of data and model techniques have increased and are highly utilized in many research studies such as [26,62].

The study systematically reviewed literature and showed the diverse concerns researchers bring up about risk mitigation and adaptation in urban areas. The concerns are grouped into six major categories: (i) socio-economic concerns; (ii) air quality concerns; (iii) sea level rise/flooding; (iv) extreme temperatures; (v) water supply/drought, and (vi) health concerns.

As mentioned elsewhere in the study, health plays a crucial role in socio-economic growth. It is, therefore, essential to emphasize the negative health effects due to extreme temperatures and air pollution, and more importantly, the role of the IPCC ARs in that regard. It is interesting to note that negative health-related issues with regard to this review only appeared in the years 2009−2020 and were based on scenarios at the national and local scales. Thus, this review did not find studies on negative health effects arising from extreme temperatures and air pollution in the IPCC's first four ARs (i.e., no study was identified from 1990−2007). However, from 2009−2020, 20 studies (indicating 5%, see Figure 4) were found, with more than half of the studies (14) appearing after the IPCC's AR5 in 2014. The high number of studies on the negative health concerns could be due to the introduction and significance that was first given to urban areas in the IPCC AR5 [46].

Considering the diverse concerns and issues confronting numerous urban areas indicated in this review, it is interesting to note that many studies failed to propose specific risk mitigation measures and adaptation plans. While the urban challenges were easily identified, most researchers made general recommendations, with only a few proposing specific solutions to the urban area under study and their potential application to other urban areas. With urban areas and cities at the center of climate risk mitigation and adaptation [18,34], and population growth in urban areas being considered as a driver of global warming [14], this study believes that researchers should provide more specific evidence of risk mitigation measures and adaptation plans. For example, Rosatto et al. [69] proposed the use of green roofs in regulating the thermal change of buildings; Kousis et al. [70] proposed the global use of bio-oils for increased mitigation against urban noise islands; Cheng et al. [86] proposed the use of detention in decreasing flood hazards in the Charles River watershed in Boston, U.S.A., and Lassandro et al. [101] proposed the use of vegetation, green roofs, and water jects for mitigating heat risk in Bari, Italy. It must be stated that this study does not stand to disregard general recommendations on risk mitigation and adaptation in urban areas. However, considering the present and potential vulnerable state of many urban areas, the provision of specific evidence is equally important for improved mitigation and adaptation of climate risks in urban areas.

There is a possibility of bias in the present results, especially on the statement that significant research studies appeared after the release of the IPCC AR5. The study placed emphasis on the relation between IPCC reports and academic research on climate risk mitigation and adaptation in urban areas, and excluded studies that did not mention IPCC. Here, we must state that climate-related problems of urbanization were known and discussed in scientific papers well before the formation of the IPCC. For instance, the studies of Clarke [116] on urban structure and heat mortality, and Oke [117] on climatic impacts of urbanization.

6. Conclusions

The impacts of IPCC ARs on academic research on risk mitigation and adaptation concerns in urban areas have been systematically appraised. It has been established that greater significance was attached to risk mitigation and adaptation in urban areas starting from the last two ARs. These ARs challenged countries and researchers to further risk mitigation and adaptation research for increased urban resilience and sustainability. This review has shown the great interest by the East Asia and Pacific, and Europe and Central Asia regions in IPCC ARs, reflecting their increased number of scientific studies on risk mitigation and adaptation in urban areas. The interests of the Americas (North America, Latin America, and the Caribbean regions) also need to be acknowledged. Notwithstanding, the Sub-Saharan African and the Middle East and North African regions need to be encouraged with motivation and resources for increased contribution and interest in IPCC ARs. Specific country determinations to risk mitigation and adaptation plans in urban areas were high in China and the U.S.A.

Several urban concerns, including socio-economic, air quality, extreme temperature, sea level rise/flooding, health, and water supply/drought, were revealed by the research following the release of each IPCC AR. This, thus, demonstrates the impact and influence of the IPCC ARs on risk mitigation concerns in urban areas. The concerns of most research studies were expressed in relation to socio-economic issues rather than extreme temperatures, which have received the most attention in the IPCC ARs, particularly the attempts to limit global warming at 1.5 °C (see https://www.ipcc.ch/sr15/faq/faq-chapter-1 accessed on 2 January 2022). Even though this raises doubt, we believe that these studies are moving in the right direction because increasing extreme temperatures are demonstrated by socio-economic and ecological impacts and the associated susceptibilities.

This review emphasized the negative health outcomes that arise from extreme temperatures and air pollution. This emphasis was made given the crucial role of health in urban development, especially in recent times where urban risk mitigation and adapta-

tion are at the forefront. Considering the impact of IPCC ARs on climate risk mitigation and adaptation research promotion in urban areas, this review established that the negative health effects due to extreme temperatures and air pollution were not considered in the first four IPCC ARs. Thus, since the first release in 1990 until the fourth in 2007, no study on the negative health effects of extreme temperatures and air pollution was found with regard to this review. Negative health concerns, however, started to appear in 2009 and, with more concerns, raised after the launch of the IPCC AR5 in 2014. As the IPCC AR5 placed significant attention on urban areas and the urbanization process, it is equally important that the IPCC consider the negative health outcomes that arise from the climate–atmosphere interactions.

This review again demonstrated that risk mitigation policies in urban areas outnumbered adaptation policies or the combination of both policies. While this confirms urban centers' efforts to reduce climate risk, we advocate for the combination and increased use of both policies in urban areas as stressed elsewhere in this review. Although their integration comes with a huge cost, we believe that mitigation and adaptation complement each other. It must be stated that some countries and their urban centers already have both (mitigation and adaptation) policies. However, the extensive admission and application of both policies in all urbanized centers of the world should be the focus. The IPCC, with greater influence, can help push in that regard. Additionally, studies following the IPCC ARs and demonstrating their impact should also advocate for both risk mitigation measures and adaptation plans with specific evidence. The provision of specific mitigation and adaptation plans in the study outcome for a particular urban area can be applied to other urban areas with similar challenges. In this way, the new urban agenda in facilitating resilient urban areas and cities can be attained.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/cli10080115/s1, Table S1: Keywords combination used in WoS and Scopus databases, Table S2: Summary of all the studies (370) used in the systematic review.

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1.2.7. Future climate projections: uncertainties, models, scenarios, and applications

Regular projections of possible future changes and impacts caused by anthropogenic greenhouse gas emissions are necessary due to ongoing global climate change, variability, and extreme events. Miao et al. (2014) highlighted the increasing interest in future climate projections and their related applications in recent years. Collins et al. (2013) argue that, despite the growing attention, predicting future climate change is more challenging than forecasting weather. Collins et al. (2013) state that the predictions of climate change are uncertain because they depend on scenarios of future anthropogenic and natural forcings, the limited understanding and imperfect models of the climate system, and the presence of internal climate variations. Collins et al. (2013), however, maintain that it is possible to comprehend and project future climate change by utilising enhanced models to describe potential outcomes and uncertainties based on specific assumptions about future forcing scenarios.

This has led to the development of models capable of simulating present and possible future climate change under various greenhouse gas emissions and aerosol scenarios (Buser et al., 2009; Miao et al., 2014). Covey et al. (2003) emphasised that global coupled Atmospheric-Ocean General Circulation Models (coupled AOGCMs) have conventionally been used to theoretically evaluate climate change mechanisms. Miao et al. (2014) asserted that employing GCMs not only facilitates the simulation of present and projected future climate change under various scenarios but also enables the distinction between natural climatic variability and human-induced impacts. Taylor et al. (2012) highlighted that the development of the fifth phase of the Coupled Model Intercomparison Project (CMIP5) enhances our understanding of climate variability and potential future climate change. Siew et al. (2014) state that the GCM CMIP5 in the IPCC AR5 supersedes the AR4. The GCMs in the CMIP5 of the AR5 consist of different types of models, such as climate and earth systems models (Fowler et al., 2007; Liu et al., 2013; Miao et al., 2014). These models have incorporated additional collaborative elements, including atmospheric chemistry, aerosols, dynamic vegetation, ice sheets, and the carbon cycle. (Fowler et al., 2007; Liu et al., 2013; Miao et al., 2014; Siew et al., 2014; Zhang et al., 2016; Zhou et al., 2015). Several studies, including Chhin and Yoden (2018), Hu et al. (2017), Lun et al. (2021), Miao et al. (2014), and Navarro-Racines et al. (2020), have compiled a list of the CMIP5 GCMs in the IPCC AR5 in their respective studies. In the CMIP5 GCMs, there exist representative concentration pathway scenarios (i.e., RCPs 2.6, 4.5, and 8.5) that aid the climate change

projection, as highlighted by Moss et al. (2010). According to Moss et al. (2010), the RCPs reflect the various levels of greenhouse gases, with their projections spanning from 1850 to 2100 and further projections extending up to 2300.

Researchers have extensively utilised GCMs to predict climate change and variability on a global and continental level (Liu et al., 2019; Sunyer et al., 2012). These models have varying spatial resolutions, ranging from around 100 to 300 km (Chim et al., 2021; Liu et al., 2019; Sunyer et al., 2012). Although the GCMs have the capacity to predict possible climate change and variability in the future, Chim et al. (2021) and Wu et al. (2012) contend that the products are only available at a broader resolution. These products, as reiterated by Chim et al. (2021), Hay et al. (2000), and Wilby et al. (2000), are not appropriate for regional- and local-scale climate change projections. Several other researchers, such as Ali et al. (2019), Fowler et al. (2007), Maraun et al. (2010), Shahriar et al. (2021), Siabi et al. (2021), Sillmann et al. (2013), Tarekegn et al. (2022), and Wu et al. (2012), have raised the same concerns about the coarse nature of the GCMs. Ali et al. (2019) and Sillmann et al. (2013) have contended that GCMs lack the ability to accurately represent complex mountain landscapes and provide detailed climate information at a local level due to their coarse spatial resolution and inherent biases. The coarse nature of GCMs has led to the development of downscaling techniques to narrow the gap in climate change and variability projection at the regional and local scale (Ali et al., 2019; Sunyer et al., 2012; Wood et al., 2002; Wu et al., 2012). According to Wu et al. (2012), downscaling techniques are considered a valuable method for linking global-scale predictions with regional dynamics in order to collect significant local climate data. Ali et al. (2019) also describe downscaling techniques as a process of generating large-scale information from a coarser one. There are two commonly recognised downscaling techniques in the literature: dynamic downscaling and statistical downscaling (Ali et al., 2019; Maraun et al., 2010; Shahriar et al., 2021; Sunyer et al., 2012; Tarekegn et al., 2021).

Dynamic downscaling focuses on a specific area by incorporating it into a regional climate model (RCM) within a global GCM or by defining large-scale variables as the boundary condition for the RCM (Shahriar et al., 2021; Sunyer et al., 2012; Xu et al., 2019; Zou & Zhou, 2017). This allows for a more detailed examination of the relationship between atmospheric physics and a specific area of interest in the grid box resolution. (Liu et al., 2019; Maraun et al., 2010). The statistical downscaling technique is based on the statistical relationships between local area characteristics and large-scale variables (Maraun et al., 2010; Vogel et al., 2023; Wilby et al., 2002). Dynamic downscaling has

some limitations, including the need for a lot of processing power, high costs, extensive data storage requirements, and biases when transitioning from GCMs to RCMs (Ali et al., 2019; Boé et al., 2023; Wood et al., 2004). Researchers widely recognize statistical downscaling for its effectiveness, user-friendliness, and capacity to integrate connections between observations and GCM outputs (Boé et al., 2023; Fowler et al., 2007; Lanzante et al., 2018). Although the statistical downscaling technique is efficient and user-friendly, researchers like Dayon et al. (2015) and Lanzante et al. (2018) have pointed out its limitations in capturing all the important physical processes that influence regional climate change. Despite their limitations, multiple bias correction methods have been created and are frequently utilised in climate impact research (Ali et al., 2019; Rahimi et al., 2021; Vogel et al., 2023; Wood et al., 2004; Wood et al., 2002). Researchers, including Maraun (2016) and Maraun and Widmann (2018), have conducted a comprehensive analysis of the current downscaling and bias correction methods. Researchers have compared and evaluated several methods for correcting bias and downscaling climate variables like precipitation and temperature in different regions: Ayugi et al. (2020) in Kenya, East Africa, Dieng et al. (2022) in West Africa, Gutiérrez et al. (2019) in Europe, Ji et al. (2020) in the Yarluzangbu-Brahmaputra River Basin in Asia, Langousis et al. (2016) in the Flumendosa River Basin in the Island of Sardinia, Italy, Lober et al. (2023) in Canada and Alaska, Räty et al. (2014) in northern and southern Europe, Vogel et al. (2023) in Australia, Xavier et al. (2022) in São Paulo, Brazil, and Yoshikane and Yoshimura (2023) in southwestern Japan.

Several studies, including those conducted by Alvarez et al. (2024), Bint-e-Mehmood et al. (2024), Chim et al. (2021), Chong-Hai and Ying (2012), Dike et al. (2015), Disasa et al. (2024), Faggian (2021), Hussain et al. (2017), Lee et al. (2014), Mamba and Randhir (2024), Ongoma et al. (2018), Sun et al. (2015), Tefera et al. (2024), and Tewari et al. (2022), have made projections regarding possible future climate change, specifically in terms of precipitation and temperature, in various locations worldwide. Chong-Hai and Ying (2012) predicted that the northern regions of China will experience more significant warming compared to the southern regions in all areas, as per the RCP. According to Chong-Hai and Ying (2012), there is a projected decline in precipitation in the southern regions of China and a considerable increase in the northern regions from 2011 to 2040, particularly under the RCP 8.5 scenario. Chong-Hai and Ying (2012) warned about the unavoidable uncertainties in their study. Sun et al. (2015) discovered comparable projected regional changes in both warming and precipitation patterns in ten river basins in China,

corroborating the earlier investigation conducted by Chong-Hai and Ying (2012). Lee et al. (2014) found that significant warming will increase the intensity of monsoonal precipitation in East Asia. According to Lee et al. (2014), there is a projected increase of 131% and 111% in extreme weather events, specifically heat waves with temperatures surpassing 30 °C, in South Korea under the RCP 8.5 scenario. Additionally, there is expected to be a 24% and 31.5% increase in more frequent and variable heavy rains in the same region. In their study, Hussain et al. (2017) found that the maximum temperature in Kuching, Bintulu, and Limbang, located in the Sarawak State of Malaysia, is expected to increase by 1.94 °C, 0.09 °C, and 1.29 °C, respectively, from 2071-2100 compared to the baseline period of 1981–2010. This projection was made under the RCP 8.5 scenario. Based on Hussain et al. (2017), temperatures are expected to increase by 1.21 °C in Kuching, 0.15 °C in Bintulu, and 2.08 °C in Limbang under the same conditions. Ongoma et al. (2018) documented an increase in the projected amount of rainfall in East Africa throughout the time frame of 2071-2100. According to the study, there will be a more significant rise in rainfall during the October–December season compared to the March–May season under RCP 8.5 than under RCP 4.5 (Ongoma et al., 2018). According to the findings, East Africa is projected to experience a temperature increase of 1.7 to 2.8 °C under the RCP 4.5 scenario and 2.2 to 5.4 °C under the RCP 8.5 scenario (Ongoma et al., 2018). According to Araya-Osses et al. (2020), it is expected that both the minimum and maximum temperatures in Chile will increase throughout all seasons. According to the researchers, the RCP 8.5 scenario predicts that by the end of the 21st century, winter maximum temperatures will increase by more than 6 °C and winter minimum temperatures will increase by more than 2 °C. Additionally, winter precipitation is expected to decrease by more than 40% in the central-southern area and increase by over 60% in the northern Andes (Araya-Osses et al., 2020). In their study, Bint-e-Mehmood et al. (2024) found that the eastern and western Potohar semi-arid regions of Pakistan are expected to experience a considerable mean temperature increase of 3.2 °C and 2.8 °C, respectively, under the RCP 4.5 scenario. According to the RCP 8.5 scenario, Bint-e-Mehmood et al. (2024) predict a temperature rise of 3.9 °C and 4.0 °C in the eastern and western regions, respectively. The researchers found that there were considerable variations in precipitation in both the eastern and western Potohar regions, but no clear long-term patterns were observed (Bint-e-Mehmood et al., 2024).

1.2.8. Climate change and coastal zones

The world's coastal zone has, since antiquity, remained one of the most habitable areas for the human population (Douglas et al., 2012; McGranahan et al., 2007; UN-Habitat, 2008). This is due to the essential services such as protection against erosion, inundation, storms, sea level rise, and saltwater intrusion, among others (Martinez, 2007; Basset and Abbiati, 2004; Kjerfve, 1994) and benefits including food, recreation, trade and transport, employment, habitat for marine species, educational opportunities, and health promotion (Wheeler et al., 2012) it provides to humans and other species. The literature indicates that about 60% of the world's population lives in coastal zones (Fan et al., 2010; Small & Nicholls, 2003). Of these population, about 23% are located in a distance of one hundred kilometres (km) from the shore and below one hundred metres (m) above sea level (Small & Nicholls, 2003). With high preference for settlement, most coastal landscapes have been transformed into different functions and purposes as reiterated by Valiela (2006). People's willingness to live in the coastal zone has resulted in migration and urbanisation of the global coastal zone (Nicholls et al., 2007; Seto, 2011). As highlighted in the studies of Brown et al. (2013) and Nicholls et al. (2007), the world's coastal zones contain 39 metropolises with more than 5 million inhabitants, which put huge pressure and threat on the coastal zone and the related ecosystems.

Coastal communities and ecosystems have become one of the most susceptible in the world in terms of climate change and variability impacts (Barbier, 2015; Rabbani et al., 2015; Bunce et al., 2010; Nicholls & Cazenave, 2010; IPCC, 2014b, 2001b). Anthropogenic actions have significantly contributed to recent climate change (He & Silliman, 2019). Human industrial actions have generated large quantities of greenhouse gases such as CO_2 and CH_4 emissions. This has caused several physiochemical changes in the atmosphere, the biosphere, the ocean, and the cryosphere (He & Silliman, 2019). The most evident physiochemical changes occurring in the coastal zones include rising sea levels and storm surge, increasing ocean temperatures and salinity (Snaiki et al., 2020; Varela et al., 2018; IPCC, 2014b; Nicholls and Cazenave, 2010), changes in land surface temperature, and precipitation (Nicholls et al., 2018; IPCC, 2014b).

The physiochemical changes also cause spatiotemporal variability in the climate of coastal zones, which results in extreme climatic phenomena such as flooding, drought, heat waves, erosion, saltwater intrusion, inundation, and shoreline change, among others (Fang et al., 2021; Xiao et al., 2018; IPCC, 2014b; Pugh & Woodworth, 2014; Gornitz, 2013). Spatiotemporal variability also affects ocean circulation and upwelling (IPCC, 2014b). For instance, despite current strong changes in land surface temperature and sea level rise, the

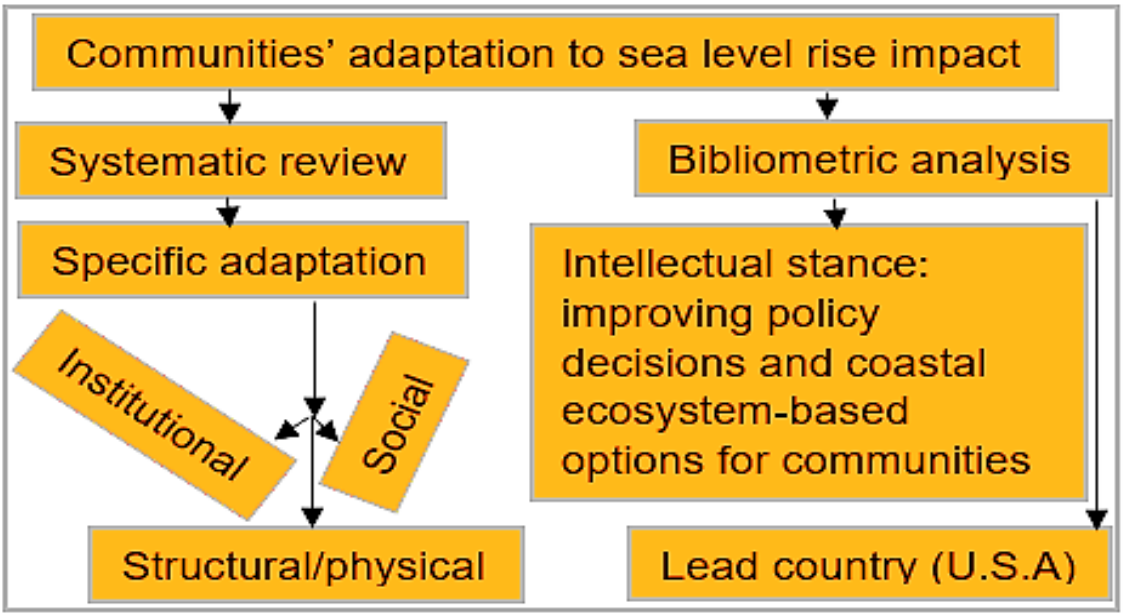
IPCC projects further increases in these variables in the future (IPCC, 2014b). Physiochemical dynamics in the coastal zones, therefore, have significant negative effects on communities and environments.

The number of studies highlighting the negative effects of the changing and variable climate on coastal zones has risen substantially. Several of these studies encompass original research and a comprehensive examination of existing literature. Original studies utilise a series of impact assessment models to examine the effects of climate change and variability on coastal zones. Studies such as those conducted by Alizad et al. (2018), Bruno et al. (2018), Kleisner et al. (2017), Reimann et al. (2018), Rodríguez et al. (2017), Thorne et al. (2018), Sanford et al. (2019), Serpetti et al. (2017), Valiela et al. (2018), and Vitousek et al. (2017) have analysed climate change and variability impacts on coastal ecosystems, while Dhiman et al. (2019); Uddin et al. (2019); Makame and Kangalawe (2018) have analysed climate change and variability impacts of coastal communities and their livelihoods.

Reimann et al. (2018) highlighted that by the year 2100, the risk associated with flooding and erosion will rise by 50% and 13%, respectively, across the low-lying coastal heritage sites in the Mediterranean regions. Serpetti et al. (2017) investigated the influence of ocean warming (rising temperature) and related declines in fish species such as cod, herring, and grey seals, among others. Using principal component analysis, Uddin et al. (2019) demonstrated the potential changes in vulnerability of the coastal areas of Bangladesh. Makame and Kangalawe (2018) also reported the water security challenges in the coastal communities of Zanzibar due to climate change. Review studies have also analysed literature to recognise the state-of-the-art on climate change and variability impacts on coastal zones. For example, Carstensen and Duarte (2019), Giffin et al. (2020), Grieger et al. (2020), Griffith and Gobler (2020), and Mehvar et al. (2018) have reviewed literature on climate change and variability impacts on coastal ecosystems. Other studies, such as those of Bukvic et al. (2020), Busayo and Kalumba (2020), Solecki and Friedman (2021), and Toimil et al. (2020), have also studied the adaptation and vulnerability of coastal communities to climate change and variability.

1.2.9. Geospatiality of sea level rise impacts and communities' adaptation: A bibliometric analysis and systematic review

Paper 2



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REVIEW ARTICLE

Geospatiality of sea level rise impacts and communities' adaptation: a bibliometric analysis and systematic review

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Abstract

The impacts of sea level rise under a changing climate negatively affect the world's coastal zones and threaten livelihood opportunities of the dependent communities, thereby highlighting the need for improved coastal adaptation strategies. The study employed a two-step methodology (i.e. bibliometric and systematic review) to analyse the geospatiality of sea level rise impacts and communities' adaptation. In total, 363 papers were retrieved from Scopus and Web of Science databases, and 292 were considered eligible and used for the bibliometric analysis. In the systematic review, the study aimed for specific community adaptation strategies from the 292 papers, and 118 papers were eligible following developed criteria. Results indicate that countries are committed to helping their coastal communities to adapt to sea level rise impacts and the USA has been significant in that regard. Coastal communities adapt to sea level rise impacts by increasing their structural/physical or social options; however, policy/institutional assistance to intensify these options is limited. Also, specific community adaptation strategies to sea level rise impacts have been more of the engineered and built environment (67%) strategies and few on ecosystem-based strategies (7%). More ecosystem-based strategies are, thus, needed considering their socio-ecological benefits. Further research and increased communities-policymakers engagement for enhanced adaptive capacity is required.

Keywords Sea level rise · Climate change · Climate change adaptation · Vulnerability · Coastal resilience · Coastal flooding

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1 Introduction

The world's coastal regions continue to be the most settled (Zheng et al. 2020) and have been the preferred source for human habitation due to their livelihood-pleasing characteristics which favour economic development (Lima and Bonetti 2020). Increased economic development and related anthropogenic activities have made the world's coastal regions one of the most affected by the negative impacts of climate change (Intergovernmental Panel on Climate Change (IPCC 2014); Nicholls and Cazenave 2010). Recent climate change is highly attributed to anthropogenic activities (IPCC 2014), and the related impacts, such as sea level rise, cause negative effects on the world's coastal regions (IPCC 2014).

Sea level rise is considered one of the major impacts of climate change (Nerem et al. 2018). Climate change-related sea level rise is primarily attributed to ocean thermal expansion and glacier melting (Church et al. 2001; IPCC 2014; Markphol et al. 2021). Future global mean sea level is projected to rise by 0.84 m ($0.61-1.10$ m, likely range) under the Representative Concentrative pathway (RCP8.5) by 2100 (Oppenheimer et al. 2019). The rise is expected to continue for centuries beyond 2100 (Oppenheimer et al. 2019). Coastal erosion, inundation, and floods are the most visible impacts of sea level rise (Doelle and Puthucherril 2021; Kaplanis et al. 2020). Sea level rise causes the advancement of saline water into estuaries, lagoons, and other coastal freshwater bodies. Besides, sea level rise affects beaches and their morphologies, coastal low-lying areas, and displaces human populations (Doelle and Puthucherril 2021). As indicated by the IPCC, global sea levels are rising and will continue to rise (IPCC 2019). Despite countries' commitment to their national determined contributions to limiting emissions in accordance with the Paris Agreement as stressed by Doelle and Puthucherril (2021), or the net zero initiative by mid-century and maintaining warming to 1.5 ℃ in the recent Conference of Parties (COP26) held in Glasgow, sea level rise will continue to pose challenges to the world's coastal regions. Consequently, adaptation is a crucial aspect of the management of sea level rise threats to the world's coastal regions.

Adaptation to sea level rise impacts involves the employment of plans and actions that aim to reduce the susceptibility or harm of socio-ecological systems (Doelle and Puthucherril 2021; IPCC 2018). Since adaptation is a dynamic procedure, there has always been difficulty in classifying it into the right group. Adaptation can be seen as proactive in situations where initiatives already exist before the occurrence of a phenomenon and its consequences become obvious (IPCC 2018). Warren et al. (2004) also indicated adaptation to be reactive when initiatives are employed after the occurrence of phenomena. Likewise, Pittock and Jones grouped adaptation into planned and autonomous (Pittock and Jones 2000). As a result, adaptation that follows a deliberate policy decision is seen as planned, and the opposite is the case with autonomous adaptation (Pittock and Jones 2000). Adaptation to sea level rise, therefore, takes diverse forms and approaches. Adaptation approaches to sea level rise have relied heavily on conventional methods that employ engineering mediations like seawalls, levees, bulkheads, revetments, dykes, groynes, tide gates, storm surge barriers, artificial islands, and floating cities and homes (Hill 2015; Temmerman et al. 2013). While conventional methods have been the more utilised method for sea level rise adaptation, they have received some criticism, including habitat loss and reduction in aquatic species abundance (Sutton-Grier et al. 2015), human fatalities and property damage (Ashley and Ashley 2008), prevention of natural migration of wetlands and mangroves (Gilman et al. 2006), and restricting public access (Rodriguez et al. 2008). Currently, there

has been an increasing acknowledgment of nature-based adaptation solutions to balance the conventional methods of addressing the threats of sea level rise (Doelle and Puthucherril 2021; Hirschfield et al. 2021). Nature-based adaptation solutions employ actions that aim to protect, manage sustainably, and restore natural or modified ecosystems and address societal adaptation challenges and contribute to human welfare and biodiversity benefits (Cohen-Shacham et al. 2016).

How communities adapt to the impacts of sea level rise continues to be a challenge, especially where a successful adaptation depends on the adaptive capacity of the affected community (Kuriakose et al. 2009). Adaptive capacity differs between the developed and developing world. Smit et al. (2001) echoed problems such as illiteracy, underdevelopment, extreme poverty, unemployment, gender bias, institutional weaknesses, and corruption as the major barriers that weaken the growth of adaptive capacities. As reiterated by Kuriakose et al. (2009), most developing countries are disregarded politically, socially, and economically and have several barriers that reduce their adaptive capacities. These barriers slow the adaptation process and result in harmful effects like maladaptation (IPCC 2007).

Several research studies on sea level rise impacts and communities' adaptation are available, including original research and literature reviews. Original research studies employ a sequence of impact appraisal models to analyse how coastal communities adapt to the impacts of sea level rise (e.g. Doelle and Puthucherril 2021; Markphol et al. 2021; Onat et al. 2018; Timmerman et al. 2021). Review studies have also been conducted in order to identify the state-of-the-art in how coastal communities adapt to impacts of sea level rise (e.g. Hinkel et al. 2018; Molinaroli et al. 2019; Woodruff et al. 2020). As the original research continues to grow, literature review studies analysing how coastal communities adapt to sea level rise impacts have also increased. Despite the increasing research, studies on the geospatial nature of communities' adaptation to sea level rise impacts are limited. In a similar conceptual domain, Lima and Bonetti (2020) employed the bibliometric approach to analyse the global scientific production on coastal communities' social vulnerability to climate change and the impacts of extreme events. Pathmanandakumar et al. (2021) also utilised the bibliometric approach to provide an overview of the scientific literature on climate change and coastal tourism. Similarly, Bertolini and da Mosto (2021) applied this approach to the scientific literature on coastal wetland restoration research in the last 30 years. In addition, Wang et al. (2014) utilised the same method to quantitatively analyse the global scientific performance and hot research areas in climate change vulnerability. Besides, Leal et al. (2022) employed the same method to present the status of the global scientific production of studies that showed evidence of the impacts of storm surges on coastal zones. Though the studies (Leal et al. 2022; Lima and Bonetti 2020; Wang et al. 2014) are conceptually related to the present study, the researchers made no attempt to underline how communities adapt to sea level rise impacts, which is an essential element in coastal vulnerability assessment (Birkmann et al. 2022; Salik et al. 2015). A study of this nature is pertinent, particularly in the light of the justification for vulnerability assessment as a step in the adaptation planning process (Fu et al. 2019; IPCC 2014).

To respond to this gap, it is imperative to identify methodologies that can reveal the conceptual, intellectual, and state-of-the-art stance concerning the subject. In this regard, this study builds on the bibliometric method already utilised in the studies of (Leal et al. 2022; Lima and Bonetti 2020; Wang et al. 2014) and extends it to include the systematic review approach to understand the specific adaptation strategies undertaken by coastal communities to sea level rise impacts. Thus, incorporating a two-step methodology for the present study, the combined bibliometric and systematic review methods have been applied to various subjects (e.g. in marine transport by Gil et al. (2020), in education by Wafa et al.

(2022), and in health by Adunlin et al. (2015). To the best of our knowledge, no study has used both bibliometric and systematic methods to show how communities are adapting to the effects of sea level rise. This is an important area to study, especially since coastal areas are facing more and more threats from climate change and climate variability that require planned adaptation (Adger et al. 2003; Badjeck et al. 2010; Smit et al. 2000).

This study, therefore, analysed the geospatiality of communities' adaptation to sea level rise impacts. Employing the aforementioned approaches and in a broader perspective, this study first analysed the global scientific production on the subject through the bibliometric approach to chart the wider bibliographic data from scientific articles available in established internet databases. Thenceforth, the study systematically appraised the community-specific adaptation strategies to sea level rise impacts. The aim of the bibliometric analysis is to understand the global scientific production and the geospatial distribution, the intellectual and conceptual stance, and the state-of-the-art knowledge on the subject, while the key question that drives the systematic review is: what specific strategies are being undertaken by coastal communities in their attempt to adapt to sea level rise impacts? Considering the recent Conference of Parties (COP26) discussions in Glasgow, which highlighted sea level rise and the need for increased adaptation to the negative impacts, combined bibliometric and systematic analyses on the geospatiality of communities' adaptation to sea level rise impacts is essential. This will help to indicate objectively the current state of research, geographical dissemination and the community-specific adaptation strategies undertaken by coastal communities in an attempt to adapt to sea level rise impacts. This study, therefore, contributes to the increasing body of literature on sea level rise impacts and adaptation under a changing climate in the world's coastal regions.

2 Materials and methods

This section describes the two-step methodology (i.e. bibliometric and systematic review methods) that was employed to analyse the global scientific production on the geospatiality of sea level rise impacts and communities' adaptation, and the specific adaptation strategies undertaken by communities.

2.1 Bibliometric method

The Bibliometric analysis of scientific literature employs a statistical technique to chart the structure and form of scientific knowledge using reputable data sources (De Oliveira et al. 2019). Initially, the objective of this method was to determine the academic performance of individual authors and/or institutions. However, in recent years, it has been utilised extensively to comprehend the development and pattern of numerous knowledge fields (Soares et al. 2016). The method is essential for analysing and evaluating the research and publication performance of individual authors and their institutions, and it is useful for charting the current state of scientific topics (Cobo et al. 2015). According to Lima and Bonetti (2020), the bibliometric approach is essential for researchers conducting a bibliographic analysis of a particular field of study because it reveals the structural and dynamic nature of scientific fields. It contributes to the quality of review by ensuring the transparency and reproducibility of the review process (Cobo et al., 2015). Furthermore, as highlighted by Lima and Bonetti (2020), the method aids in understanding the contributions to a topic from a variety of academic disciplines. It also assists in understanding emerging trends

and the evolution of knowledge, the most productive and cited authors and institutions, author collaborations, the research pioneers and research lines in a particular field, and the major publications that disseminate the scientific output of a particular field of knowledge (Pathmanandakumar et al. 2021). Pathmanandakumar et al. (2002) stressed that the bibliometric method of graphing scientific data is an excellent complement to meta-analysis and structural-analysis of the literature.

The five-step methodological plan of Zupic and Čater's (2015) was adapted (Fig. 1) for the purpose of conducting a bibliometric analysis of the global scientific production on the geospatiality of communities' adaptation to sea level rise impacts. This methodology was utilised by Lima and Bonetti (2020) in their research on bibliometric analysis of the social vulnerability of coastal communities to climate change and the effects of extreme events. The methodological plan of Zupic and Čater's follows a five-step approach to thematic mapping.

In the first step, the study needs to clearly define its goals with respect to the usage of bibliometric analysis. Following this, the present study acknowledged the combined theoretical foundation (principal authors), present trends in research (country/geographical prevalence, and the relevant journals), and the established network of research (key concepts and keywords addressed over the years) concerning the topic. Bibliographic database selection and compilation occurs in the second step. The most utilised databases are Web of Science (WoS) (Clarivate Analytics), Scopus (Elsevier), and Google Scholar (Google Group). The WoS is a reliable database with over 33,000 journals encompassing over 256 disciplines. Likewise, Scopus incorporates more than 22,800 peer-reviewed journals from more than 5,000 publishers globally. Google Scholar is a website and search engine used, among other things, to locate academic journals, books, and reports. In this review, the WoS and Scopus databases were utilised. The WoS and Scopus have multiple indexes and are regarded as reliable, extensive databases for a variety of uses (Pranckut 2021; Zhu and Liu 2020). Google Scholar is a free web search engine, but it has several weaknesses, such as a lack of consistency, transparency, and accuracy, as well as the inability to export its data (Boeker et al. 2013; Pranckut 2021). As underlined by Lima and Bonetti (2020), these databases are of scientific merit, incorporate a broad range of knowledge fields, and permit coherent interpretations on of the subjects investigated.

Following the statements of Lima and Bonetti (2020) on the need to merge databases, this study made an effort to combine the Web of Science (WoS) and Scopus databases for the bibliometric analysis. The merging process has been described in our previous study (see Ankrah et al. 2022). This study utilised documents indexed in both WoS and Scopus

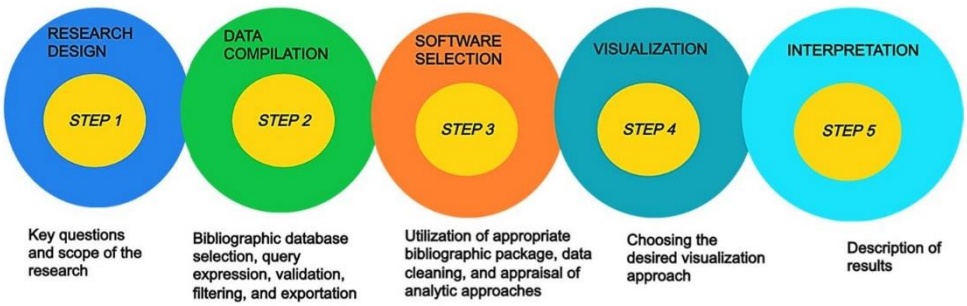


Fig. 1 Steps for scientific data charting using bibliometric approach. Adapted from Zupic and Čater (2015)

databases to analyse the global scientific production of coastal communities' adaptation to sea level rise impacts. The criteria utilised for the study's inclusion and selection were: (a) Study communities must be situated in a coastal region; (b) Impact should be the result of sea level rise; and (c) Communities' adaptation should be towards sea level rise impact. Studies outside these three points were excluded. Next, the usage of Boolean operators and quotation marks is very essential as this helps to avoid publications that include comparable phrases but lack the necessary semantic context (Lima and Bonetti 2020).

After several tests and deliberations on keywords, the study established a range of terminologies associated with the concepts of sea level rise impacts and communities' adaptation. These keywords were mixed with Boolean operators (e.g. OR, AND) and were used to search for relevant studies on sea level rise impacts and communities' adaptation. The following keywords were, thus, used for the search in both the Scopus and WoS databases (Table 1). The functions Title, Abstract, Keywords (TITLE-ABS-KEY) in Scopus and Topic (TS) in WoS were utilized. There were no restrictions on publication year, and thus, the "All years to present" function was used. Besides, no restrictions were placed on the document types, given that the purpose of the study was to catalogue the global scientific output on the subject. Although only scientific articles should be included in the analysis, the study also included grey documents, which provided rich information in addition to the scientific articles. The grey documents included in this analysis were peer-reviewed and satisfied all the Scopus and WoS-established evaluation criteria. All subject area functions were further selected to include all fields of study to widen the study's scope. The study employed selection criteria to titles and abstracts based on the evidence of the inclusion of communities' adaptation to sea level rise impacts and selected only studies within the scope. Considering the keywords utilised for document search and selection procedures, there could be a chance of missing some important documents and pioneer contributors on the subject studied.

After reading the titles and abstracts, 235 and 128 documents in Scopus and WoS, respectively, were found eligible. From this point, searched data were exported in both *.bib* and *plain text* formats (these formats were useful for the combination of the two databases). Of those 363 documents, 71 were identified as duplicates and removed by the bibliometric R package. Following this, 292 documents (Table 2) were finally considered eligible and were used for the analysis under this method.

In the third step, the selection of a particular bibliometric analysis software for data management is encouraged. This study utilised the Bibliometric R package (version 2.2.0) and the Visualization of Similarities (VOSviewer) software (version 1.6.17) to perform statistical analysis of data. The bibliometric R package presents a sequence of procedures to import bibliographic data for bibliometric analyses through assumptions on statistics

Table 1 Keywords utilized for document search

Scopus
TITLE-ABS-KEY(("sea level rise" OR "sea level change" OR "sea level" OR "sea-level rise" OR "sea-level change" OR "sea-level") AND ("impact" OR "effect") AND ("coastal communit*" OR "coastal households") AND (adapt* OR "coping capacity" OR "mitigation" OR strateg* OR approach* OR "method" OR "plan"))
WoS
TS = (("sea level rise" OR "sea level change" OR "sea level" OR "sea-level rise" OR "sea-level change" OR "sea-level") AND ("impact" OR "effect") AND ("coastal communit*" OR "coastal households") AND (adapt* OR "coping capacity" OR "mitigation" OR strateg* OR approach* OR "method" OR "plan"))

Table 2 Document types employed in communities' adaptation to sea level rise impacts

Document types	Result
Article	211
Book	2
Book chapter	23
Conference paper	39
Editorial	2
Review	15

such as citations and keywords. The bibliometric package was utilised in this study due to its ability to establish several options for data analysis (Aria and Cuccurullo 2019). The VOSviewer is also an open bibliometric visualizer with an insightful and user-friendly interface. This software was used in this study because it can analyse large data sets completely and create numerous variations of bibliometric networks (Van Eck and Waltman 2021). The citation and keyword analyses were the bibliometric approaches utilised in these packages. The citation analysis helps to respond to questions regarding the theoretical foundation and present research trends. In this analysis, the number of citations is used to determine impact and is helpful in data clustering (Lima and Bonetti 2020). As highlighted by Van Eck and Waltman (2021), the Citation Analysis assumes that the most cited authors, research, countries, and journals are those with the highest impact. The keyword analysis reports issues pertaining to the research network. This approach assumes that the repetitive nature of words in many studies gives an indication of the conceptual relatedness of these words (Van Eck and Waltman 2021). In furtherance to this, country analysis, conceptual structure, thematic progression, and intellectual structure through direct citation analyses were also performed. This helped to reveal the supporting countries and intellectual structure on the topic.

The fourth step deals with data importation and the application of the correct statistical methods to gather and visualise the selected bibliographic information in step three. This study used multidimensional scaling (MDS) as the clustering approach. This helped to understand the subgroups, similarities and homogeneity, and the inconsistencies in the variables analysed (Aria and Cuccurullo 2017; Van Eck and Waltman 2021).

The interpretation of results occurs in the fifth step. Here, the study presents results based on the document type, publication year, recurring sources and terms, authors, relevant publications, performing countries, topic progression, and the intellectual structure.

2.2 Systematic review

The study performed a systematic review of research identifying the specific adaptation strategies undertaken by coastal communities in their attempt to adapt to sea level rise impacts, following the preferred reporting items for systematic reviews and meta-analyses (PRISMA) (Moher et al. 2009). The systematic review approach ensures a careful, comprehensive, and repeatable procedure for the literature (Ford et al. 2011; Xu et al. 2015). Using this approach, a specific research question(s) needs to be recognized, criteria for inclusion and exclusion stated, database(s) search and selection procedures followed, and the details of the data extraction process, analysis, and results dissemination provided (Xu et al. 2015). Here, the key question that guides the systematic review is: What specific

strategies are being undertaken by coastal communities in their attempt to adapt to sea level rise impacts?

2.2.1 Resources and search procedure

The study conducted a systematic search for evidence of the specific communities' adaptation strategies to the impacts of sea level rise. Documents were searched for using the Web of Science (WoS) and Scopus databases. The WoS, created by Clarivate Analytics, is a robust database containing over 33,000 journals and covering over 256 disciplines, including social sciences, environmental studies, interdisciplinary, development, and planning, among others (Shaffril et al. 2018). Thus, WoS has more than a century of backfile and citation information. The Scopus database also contains over 22,800 journals with peer-reviewed content from over 5000 publishers worldwide. Scopus is one of the largest databases of abstracts and citations. It covers a wide range of topics, such as the social sciences, the environment, and agriculture, among others (Shaffril et al. 2018). The systematic review utilised the same keywords and search terms as in (Table 1).

2.2.2 Eligibility criteria and selection process

In this study, the inclusion and exclusion criteria outlined in the bibliometric method (Sect. 2.1) were adhered to. The Scopus and WoS searches yielded 235 and 128 documents, respectively, with the bibliometric R package identifying 71 documents as duplicates. The bibliometric R package generated 292 documents, which were exported to the EndNote reference management software in Microsoft Excel® format for organisation. The authors independently evaluated the eligibility of the submitted documents. The authors employed selection criteria for titles and abstracts via an independent review. The authors selected a large number of documents based on their titles and abstracts as a first step. From this point forward, the inclusion criteria were restricted to include only documents that demonstrated the incorporation of specific communities' adaptation strategies to sea level rise impacts. Documents lacking supporting evidence were excluded. Thus, the study established exclusion criteria based on the evidence of the inclusion of communities' adaptation strategies to the impacts of sea-level rise. Consequently, 174 documents were excluded because they lacked any indication of a specific adaptation strategy implemented by communities. Throughout this process, the authors met frequently to resolve any ambiguities regarding the reviewed documents. In instances where consensus on a particular document was difficult to reach, a third researcher was contacted. Finally, 118 documents were utilised for the systematic review (Fig. 2).

2.2.3 Data extraction and analysis

In the data extraction and analysis phase, document characteristics including title, authors, year, study location, spatial dimension, impact, conceptual domain, key finding, research gap, specific adaptation strategy, and journal source (doi) were retrieved. The review adopted the adaptation options and categories proposed in the IPCC Fifth Assessment Report (AR5) (see https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-PartA_FINAL.pdf), to classify the specific strategies undertaken by coastal communities in their attempt to adapt to sea level rise impacts. These adaptation options include structural and physical, social, and institutional (Noble et al. 2014). Specific categories under the

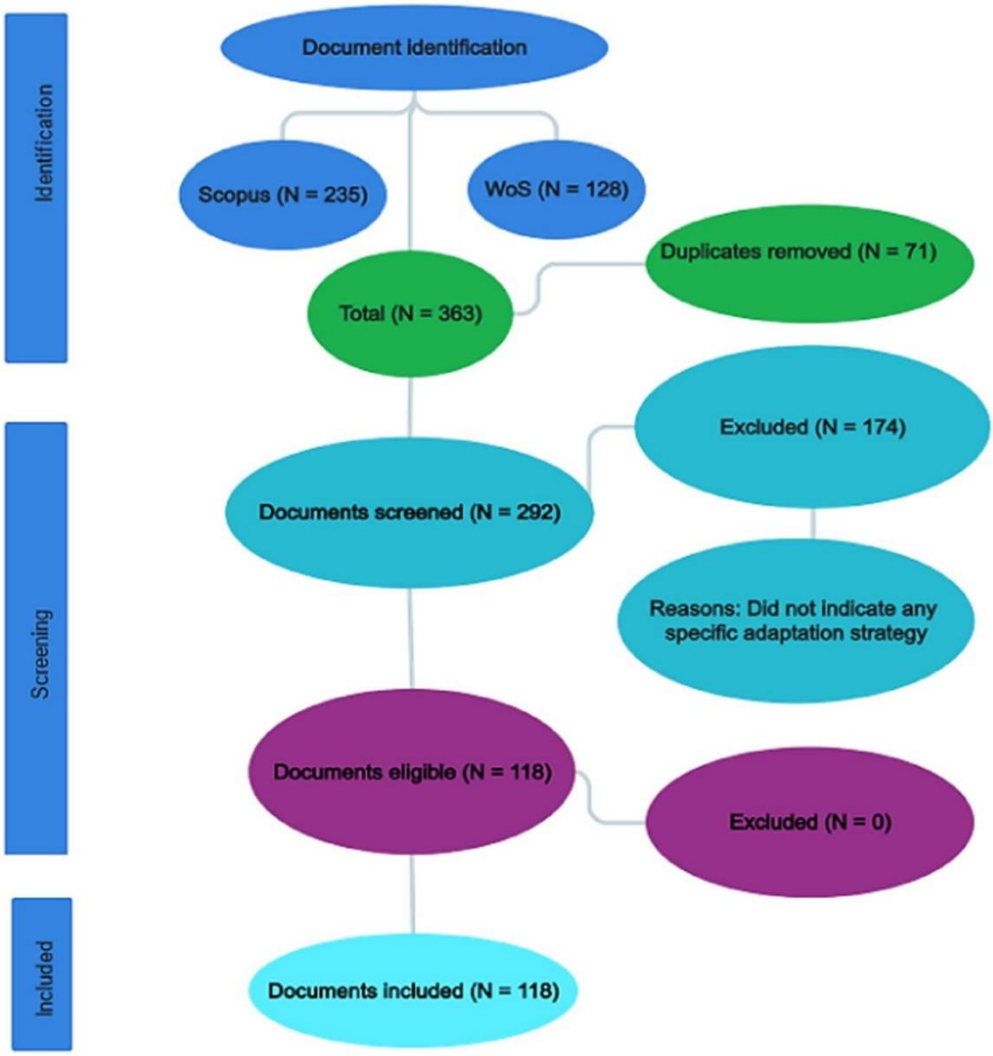


Fig. 2 Diagram showing the systematic review procedure

aforementioned adaptation options were also highlighted (see Fig. 10). Specific categories under the aforementioned adaptation options were also highlighted (see Fig. 10). The identified specific adaptation strategies were investigated using inductive qualitative analysis of data.

2.2.4 Description of specific adaptation options and strategies

The study adopted the adaptation options and strategies proposed in the IPCC AR5 (Noble et al. 2019) to classify communities' adaptation options. According to the IPCC AR5 proposal, adaptation options can be structural and physical (e.g. engineered and built, technological, ecosystem-based and services), social (e.g. educational, informational, and behavioural), and institutional (e.g. economic, laws and regulations, and government policies and programmes). These options served as a checklist and were applied to each of

the documents reviewed in this study. During full-text reading of documents, the authors independently searched for evidence of each of the three adaptation options and the specific strategies. For example, in a study, if a particular community plants and nurtures mangroves, then the ecosystem-based option of the structural and physical adaptation is checked. The engineered and built environment option is selected if there is evidence of seawalls, beach nourishment, or levees, etc. If there is evidence of both strategies in a community, then this is classified under both options. Also, if a study presents evidence of awareness-raising about the sea level rise impact on a particular community, then this is put under educational for the social adaptation option. This process was done independently for each document by the authors. At the end of the process, the authors met and made a conclusion on the checklists. In the instances where authors had difficulties in reaching a consensus about a particular study, a third researcher with knowledge of the subject was contacted. A summary of the different communities' options and strategies for adapting to the impacts of sea level rise is displayed in (Online resource 1).

3 Results

3.1 Results from bibliometric analysis

3.1.1 Publication characteristics, relevant journals, and authors in geospatiality of sea level rise impacts and communities' adaptation

Figure 3a–c shows the publication development, most relevant journals, and authors in sea level rise impacts and communities' adaptation. From Fig. 3a, the majority (47) of the studies were published in the year 2020, followed by 2019 (34) and the lowest zero (0) in the years 1997–2002 and 2004. In Fig. 3b, most of the documents (19) on the subject were published in the Ocean and Coastal Management Journal, followed by Natural Hazards (11) and by Sustainability (Switzerland) and the Journal of Coastal Research both with (7) documents published. The documents included in this study spanned from 1996–2022 (about 3 decades). Between 1996 and 2022, the number of publications on the subject grew at an average annual rate of 8.3%. Among the top-5 authors (Fig. 3c), Peng Z has the most published documents (6), and Beck M, with (4) documents, takes the last place. A summary of all the 292 documents used in the study can be found in the table (Online resource 1).

3.1.2 Country analysis

3.1.2.1 Country production and collaboration Figure 4a and b reveals the productive countries and the collaborative network in sea level rise impacts and communities' adaptation. Of the 47 countries (Fig. 4a), the USA was identified as the country with the most production (167), followed by Australia (40), and the lowest (1), occurring in countries such as Egypt, Iran, and Sweden, among others.

The VOSviewer software was used in the country collaboration analysis. It must be stated that the minimum number of documents per country in the collaboration analysis was set at 4. Considering the diversity and scale variations in sea level, countries' partnerships resulting in 4 documents indicate a country's determination to develop

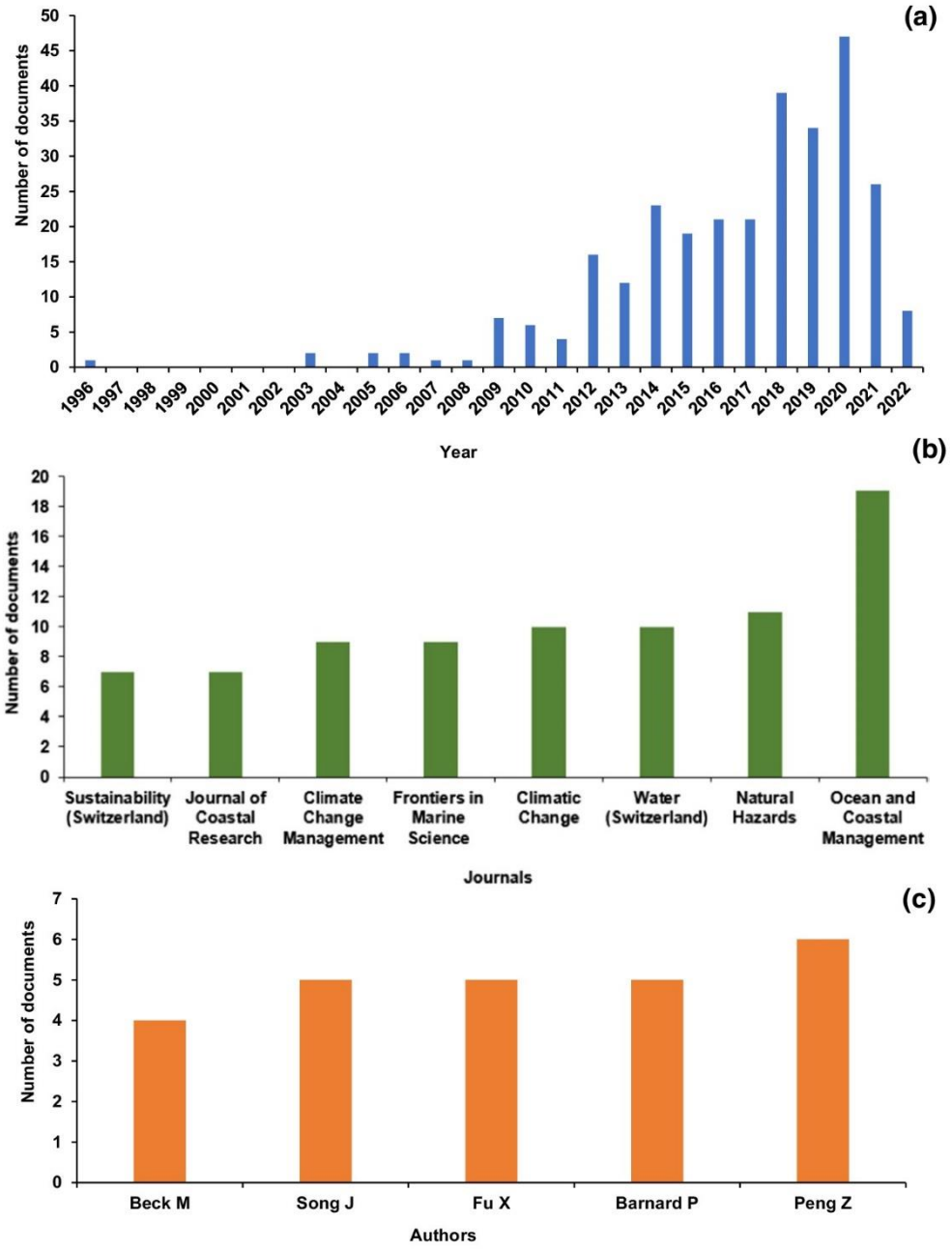


Fig. 3 Publication characteristics **a**; Most relevant journals **b**; and Top-5 authors **c** in sea level rise impacts and communities' adaptation from 1996–2022. Note: The year 2022 includes only the first quarter

adaptation plans against sea level rise impacts for their communities. Of the 185 countries, 28 met this threshold. In Fig. 4b, six colour clusters can be observed. Correspondingly, the USA has the greatest collaboration with other countries, followed by Australia, the United Kingdom, Canada, the Netherlands, and Indonesia.

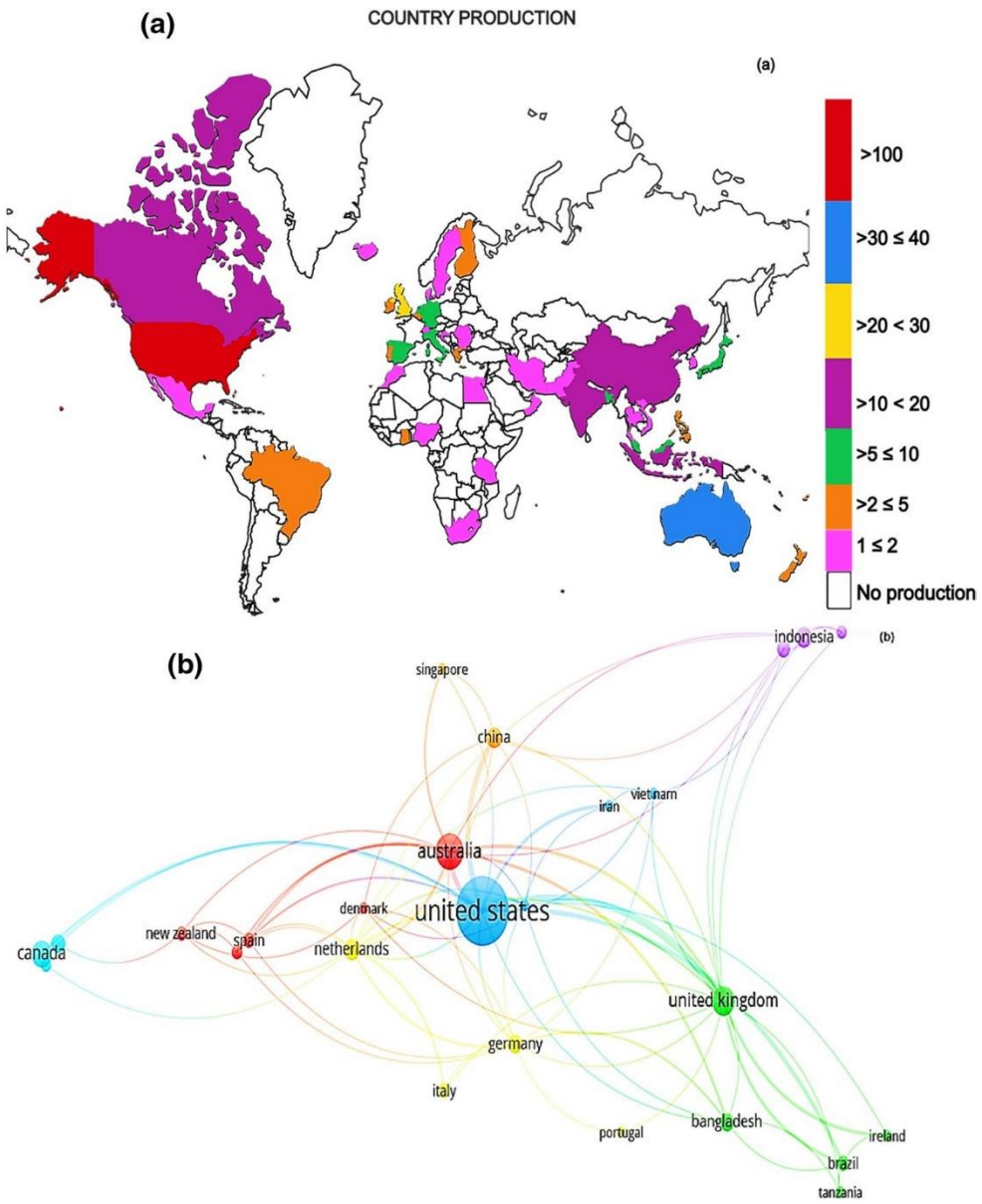


Fig. 4 Country production **a** and country collaboration analysis **b** in sea level rise impacts and communities' adaptation from 1996–2022

3.1.3 3.1.3. Keyword analysis

3.1.3.1 Co-occurrence of keywords In this analysis, the VOSviewer software was again used. The minimum number of occurrences of a keyword was set at 5. The authors believe that the occurrence of a word five or more times reflects how important that word is to a concept and its relatedness to other conceptual structures. Of the 757 keywords, 27 met the threshold. In Fig. 5, 5 distinct colour groups can be observed with varied sizes, reflecting

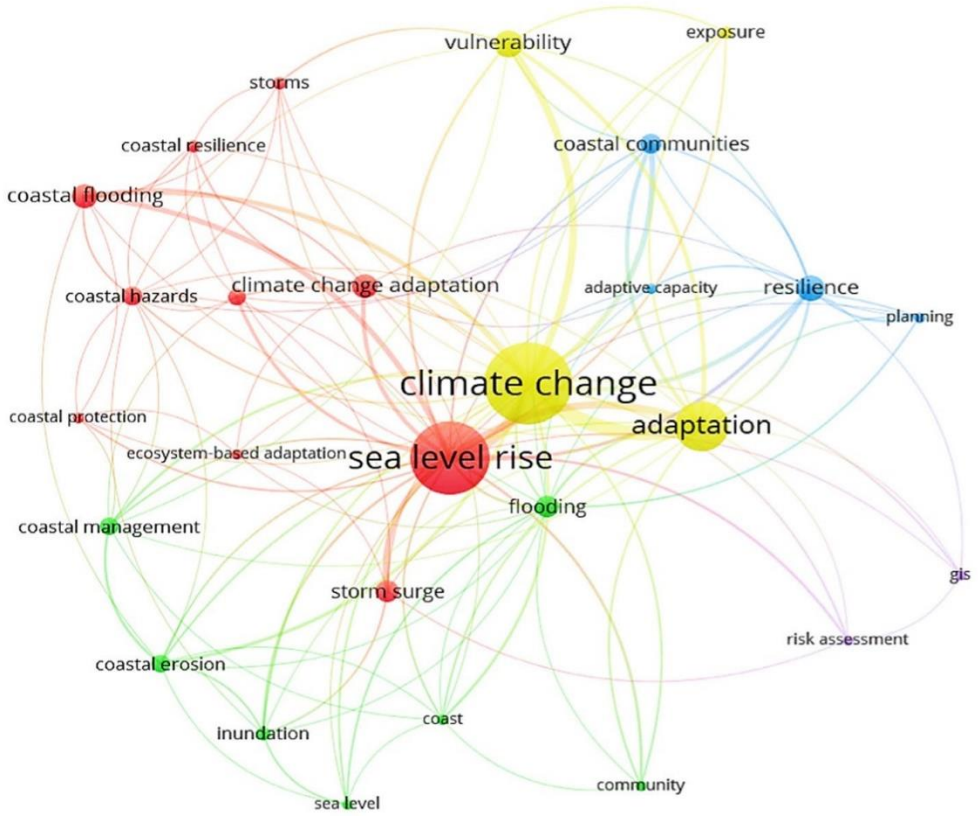


Fig. 5 Keyword co-occurrence in sea level rise impacts and communities' adaptation from 1996–2022

the link and strength of keywords. The yellow colour with keywords like climate change, adaptation, and vulnerability is of significant dimensions. This is followed by keywords such as sea level rise, climate change adaptation, and coastal flooding in the red colour group. Again, the blue colour group containing keywords like resilience, coastal communities, and adaptive capacity came next. Keywords like flooding, coastal erosion, and coastal management in the green colour group were also essential, as was the purple colour group with keywords like GIS and risk assessment.

3.1.4 Conceptual structure by multidimensional scaling approach

Figure 6 shows the multidimensional scaling (MDS) map of the author's keywords used to the subject of communities' adaptation strategies to sea level rise impacts. The MDS was run using the bibliometric R package. The MDS was utilised to identify the author's keywords in a low-dimensional plane where the distance between any two keywords indicates their similarities and the opposite for dissimilarity. Here, the smaller the distance between concepts, the stronger the relationship between keywords and vice versa. In Fig. 6, a two-dimensional map of distance and dissimilarity can be observed. From Fig. 6, it can be observed that keywords or concepts such as sea level and inundation, and flooding and coastal flooding are totally similar, as is the case of vulnerability assessment and risk, and coastal risk and social vulnerability. Also, mangroves and sustainability appear to be

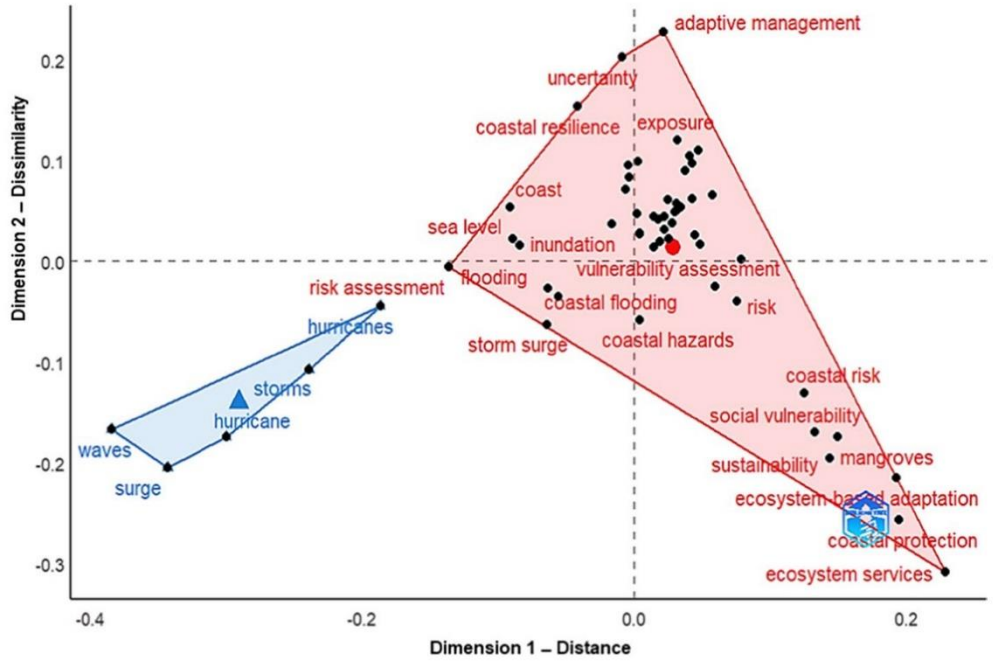


Fig. 6 Conceptual structure map on sea level rise impacts and communities' adaptation from 1996–2022

similar. Adaptive management and ecosystem services are the most different from each other (they have a dissimilarity matrix of 0.23).

3.1.5 Thematic progression

Figure 7 shows the primary research themes reflecting the scientific production on sea level rise impacts and communities' adaptation. From Fig. 7, a four-theme quadrant with varying dimensions is observed. The motor theme showing the keyword sea level in the upper-right quadrant is of current significance to the subject under study. The keyword sea level is highly visible and shows better relationships with other concepts. The keyword climate change in the lower-right quadrant is observed as the fundamental keyword (basic themes) used on the subject to depict concepts. Storm surge located in the upper-left quadrant (niche themes) is considered as a specialised keyword on the subject with high and low internal and external connections, respectively. In the lower-left quadrant (emerging or declining themes), the keyword adaptation is considered as an emerging theme in the subject.

3.1.6 Intellectual structure

3.1.6.1 Direct citation network analysis The intellectual structure on sea level rise impact and communities' adaptation evidenced through the historical direct citation network analysis is presented in Fig. 8. The direct citation network analysis reflects the essential direct citations that arise from a reference directory (Borgman and Furner 2002). From Fig. 8,

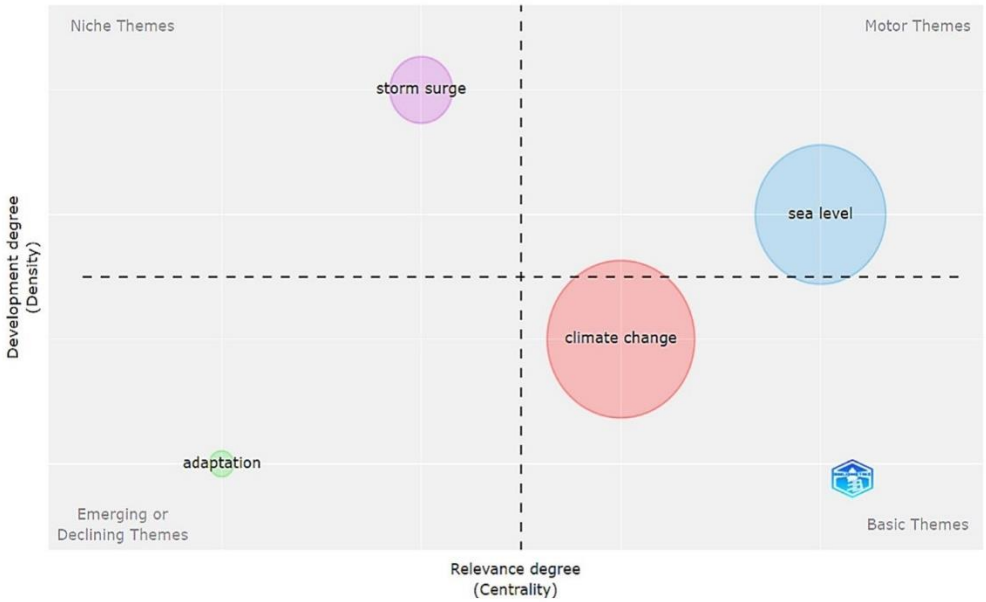


Fig. 7 Thematic progression on sea level rise impacts and communities' adaptation from 1996–2022

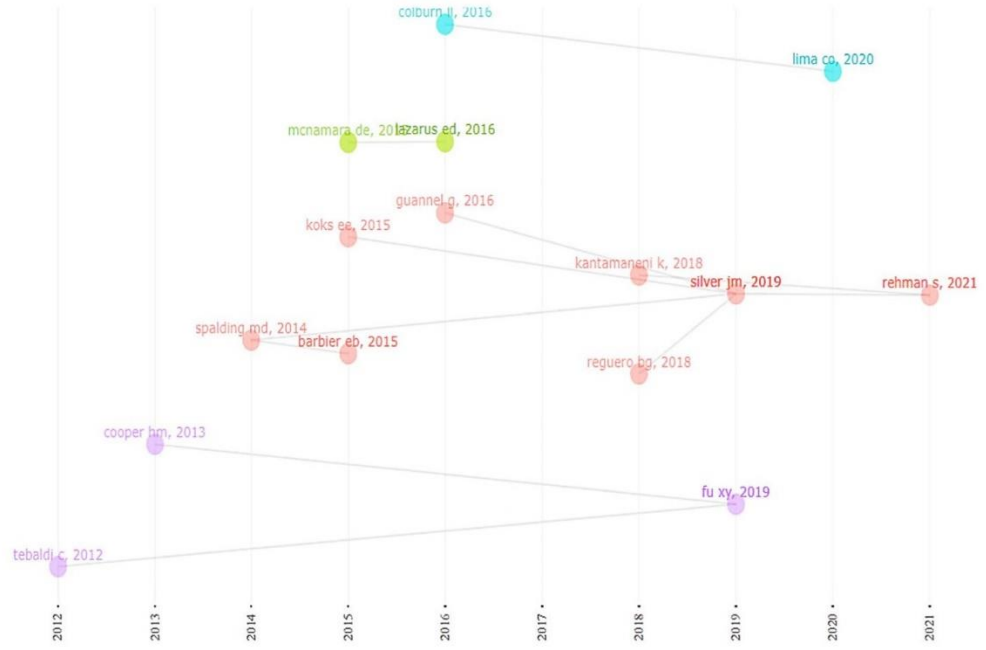


Fig. 8 Historical direct citation analysis on sea level rise impacts and communities; adaptation from 1996–2022

a 4-colour group is observed, reflecting the studies with direct citation. A comprehensive review was performed to understand the subject's intellectual stance.

In Fig. 8, it can be observed that a direct historical citation on the subject first appeared in the year 2012 through the study of Tebaldi et al. (2012) (in purple). The study of Cooper et al. (2013) came next in this colour group. Both studies received a direct citation by Fu et al. (2019). Tebaldi et al. (2012) investigated the influence of sea level rise on expected storm surge-driven water levels and their frequencies along the contiguous USA and reported great shifts in the incidence of the occurrence of extreme water levels in locations with slow local sea level rise. The research gap identified by Tebaldi et al. (2012) and which their study addressed was the need for coastal policy approaches to non-stationarity of extreme events. Again, Cooper et al. (2013) used a light detection and ranging (LiDAR) derived digital elevation model (DEM) to map low-lying lands that are vulnerable to sea level rise in Kahului and Lahaina, Maui, Hawai'i, USA, and estimated a socio-economic loss of approximately $18.7 to $296 million under the worst case sea level rise scenario for marine inundation and drainage problems due to a high water table if no adaptive strategies are undertaken in the area. Cooper et al. (2013) found a research gap between the low understanding of the implications of climate change impacts and the need for community resilience to marine hazards and coastal planning, which their study addressed. Additionally, Fu et al. (2019) analysed how well existing sea level rise vulnerability assessments align with suggested vulnerability assessment guidance and the factors that contribute to the variation in the quality of vulnerability assessments. Fu et al. (2019) point out the differences in the content and quality of vulnerability assessment, with greater attention given to physical exposure and less assessment on adaptation plans. Fu et al. (2019) identified and addressed the research gap in the empirical understanding of adaptation planning due to the complex contextualization of vulnerability.

In the red colour group, the study of Spalding et al. (2014) led this group and was followed by Koks et al. (2015), Guannel et al. (2016), Kantamaneni et al. (2018), and Silver et al. (2019). The study of Spalding et al. (2014) was directly cited by Barbier (2015) and Silver et al. (2019), whereas that of Koks et al. (2015) was directly cited by Silver et al. (2019). The study of Guannel et al. (2016) was again cited by Silver et al. (2019). Also, that of Kantamaneni et al. (2018) received a direct citation from Rehman et al. (2021) and that of Reguero et al. (2018) was directly cited by Silver et al. (2019). The study by Spalding et al. (2014) examined the role of global ecosystems in coastal protection functions and stressed that the appropriate utilisation of ecosystem-based adaptation strategies provides valuable and effective approaches to current management. The research gap which led to this study was the potential role of ecosystems in coastal protection (Spalding et al. 2014). Again, Barbier (2015) examined and assessed the impacts of climate change on poverty in coastal areas of developing countries in low-elevation coastal zones and highlighted that 15 developing countries contain over 90% of the world's low-elevation coastal zone rural poor, and low-income countries that have the greatest incidence of poverty. The identified research gap that led to this study was the vulnerability of coastal populations in developing countries to climate change (Barbier 2015). Also, Koks et al. (2015) developed a state-of-the-art approach to assess the flood risk of households in Rotterdam, Netherlands, and showed that the diverse nature of the population is often ignored in conventional flood risk management studies. The research gap identified and addressed in this study was the need for a combined assessment of hazard, exposure, and social vulnerability for the provision of information for adaptation strategies. In addition, Guannel et al. (2016) quantified the coastal protection services supplied by coral reefs, seagrasses, and mangroves in Belize and underlined that, whereas mangroves are the most effective at protecting the coast under

non-storm and storm events, coral reefs and seagrasses also moderate the impacts of waves and storms and reduce further vulnerability of coastal regions. The found knowledge gap that led to this study was the need for comprehensive methods to design integrated management approaches that maximise coastal protection. Besides, Kantamaneni et al. (2018) assessed the physical and economic vulnerability of eleven UK sites of varying physical and economic characteristics and found that Great Yarmouth and Aberystwyth were highly vulnerable, whereas Llanelli and Lynmouth were least vulnerable. The knowledge gap found and addressed was the need for more studies on the physical and economic vulnerability of coastal regions. In furtherance to this, Reguero et al. (2018) investigated a possible direct link between reef condition and coastal protection in Grenville, Grenada, and reported that the strong and well-developed coral reef system in the southern bay keeps the shoreline in balance, while reef devastation in the northern bay is associated with severe erosion. Reguero et al. (2018) discovered a gap of scarcity in knowledge on how coral reefs prevent coastal impacts and addressed this in their study. Moreover, Silver et al. (2019) assessed the risk reduction provided by coral reefs, mangroves, and seagrass along the entire coast of the Bahamas under current and future climate scenarios and revealed that the population most exposed to coastal hazards will double with future sea-level rise and triple if ecosystems are degraded. The research gap identified and addressed in this study was the need for approaches and tools for coastal hazard and social vulnerability analysis (Silver et al. 2019). Finally, in this colour group, Rehman et al. (2021) assessed coastal vulnerability as a function of exposure, sensitivity, and adaptation in the coastal districts of India and found that high and moderate vulnerability existed in the eastern and western coastal districts, respectively. Rehman et al. (2021) identified the research gap of the need for vulnerability assessment and addressed such.

The study by McNamara et al. (2015) headed the green colour group and was directly cited by Lazarus et al. (2016). The study by McNamara et al. (2015) developed an empirically grounded, stochastic dynamic model coupling coastal property markets and shoreline evolution in North Carolina, USA, and emphasised that the policy-induced inflation of property value grows with increased erosion from sea level rise or increased storminess. However, the effect of background erosion is larger due to human behavioural feedback. The research gap that led to this study was the susceptibility of sandy shorelines. Also, Lazarus et al. (2016) examined the evolving research agenda for human-coastal systems and stated that research into human-coastal systems can profit from years of interdisciplinarity work on the intricate changing aspects of common-pool resources through computational efficacy and new techniques in numerical modelling. Lazarus et al. (2016) found the gap in the need for a human-coastal systems research agenda.

Finally, the study of Colburn et al. (2016) led the blue colour group and was directly cited by Lima and Bonetti (2020). Colburn et al. (2016) develop indicators of climate change and social vulnerability in fishing dependent communities along the Eastern and Gulf coasts of the USA and highlight that the incorporation of community social vulnerability indicators and the new climate change vulnerability indices highlight community needs for unique solutions in order to adapt to environmental and social changes and maintain their well-being. The research gap identified and addressed by Colburn et al. (2016) was the need for the development of climate change indicators. Also, Lima and Bonetti (2020) presented an original quantitative assessment of the global scientific production on coastal social vulnerability and stressed the exponential increase in scientific production on coastal social vulnerability. The gap identified was the need for standardisation and harmonisation of sectors and populations with more or less vulnerability to sea level rise and extreme events. In this analysis, the lead studies in each cluster have either one or two

direct citations. However, they could have more citations in other databases other than the two used in this review.

In summary, the review has revealed the intellectual structure of sea level rise impacts and communities' adaptation. From the review, the studies in the purple colour group focused on and addressed knowledge deficiencies on a community's vulnerability, resilience, and adaptation, and how policy decisions can be strengthened to assist coastal communities. Also, those in the red colour group focused on the vulnerable nature of the coastal zone and communities. Studies in this group focused on how communities can use coastal ecosystems and appropriate approaches to improve their adaptation to sea level rise impacts. Besides, the green and blue colour groups considered how research can be improved to address the vulnerability of coastal communities to sea level rise impacts.

3.2 3.2. Results from systematic review

3.2.1 Study characteristics

Figure 9a–d shows the publication characteristics, impacts studied, spatial scale, and the study locations. In Fig. 9a, the majority of the studies (17) were published in 2018 and 2019, and at least (1) in 1996, 2007, and 2008. The majority of studies (70) investigated multiple sea level rise (Fig. 9b), followed by a single flooding impact (20), and the fewest (1) investigated hurricane, land subsidence, and saltwater intrusion. The greater part (76) of the studies were conducted at the local scale and the minimum (1) at the global level (Fig. 9c). The USA has the most studies (34) while Mexico, the Solomon Islands, Cuba, and Ghana, among others have the fewest (1). A summary of all the 118 studies used to show the specific strategies coastal communities undertake to adapt to the impacts of sea level rise is displayed in (Supplementary data: Table A.1-in grey colour highlight).

3.2.2 Specific strategies undertaken by coastal communities to adapt to sea level rise impacts

From Fig. 10, the majority (71) of the specific strategies used by coastal communities to adapt to the effects of sea level rise were structural/physical in nature, with the least (7) being in institutional. Under the structural/physical strategy, the engineered and built environment was the most (67%) specific option utilized. The highest (43%) specific option in the social strategy was informational, while economic (43%) was the greatest specific option used under the institutional strategy.

3.3 Systematic review: Qualitative analysis of the literature

Following the IPCC AR5 proposal for adaptation options, this review classfied the specific adaptation options undertaken by coastal communities into three categories: structural/physical, social, and institutional (Noble et al. 2014).

3.3.1 Structural/physical options

Several specific adaptation strategies, such as beach nourishment, seawalls/sea defences, levees, barriers, building dykes, sediment distribution, dune restoration, groynes, jetties,

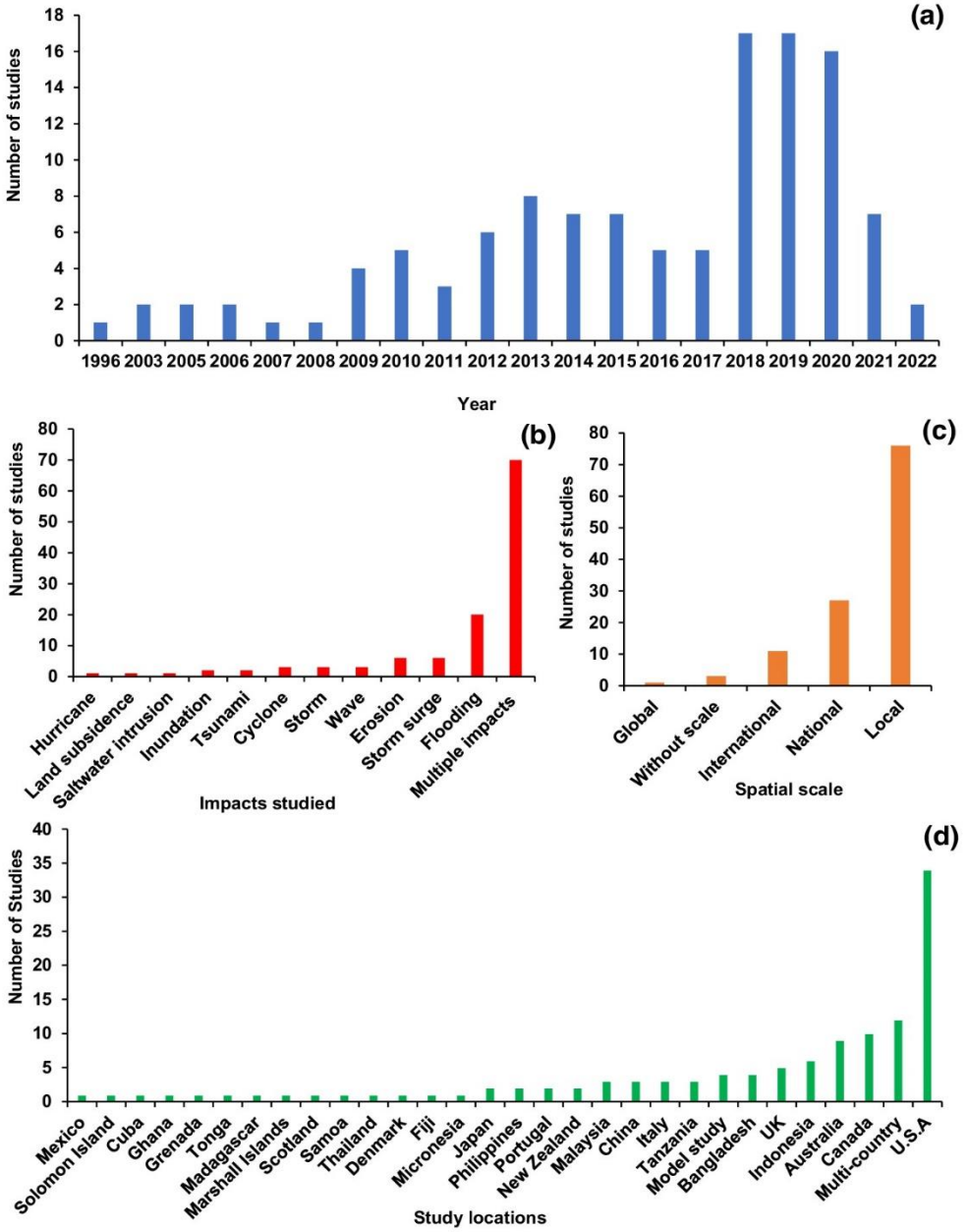


Fig. 9 Publication years **a**, Sea level rise impact studied **b**, spatial scale **c**, and study locations **d** in systematic review of literature on specific strategies undertaken by coastal communities in their attempt to adapt to sea level rise impacts. Note: multiple impacts in **b** show the study of two or more sea level rise impacts. Specific study location of application can be found in (Online resource 1—in grey colour highlight)

planting/nurturing mangroves, building canals, breakwaters, riprap, and rainwater collecting bags, were identified under the structural/physical option. Coastal communities have adapted to the effects of erosion, storms, and flooding through beach nourishment. As evidenced by research (Leatherman 1996; McNamara et al. 2015) and (Maiolo et al.

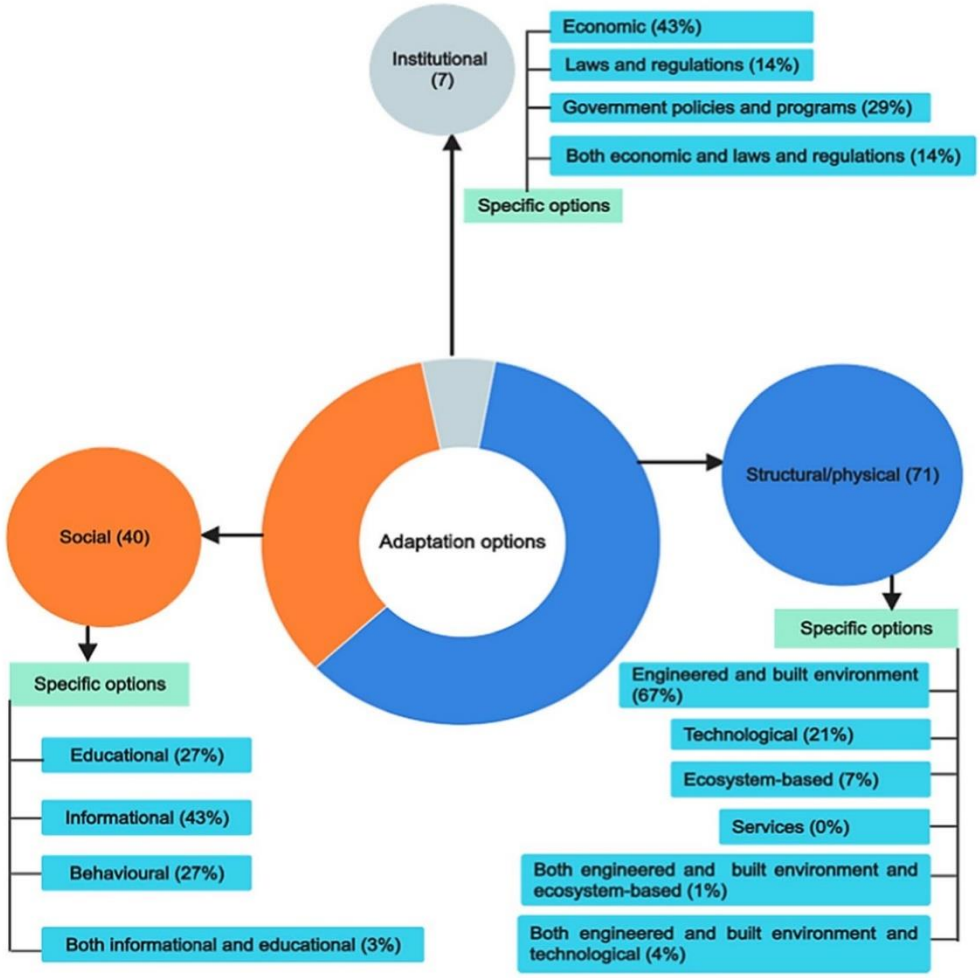


Fig. 10 Specific strategies undertaken by coastal communities in their attempt to adapting to sea level rise impacts

2020) conducted in coastal communities in the USA and Calabaia Beach, Italy, accordingly. In addition, some communities have constructed seawalls/sea defences, levees, dykes, groynes, jetties, barriers, dune restoration, breakwaters, canals, and riprap as a form of adaptation strategy in the light of the numerous effects of sea level rise. For example, the construction of seawalls/sea defences by the coastal communities in the USA as underlined in the studies of (Fisk 2019; Han et al. 2020), in Bohai Bay, Laizhou Bay, Yellow River Delta, Yangtze River Delta, Zhejiang, Pearl River Delta in China as told by Yang et al. (2012), in communities in Lakes Entrance, Australia (Graham et al. 2014), in coastal communities in Scotland, Ireland, Norway, and Iceland reported by Muir et al. (2014), in Charlottetown, Prince Edward Island, Canada informed by Lane et al. (2017), in Fairbourne, Wales, UK (Buser 2020), in Portugal (do Carmo 2019), and in Ghana (Evadzi et al. 2018). Again, there is creation of levees by coastal communities in the USA (Peng and Song 2018; Walsh et al. 2019), and the application of dykes, groynes, jetties, and ripraps evidenced in communities like Florida, USA (Bloetscher et al. 2010), Zhejiang, China

(Jianjun and Francisco 2013), Little Anse, Richmond County, Cape Breton, Nova Scotia, Canada (Mostofi Camare and Lane 2015), Tohoku, Japan (Rahman et al. 2016), Thyborøn, Denmark (Sorensen et al. 2018), Carahatas, Cuba (Aragón-Duran et al. 2020), Semarang, Indonesia (Muktiali 2020), and Pahang, Malaysia (Islam et al. 2021). Besides, many communities plant and nurture mangroves and vegetative cover, which assist in their adaptation efforts. These strategies have been applied in communities such as O'ahu, Hawai'i, USA (Onat et al. 2018), in the Philippines (Gevaña et al. 2019), in Kepulauan Seribu-Jakarta, Indonesia (Dalimunthe 2018), and in Malaysia (Ghazali et al. 2016). The coastal communities in Yap, Micronesia, have technologically employed the use of rainwater collection bags as a way of adapting to sea level rise impacts (Krishnapillai 2018).

3.3.2 Social options

The social options found included awareness creation and education, the development of tools and decision support systems, relocation, and livelihhod changes/diversification of activities. For example, as reported in the study of Naylor et al. (2003), the coastal community of East Anglia, UK, in the efforts to adapt to sea level rise impacts, raised local awareness and knowledge among the community members. This strategy was similarly applied to the coastal communities in British Columbia, Canada, as informed by Dolan and Walker (2006). Again in Canada, Kerry et al. (2012) found that the coastal communities in New Brunswick have improved their local knowledge about sea level rise and think critically about the related impacts, thereby considering these in their decision-making. In fact, Pruneau et al. (2013) highlighted the general improvement in awareness and knowledge about sea level rise impacts across all coastal communities in Canada and indicated the competence of people in adapting to sea level rise impacts. Additionally, in West Java, Indonesia, awareness, encouragement, and education on flooding due to sea level rise were given to communities by local cadres and counselors as underlined in the study of Sumardjo et al. (2019). Similarly, in Kampong Tambak Lorok-Semarang, Indonesia, there has been massive social communication on inundation and the need for increased capital and the cultivation of green mussels as an adaptation strategy (Amin et al. 2019). Also, detailed education on climate change and sea level rise impacts, in particular, has again been given to the fishermen in Central Java, Indonesia (Mulyasari et al. 2021).

To adapt to sea level rise impacts, many communities have developed tools and decision support systems to increase efforts. Webster et al. (2006) developed Lidar-derived maps to assist the adaptation efforts of coastal communities in New Brunswick, Canada. Geographic Information System (GIS) and other computer simulations have been utilised to produce meaningful graphics and maps that help communities adapt to sea level rise impacts. Coastal communities with this advantage include Florida, USA, reported in Snow and Snow (2009), in Queensland, Australia by Sahin and Mohamed (2010), in Jakarta, Indonesia revealed by Ward et al. (2011); Maui, Hawai'i, USA by (Cooper et al. 2013; Guiles et al. 2019); in New Jersey, USA by Kijewski-Correa et al. (2020); and in Boeboe, Solomon Islands by Leon et al. (2015). Moreover, many communities have relocated. As stressed by Alexander et al. (2012), many coastal communities in Australia, as of the time of their survey, preferred to relocate their homes and infrastructure because of coastal erosion and storm surge. This was confirmed by Zander et al. (2013), who said that many coastal communities in Australia have relocated due to the impact of tropical cyclones. Costas et al. (2015) further stated that coastal communities in Praia do Faro, Portugal, preferred to relocate to adapt to storms and erosion. Similar situations were found in Alaska,

Louisiana, Washington-USA, Panama, Fiji, Papua New Guinea, Solomon Islands, and Vanuatu, revealed by Dannenberg et al. (2019), and in the coastal communities of Bangladesh (Ahmed and Eklund 2021). Likewise, some coastal communities have changed their livelihoods and diversified their activities as an adaptation strategy to sea level rise impacts. Communities using this strategy include Baja-California, Mexico, as reported by Salvadeo et al. (2021), and the Rufiji Delta, Tanzania as reported by Nyangoko et al. (2022).

3.3.3 Institutional options

A few options were identified under the institutional options. Sales (2009) informed about the capacity-enhancing measures and calamity fund allocation instituted by the local coastal communities in the Philippines. In Spain and Romania, there is proper implementation of coastal zone management policies to support coastal communities in their adaptation efforts (Sano et al. 2011a), and the same for the community of Gold Coast, Australia (Sano et al. 2011b). In Thailand, coastal communities save part of their incomes to adapt to the impact of sea level rise (Kulpraneet 2013). Also, communities in Namdrik Atoll, Marshall Islands, re-invest their profits from black-lipped oyster farming for residential renovation and procurement of water tanks and pumps (Zackhras et al. 2018), and in Nova Scotia, Canada, communities have planned to deal with flooding due to sea level rise and share the cost and benefit of their economic activities (Khan et al. 2018).

4 Discussion

The global scientific production on sea level rise impacts and communities' adaptation has been analysed and the specific adaptation strategies systematically appraised. This review has revealed the increasing scientific developments on the subject. In this review, it has been established that coastal communities made efforts to adapt to sea level rise impacts as far back as 1996. The strong literature discussions on climate change and related sea level rise impacts in the early and late 1980s (Bradner and Resch 1981; Schneider 1989) could be a factor for in the increased communities' adaptation efforts. This review also believes these literature discussions have caused the IPCC to recognise the vulnerabilities related to sea level rise and the need to manage coastal zones and thereby proposed strategies for adaptation to sea level rise in their First Assessment Report (FAR) in 1990 (IPCC 1992) and have given significant emphasis in the subsequent assessment reports.

It can be said that efforts were low during this time, as reflected in the few studies on the subject. Notwithstanding, communities' efforts and that of the scientific community towards adaptation strategies to sea level rise impacts increased as the years progressed (see Fig. 3a). Researchers and countries choose diverse journals to disseminate studies on sea level rise impacts and communities' adaptation. The Ocean and Coastal Management Journal is of high importance in that regard. This journal is recognised as the most important source for dissemination due to its commitment to publishing all aspects of ocean and coastal management issues from the local to global scale. Although countries are committed to helping their coastal communities adapt to the negative impacts of sea level rise, strong commitments in this regard are observed in only a few countries. This is reflected in the low level of collaboration efforts by countries on the subject.

The review through the multidimensional scaling approach has revealed the relatedness and similarities in the conceptual structures of sea level rise impacts and

communities' adaptation. Concepts such as sea level and inundation, flooding and coastal flooding were totally similar, as were vulnerability assessment and risk. A clear dissimilarity was established between adaptive management and ecosystem services. Coastal communities have in recent times given attention to ecosystem services and ecosystem-based adaptation approaches as effective ways of protecting coastal areas and their communities against coastal risk for improved sustainability. However, more needs to be done, especially considering the current number of studies (7%) (see Fig. 10). More ecosystem-based adaptation approaches are required due to their numerous socio-ecological benefits, such as serving as buffers for coastal communities against the negative impacts of sea level rise; carbon storage and sequestration; habitat for fisheries; and for tourism and recreation (Jones et al. 2012).

Thematically, the subject under study has progressed substantially. The subject falls under the broad theoretical structure of climate change, making sea level research a hot topic (see Fig. 7), under the current scientific discourse. The theme of adaptation appeared in the 13th century, had its conceptual source in the theory of evolution, and was used on different subjects (Simonet and Duchemin 2010). However, on the subject of communities' adaptation strategies to sea level rise impacts, it is considered an emerging theme. Intellectually, the research subject has advanced. Researchers on the subject are committed to highlighting sea level rise impacts and how coastal communities can adapt strongly. Intellectual structures on the subject are activated by identifying and addressing knowledge gaps. For instance, Tebaldi et al. (2012) identified and addressed the knowledge gap on the need for coastal policy approaches on the non-stationarity of extreme events. Again, Barbier (2015) addressed the gap in the vulnerability of coastal populations in developing countries to climate change. The intellectual structure on the subject also emphasised how policy and governance decisions can assist coastal communities in their adaptive capacity to the impacts of sea level rise. Greater intellectual efforts have also been dedicated to communicating the appropriate use of coastal ecosystems to assist communities in adapting to sea level rise impacts.

Specific adaptation strategies are being undertaken by coastal communities in many countries, with the USA being prominent in that regard. Coastal communities are dedicated to adapting to multiple sea level rise impacts. From the individual impacts (Fig. 9b), it can be deduced that many coastal communities adapt to the impact of flooding due to sea level rise. This review has established that sea level rise adaptation options differ. However, as shown in Fig. 10, many of the adaptation options used by coastal communities are structural/physical in nature, particularly, engineered and built environment strategies. This is in conformity to the earlier studies of (Hill 2015; Temmerman et al. 2013), who stressed the dominance of hard engineering structures in coastal protection. Although the engineered and built environment strategies offer massive support to coastal communities to adapt to the impacts of sea level rise, they result in problems like habitat loss and prevent the growth of wetlands and mangroves (Gilman et al. 2006; Sutton-Grier et al. 2015) and have huge economic costs (Hinkel et al. 2014). Considering the aforementioned weaknesses, it is essential for coastal communities to give significant attention to ecosystem-based adaptation options. Ecosystem-based adaptation strategies are cost-effective, managed sustainably, restore natural ecosystems, and contribute to human wellbeing (Cohen-Shacham et al. 2016; Spalding et al. 2014).

5 Conclusion

The study employed a two-step methodology to analyse the global scientific production on the geospatiality of sea level rise impacts and communities' adaptation, and the specific strategies undertaken by coastal communities in their attempt to adapt to sea level rise impacts. A key conclusion in this review is that coastal communities have made efforts to increase their adaptive capacity to sea level rise impacts through improved structural/physical and social options. However, the policy (institutional) assistance to intensify these efforts is limited.

The scientific research on the subject has increased substantially, indicating the growing concerns about the impacts of sea level rise and the need to increase the adaptive capacity of communities. The conceptual structures on the subject reflect the vulnerable nature of coastal communities to sea level rise impacts in a changing climate and underline the need for the development of proper adaptation plans. This concept does not deviate from the intellectual structures of the subject. Intellectual structures on the subject place an emphasis on policymakers' ability to assist coastal communities in their adaptive efforts to sea level rise impacts. This study reiterates the intellectual stance on the support of policymakers since effective adaptation plans to sea level rise and climate risks in general involve a collective effort. Policymakers, institutions, and local communities can work together to make coastal communities more resilient to the impacts of sea level rise (da Veiga Lima and de Souza 2022; de Lima et al. 2022; Seung and Ianelli 2019; Uiterwyk et al. 2019).

The study established that coastal communities' specific adaptation strategies to sea level rise impacts have been more of the engineered and built environment, especially the hard engineering strategies. While these strategies offer immense support, there are weaknesses associated with them. The balancing of these strategies with ecosystem-based strategies is highly encouraged. With regards to this review, only 7% of the ecosystem-based strategies for adapting to sea level rise impacts have been implemented by coastal communities. This needs to be improved considering its huge benefits. Enhanced adaptation strategies to sea level rise impacts necessitate additional research and greater engagement between coastal communities and policymakers.

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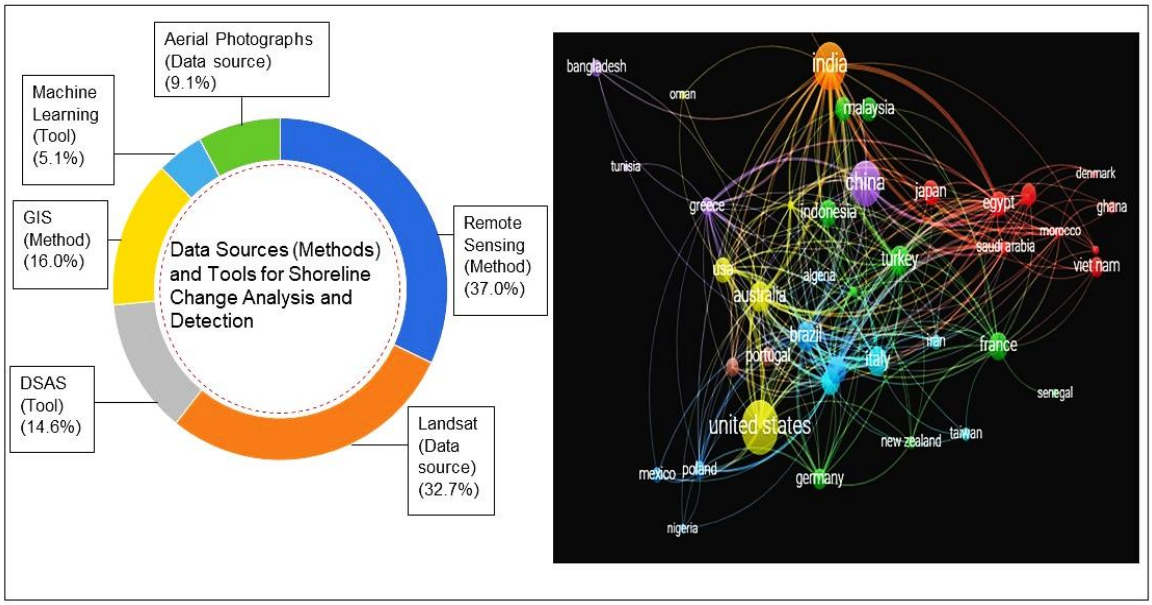
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1.2.10. Bibliometric Analysis of Data Sources and Tools for Shoreline Change Analysis and Detection

Paper 3



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Review

Bibliometric Analysis of Data Sources and Tools for Shoreline Change Analysis and Detection

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Abstract: The world has a long record of shoreline and related erosion problems due to the impacts of climate change/variability in sea level rise. This has made coastal systems and large inland water environments vulnerable, thereby activating research concern globally. This study is a bibliometric analysis of the global scientific production of data sources and tools for shoreline change analysis and detection. The bibliometric mapping method (bibliometric R and VOSviewer package) was utilized to analyze 1578 scientific documents (1968–2022) retrieved from Scopus and Web of Science databases. There is a chance that in the selection process one or more important scientific papers might be omitted due to the selection criteria. Thus, there could be a bias in the present results due to the search criteria here employed. The results revealed that the U.S.A. is the country with the most scientific production (16.9%) on the subject. Again, more country collaborations exist among the developed countries compared with the developing countries. The results further revealed that tools for shoreline change analysis have changed from a simple beach transect (0.1%) to the utilization of geospatial tools such as DSAS (14.6%), ArcGIS/ArcMap (13.8%), and, currently, machine learning (5.1%). Considering the benefits of these geospatial tools, and machine learning in particular, more utilization is essential to the continuous growth of the field. Found research gaps were mostly addressed by the researchers themselves or addressed in other studies, while others have still not been addressed, especially the ones emerged from the recent work. For instance, the one on insights for reef restoration projects focused on erosion mitigation and designing artificial reefs in microtidal sandy beaches.

Keywords: shoreline change; coastal erosion; sea level rise; remote sensing; Landsat; machine learning; GIS; climate change

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1. Introduction

Coastal systems and large inland water environments are under threat of climate change/variability and sea level rise. Several research studies have stressed the impacts of climate change, climate variability (extreme events) and sea level rise on global shorelines and related erosion [1–3]. The situation is further aggravated by the current anthropogenic pressure (urbanization) [4]. As reiterated by Ware et al. [5], human settlement has always been concentrated along the coast and large inland waterbodies. This assertion was earlier stressed by Blackburn et al. [6], who reported that 16 of the world's megacities are found within coastal regions and large deltas. A recent study by Bamunawala et al. [7] projected that the collective impacts of climate change (sea level rise, temperature, and precipitation) and anthropogenic influences (urbanization) will cause 90% of global shorelines to retreat.

A shoreline is the point of the physical border between land and water [8]. While this definition looks simple, it is indeed challenging in its practical application [9]. The

position of the shoreline changes through time due to cross-shore and alongshore sediment movement in the littoral zone, and through changes in water levels [9,10]. The temporal nature and time scale of shorelines must, therefore, be considered in shoreline investigation [9,10]. An understanding of the temporal and time scales in shoreline position is essential for science, engineering, and coastal managers [11]. Shoreline position detection is, thus, important especially considering the long history of human habitation of the coast and the banks of large waterbodies and their recent adaptation [10]. This has meant that the term shoreline change is not limited to only the coast but encompasses lake and lagoon environments as well [12–14]. Credit in this sense, should, thus, be given to earlier geoscientists such as Carr [15], de Boer and Carr [16], El-Ashry and Wanless [17], and Gulliver [18], whose work contributed to the advancement of information on shoreline change.

The term shoreline was used in the 1800s [18], while the term shoreline change appeared in the 1960s [17]. However, the combined term shoreline change analysis first appeared in the scientific articles in the late 1970s [19]. During this time, computations and the development of diverse geospatial tools including aerial photography, satellite imagery, and Light Detection and Ranging (LiDAR) were made to formalize the shoreline change analysis process. As reiterated by Burningham and Fernandez-Nunez [10], the awareness about coastal hazards and risks such as shoreline recession and their impacts on coastal inhabitants increased during this time.

The changing nature of the shoreline position drew the attention of coastal researchers to develop and adopt shoreline indicators. As emphasized by Boak and Turner [9], shoreline indicator is utilized as a proxy to show shoreline position. Boak and Turner [9] classified shoreline indicators into 3 groups. Group 1included those indicators that are based on visible coastal features (e.g., an earlier high-tide line or the wet/dry boundary). Studies such as Boye, et al. [20] and Mahapatra, et al. [21] employed these indicators. Group 2 was based on tidal data (e.g., mean high water or mean sea level) with studies such as Crapoulet et al. [22] and Moore et al. [23] utilizing these indicators. Group 3 was based on the application of image processing skills to extract proxy shoreline characteristics. Studies such as Luijendijk et al. [24] and Vos et al. [25] have employed the third indicator. Studies such as Pollard et al. [26] and Salmon et al. [27] have also utilized a combination of the three indicators.

There exist several sources of data for shoreline change analysis. However, the choice of data usage is dependent on availability [9]. Data are, thus, sourced from historical land-based photographs, coastal maps and charts, aerial photography, beach surveys, Global Positioning System (GPS), remote sensing, Multispectral/hyperspectral imaging, Airborne Light Detection and Ranging technology (LiDAR), microwave sensors, and video imaging [9]. It must be stated that each of these sources has strengths and weaknesses (see Boak and Turner [9]). The use of the Unmanned Aerial Vehicle (UAV) to source data for shoreline change analysis has gained popularity in recent times [28].

Tools used for shoreline change analysis differ. Previous shorelines change analyses were simple, as they were made by directly comparing already existing maps [10]. This period gave little or no room for accuracy and uncertainty estimates. This method of shoreline change analysis changed entirely during the 1970s due to the advancement in computer technology and the related Geographic Information System (GIS). This period allowed for the combination of diverse data types, the ability to scale, and correct geospatial elements and digitize shorelines, which transformed shoreline change analysis into a more computational perspective [10]. An earlier tool for shoreline change analysis was the Coastal Feature Mapping system developed by Underwood and Anders [29]. This tool estimates position coordinates (X and Y) through varying ground control points and finally plots multiple shoreline maps for estimating change rates [29]. Again, the Digital Shoreline Analysis System (DSAS) was developed by the United States Geological Survey (USGS). Since its original development in the early 1990s, the DSAS has undergone a series of enhancements. The first version (V.1.0) was created in 1992 by Danforth and Thieler [30], the second (V.2.0) in 2003 by Thieler et al. [31], the third version (V.3.0) in 2005

by Thieler et al. [32], the fourth version (V.4.0) in 2009 by Thieler, et al. [33], and the fifth in 2018 consisting of versions (V.5.0 and V.5.1) by Himmelstoss et al. [34,35].

The high utilization of the DSAS software is due to its easy incorporation into ArcGIS/ArcMap. This has made its utilization in shoreline change research undoubtable [36,37]. However, other GIS software such as the QGIS has also received attention in recent times. As reiterated by Burningham and Fernandez-Nunez [10], researchers nowadays use the QGIS to generate a shoreline database and create shapefiles or other form of geospatial files and import them into programming environments such as Python, MATLAB, or R, to perform shoreline change analysis. Studies such as De Lima et al. [38] and Griffiths et al. [39] have used QGIS in assessing shoreline change. Tools such as the AMBUR and the Open Digital Shoreline Analysis System (ODSAS) have also been widely recognized due to their capabilities in estimating coastal variations [40–42]. Additionally, the utilization of models and algorithms has increased in recent times, and this has provided a place for machine learning in shoreline change analysis [43–45].

There exist several research studies on shoreline change analysis and detection. Many of which are either an original article (e.g., Moore et al. [23], Vos et al. [25], Santos et al. [37], Castelle et al. [46], and Yadav et al. [47]) or review the literature (e.g. Boak and Turner [9], Apostolopoulos and Nikolakopoulos [48], and Parthasarathy and Deka [49]). As research continues to grow, it is worthwhile to understand the current state of global scientific production on the subject. So far, little or no studies have attempted anything in this regard. It is, therefore, important to utilize the bibliometric method, which can chart the history of publications and the development of scientific output on the subject [50]. The bibliometric approach uses statistical and mathematical techniques to analyze scientific publications. As reiterated by Aria, et al. [51], the bibliometric approach can be used to analyze the contributions of authors, journals, and countries to a research field. The bibliometric approach can also map out clearly important themes and reveal gaps in a particular field of study [52].

The bibliometric approach has been utilized by many authors in different fields [53–56]. However, in the field of shoreline change analysis and detection, it is less utilized. To the best of our knowledge, it is only Mishra et al. [36] who has performed a bibliometric analysis on shoreline change analysis. However, the researchers only focused on the development of the DSAS tool and did not attempt to observe the progress on data sources (methods) and other important tools for shoreline change analysis and detection. The present study thus builds on these, and extends them to include developments in data sources (methods) and tools for shoreline change analysis and detection. This study performed bibliometric analysis of data sources (methods) and tools for shoreline change analysis and detection. The following objectives were, therefore, studied: data sources (methods) for shoreline change analysis and publication growth and the critical assessment of the tools for shoreline change analysis and detection. As the global sea level continues to rise under a changing climate [1,2,57,58], information on shoreline change analysis through research is essential. This research, therefore, does not stand to benefit only coastal communities and coastal engineers or planners, but also provides understanding of the existing body of literature on shoreline change analysis and detection, which will assist potential research.

2. Materials and Methods

2.1. Search and Selection Process

This study retrieved scientific documents on data sources (methods) and tools for shoreline change analysis and detection from Scopus (Elsevier) and Web of Science (WoS) (Clarivate Analytics) databases. These two databases were chosen because they cover broad scientific disciplines and are also seen as the largest abstract and citation databases for scientific documents [59]. Several studies (e.g., Lima and Bonetti [60] and Pathmanandakumar, et al. [61]) have stressed the difficulties of merging two databases for bibliometric analysis and, thus, use a single database. This study, however, made efforts to integrate the Scopus and the Wos databases (see Supplementary Material Table S1 for details of the

merging procedure). The usage and integration of both databases in this study helped to reduce the risk of losing important documents on data sources (methods) and tools for shoreline change analysis and detection.

The authors met and discussed a range of keywords related to data sources (methods) and tools for shoreline change analysis and detection. A search for relevant documents in both databases was, therefore, performed. The functions Title, Abstract, Keywords (TITLE-ABS-KEY), and Topic (TS) for Scopus and WoS, respectively, were employed in the documents search. To include all relevant documents, the search combined Boolean operators such as 'AND' and 'OR' with the search terms (Table 1).

Table 1. Keywords used for documents search.

Scopus
TITLE-ABS-KEY(("Shoreline change" OR "shoreline mapping" OR "shoreline analysis" OR "shoreline position" OR "shoreline detection" OR "coastline change" OR "coastal erosion" OR "coastal accretion") AND ("GIS" OR "Geographic Information System" OR "QGIS" OR "remote sensing" OR "Landsat" OR "aerial photography" OR "beach survey" OR "Global Position System" OR "GPS" OR "satellite imagery" OR "multispectral imagery" OR "hyperspectral imagery" OR " Airborne Light Detection and Ranging technology" OR "LiDAR" OR "microwave sensors" OR "video imaging" OR "Unmanned Aerial Vehicle" OR "UAV"))
WoS
TS = (("Shoreline change" OR "shoreline mapping" OR "shoreline analysis" OR "shoreline position" OR "shoreline detection" OR "coastline change" OR "coastal erosion" OR "coastal accretion") AND ("GIS" OR "Geographic Information System" OR "QGIS" OR "remote sensing" OR "Landsat" OR "aerial photography" OR "beach survey" OR "Global Position System" OR "GPS" OR "satellite imagery" OR "multispectral imagery" OR "hyperspectral imagery" OR " Airborne Light Detection and Ranging technology" OR "LIDAR" OR "microwave sensors" OR "video imaging" OR "Unmanned Aerial Vehicle" OR "UAV"))

The study placed no restriction on the publication years, document types, languages, and subject/research areas. A total of 2516 and 1405 documents were found in Scopus and WoS, respectively. Documents selection criteria were applied to titles and abstracts. The study centered its exclusion criteria based on the inclusion of data sources (methods) and tools for shoreline change analysis and detection. This made sure that only studies on data sources (methods) and tools for shoreline change analysis and detection were included. After reading through the titles and abstracts, a total of 1453 and 762 studies were found that were eligible in Scopus and WoS, respectively. Eligible studies in both databases were first exported in BibTeX format and later the Plain Text format for WoS (see Supplementary Material Table S1). These formats aided the merger of the two databases in the bibliometric R and the Visualization of Similarities (VOSviewer) package. In this regard, 637 duplicates were identified and removed by the bibliometric R package. In total, 1578 documents (Table 2) were deemed eligible and were utilized in the study. The documents retrieved from both databases covered 5 decades (1968–2022).

2.2. Bibliographic Mapping

The study employed bibliographic mapping methods (quantitative approaches) to visualize the global scientific production on data sources (methods) and tools for shoreline change analysis and detection through the usage of bibliographic data [50]. Data analysis was, thus, performed through the utilization of the bibliometric R package (version 2.2.0) [50], while data visualization was performed through the VOSviewer software (1.6.17) [51]. The study used the bibliometric R package because of its capability of creating various possibilities for data analyses [62]. This package, thus, gives an order of actions for bibliographic data importation for bibliometric analyses and provides assumptions on statistics including citations and keywords. The VOSviewer, an open bibliometric visualizer, can analyze large data sets and create insightful images that help data analysis [63]. The bibliometric analysis in this study placed emphasis on the global intellectual

construction surrounding shoreline change analysis and detection and the applicable data sources (methods) and tools. This was, therefore, realized by carrying out analysis such as keyword and citation. Keyword analysis helped in the explanation of the nature of the networks and concepts utilized by authors. Analysis performed in this regard was focused on the co-occurrences of keywords. Citation analysis was also useful in detecting relevant authors. In addition, country analysis was essential and helped to understand the most prominent and productive countries that published scientific documents on data sources (methods) and tools for shoreline change analysis and detection. Analysis was further performed to understand the thematic progress and the direct citation analysis of data sources (methods) and tools for shoreline change analysis and detection.

Table 2. Document types considered in data sources and tools for shoreline change analysis and detection.

Document Type	Number
Abstract report/meeting	2
Article	1148
Data paper	2
Proceedings paper	22
Book chapter	32
Conference paper	338
Correction	3
Note	1
Review	30
Total	1578

3. Results

3.1. Scientific Mapping

3.1.1. Publication Trends in Data Sources (Methods) and Tools for Shoreline Change Analysis and Detection

Figure 1 shows the annual publication distribution of data sources (methods) and tools for shoreline change analysis and detection globally between 1968 and 2022. Although shoreline studies established itself in the 1800s [18], it is clear from Figure 1 that studies on data sources and tools for shoreline change analysis and detection appeared in the scientific journal in 1968. The scientific production has, since then, increased exponentially and has seen an annual percentage growth rate of 8.01%. A critical look at Figure 1 indicates that the year 2021 recorded the highest (202) number of publications, followed by 2020 (178), while the lowest (1) was recorded in the years 1968, 1971, 1972, 1980, 1983, and 1984. The year 2022 has a total of 32; however, it must be noted that a databases search for published articles for the year 2022 only captured the months of January and February. A total of 32 publications for one and half months, therefore, shows a promising scientific production, and this study believes that the total number of publications for the year 2022 will surpass that of 2021 as the highest as per this analysis. The percentage growth rate of 8.01% indicates the fast-changing shorelines and the impact of this globally. This echoed an increasing concern among the scientific community to realize the fundamental processes of shoreline change in order to plan for the appropriate adaptation and mitigation measures. (A list of all the studies (1578) used for the analysis carried out in the present study can be found in Supplementary Material Table S2.

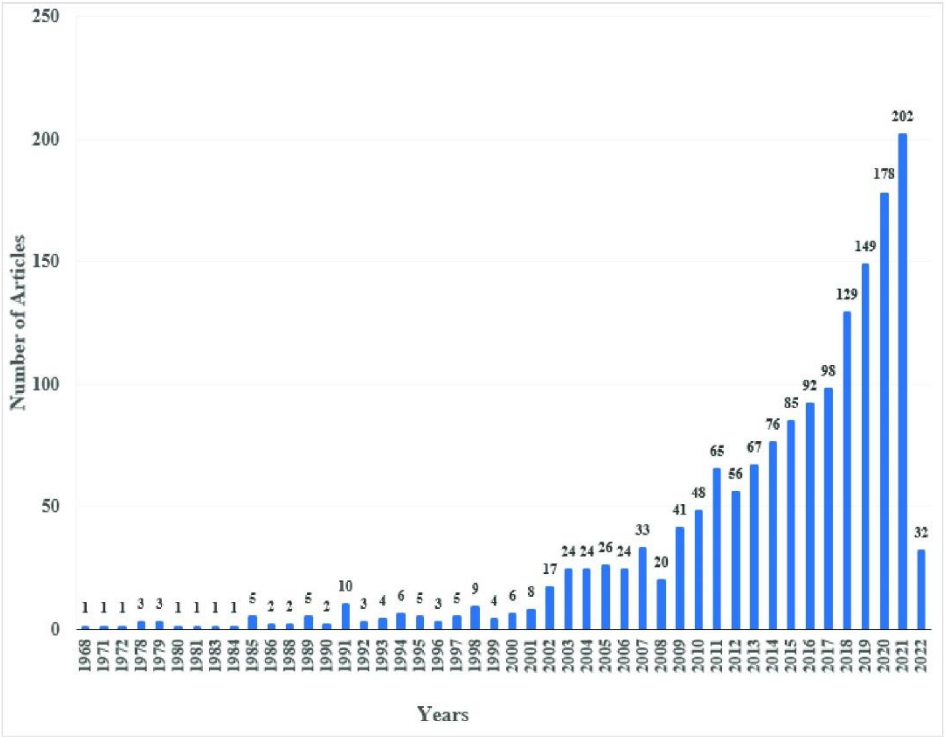


Figure 1. Annual global publication trends in data sources and tools for shoreline change analysis and detection (1968–2022). Note: The year 2022 covers only the 1st trimester.

3.1.2. Most Relevant Sources in Data Sources and Tools for Shoreline Change Analysis and Detection

Table 3 shows the top-20 most relevant journals in data sources and tools for shoreline change analysis and detection. From Table 3, the majority of the documents (192) were published in the Journal of Coastal Research, followed by Remote Sensing (46), while Marine Geodesy (15) is the lowest.

3.1.3. Most Relevant Authors in Data Sources and Tools for Shoreline Change Analysis and Detection

Table 4 shows the 20 most relevant authors in data sources and tools for shoreline change analysis and detection. From Table 4, Zhang Y is recognized as the most relevant author on the subject, while Misria A takes the last spot among the top 20 considering the fractionalized articles of the authors. It must be stated that articles fractionalized of the individual authors represents a fraction of their co-authored publications.

Table 3. Top-20 most relevant journals in data sources and tools for shoreline change analysis.

S/N	Journals	Number of Documents
1	Journal of Coastal Research	192
2	Remote Sensing	46
3	Geomorphology	45
4	IOP Conferences Series: Earth and Environmental Science	38
5	Journal of Coastal Conservation	37
6	International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences- ISPRS Archives	29
7	Marine Geology	29
8	International Journal of Remote Sensing	27
9	International Geoscience and Remote Sensing Symposium (IGARSS)	24
10	Proceedings of SPIE- The International Society for Optical Engineering	24
11	Environmental Earth Sciences	23
12	Ocean and Coastal Management	23
13	Journal of the Indian Society of Remote Sensing	20
14	Environmental Monitoring and Assessment	19
15	Arabian Journal of Geosciences	17
16	Journal of Marine Science and Engineering	17
17	Natural Hazards	17
18	ISPRS International Journal of Geo-Information	16
19	Regional Studies in Marine Science	16
20	Marine Geodesy	15

Table 4. Top-20 most relevant authors in data sources and tools for shoreline change analysis.

S/N	Authors	Articles	Articles Fractionalized
1	Zhang Y	17	6.53
2	Liu Y	14	3.04
3	Li X	13	4.33
4	Turner I	12	2.96
5	Bayram B	11	2.37
6	Wang Y	11	3.39
7	Del R L	10	2.75
8	Li J	10	2.47
9	Pardo-Pascual J	10	2.12
10	Anthony E	9	1.71
11	Goncalves R	9	2.22
12	Hou X	9	2.65
13	Jones B	9	1.80
14	Kankara R	9	2.73
15	Li R	9	2.46
16	Mishra M	9	2.08
17	Wang C	9	2.21
18	Awange J	8	2.22
19	Islam M	8	1.47
20	Masria A	8	1.95

3.2. Country Analysis

3.2.1. Most Productive Countries

Figure 2 shows a summary of the most productive countries that have contributed to scientific production on data sources and tools for shoreline change analysis and detection. The study places emphasis on the 20 most productive countries. Among the top 20, the United States of America (U.S.A.) is the country with the most scientific production (267), followed by India (191), while there is a tie between Poland and Portugal for the lowest (20) among the top 20. It must be stated that country ranking is centered on the first author's affiliation.

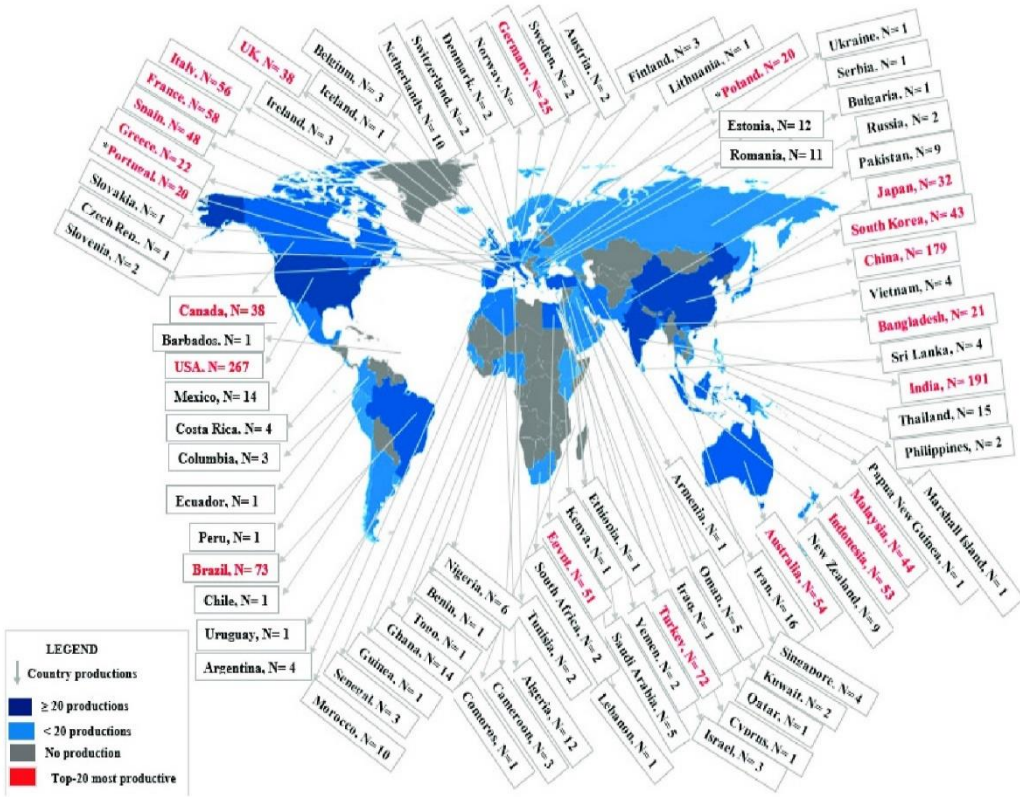


Figure 2. Most productive countries in the scientific production on data sources and tools for shoreline change analysis and detection (1968–2022). Note: *Poland and Portugal have 20 documents and so, the study saw the need to report both. N indicates number of documents.

3.2.2. Country Collaborative Analysis

In this analysis, the VOSviewer software was utilized to map and visualize the collaboration network among countries and their published scientific documents. Here, the default setting (a threshold of the minimum number of 5 documents of a country) was maintained. The study did not change this default setting, as a minimum of 5 documents gives a strong indication of a country's commitment to collaborate with other countries. Of the 282 countries identified, 51 met the threshold. The 51 countries were grouped into 9 clusters with links (221) and total link strength (474). It must be stated that, a stronger collaboration between countries is identified by the links and the total link strength.

From Figure 3, the yellow color with U.S.A. and China is recognized as the countries with the greatest collaborations. The second is the green color, consisting of countries such as the United Kingdom and Italy. The third is the violet color containing countries such as Australia and the Netherlands. France and Ghana, in a light blue color, pick up the fourth position. The blue color containing countries such as Germany and Brazil is seen as fifth. Following this is the red color, with countries such as Japan and Denmark. India and Mexico, in a light brown color, pick up the seventh spot. Indonesia and Malaysia in a white color are eighth, and Egypt and Saudi Arabia in a black color pick up the last place.

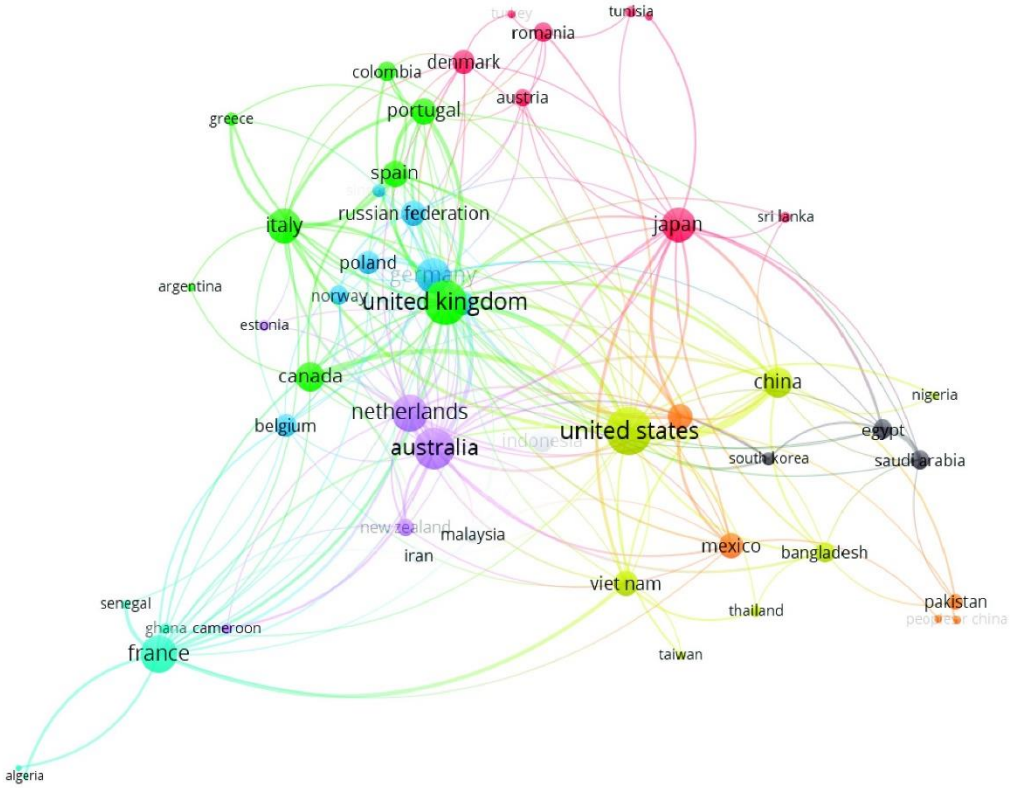


Figure 3. Countries collaboration network analysis of data sources and tools for shoreline change analysis and detection production globally (1968–2022).

3.3. Keywords Analysis

Keywords Co-Occurrence Analysis

Analysis was performed on keywords co-occurrence as shown on Figure 4. Keywords were retrieved from the titles and abstracts of the 1578 documents analyzed in the present study. The VOSviewer software was once again used in this analysis. Over here, the default setting (a threshold of the minimum number of 5 occurrences of a keyword) was maintained. The study believed that the occurrence of a keyword 5 times indicates the importance keyword to the subject. Of the 3146 keywords, 161 meet the threshold. In all, 11 clusters with links (1503) and total link strength (3161) were identified and examined based on the total link strength approach. Of these 11 clusters, 7 are of major dimensions and indicate greater co-occurrence of the resultant keywords in either the titles or abstracts (Figure 4). Clusters in circles are depicted by diverse colors and dimensions.

Of these 7 major clusters, the blue color containing keywords such as remote sensing and Landsat is the first and the most co-occurred keywords. The second is seen in the red color with keywords such as shoreline change and DSAS. The third occurred in the purple color with keywords like coastal erosion and shoreline. The green color makes the fourth and have keywords such as erosion and beach. Keywords such as GIS and Landsat 8 in the pink color make the fifth most co-occurred. The yellow color containing keywords like shoreline changes/position and coastline changes/extraction is the sixth, while the black color with keywords like coastline and shoreline protection is the less co-occurred.

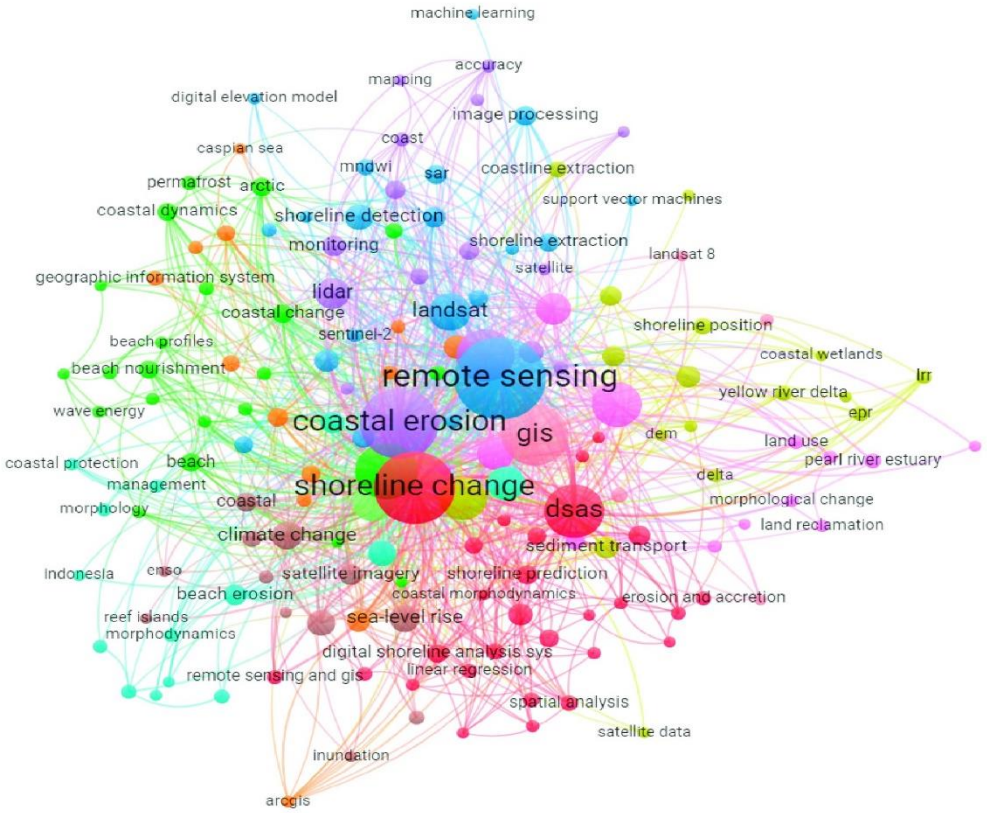


Figure 4. Keyword co-occurrence analysis of data sources and tools for shoreline change analysis and detection production globally (1968–2022).

3.4. Data Sources (Methods) and Tools for Shoreline Change Analysis and Detection

Figure 5a–c show the data sources, methods, and tools used in shoreline change analysis and detection. Figure 5a shows that Landsat (516 studies) is the most utilized data source for research on the subject, followed by the combination of multiple (425) data sources, while the least utilized includes the Global Navigation Satellite system (GNSS), the MODIS, Pléiades, and QuickBird (1) satellite imageries. From Figure 5b, the majority of the studies on the subject employ remote sensing methods (578 studies), while the photo interpretation method (1) is the least utilized method. From Figure 5c, the majority (968 studies) did not indicate any specific tool, followed by the DSAS tool (231) and the ArcGIS/ArcMap (218). The least (1) utilized tools include the beach transect the, Coastal Analyst System from Space Imagery Engine (CASSIE), CoastSat, IDRISI, Intergraph, LaeNet, Spatial analysis of coastal risks (MAp-RISC), Spreadsheet Mapper, SPSS, and VEdge_Detector.

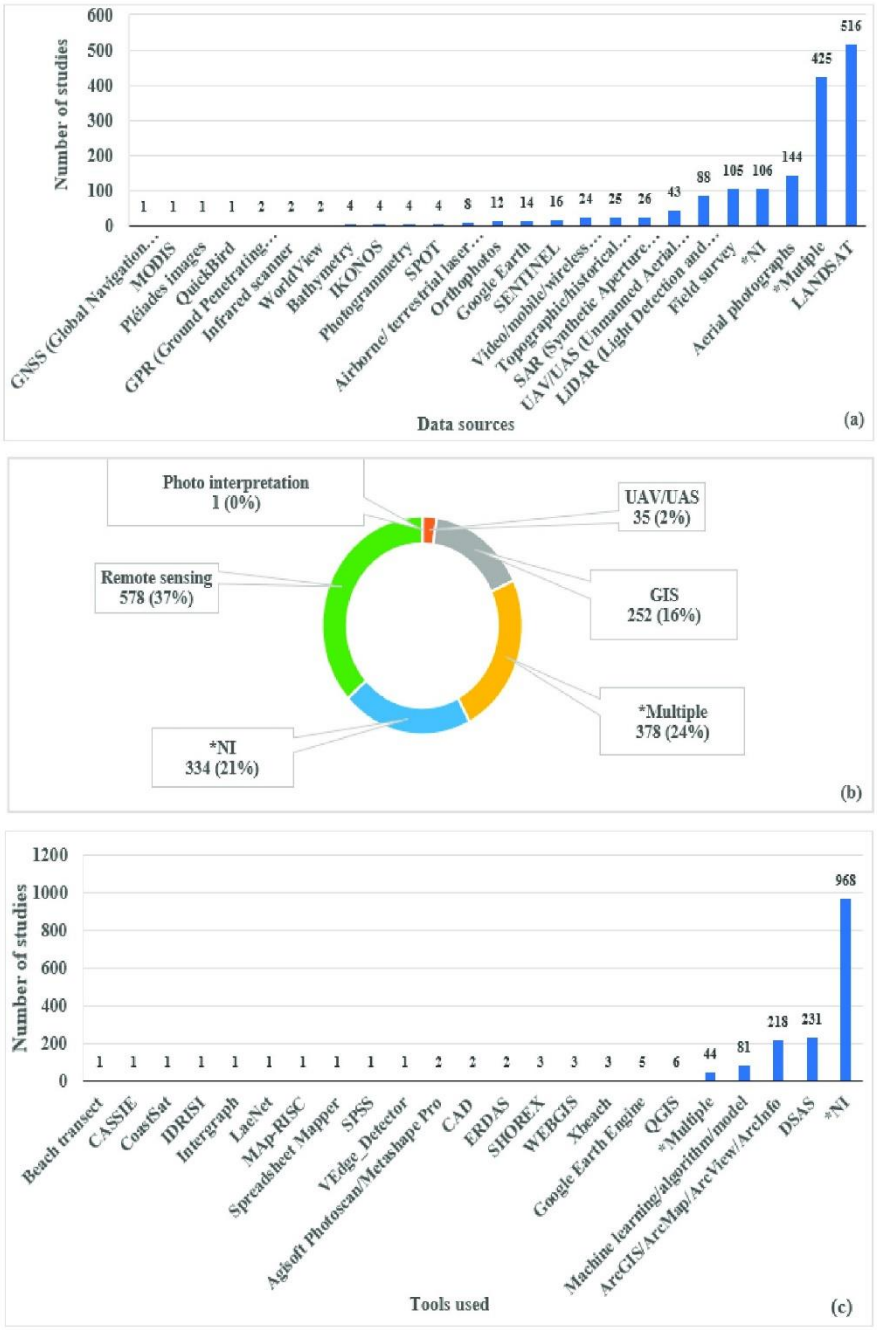


Figure 5. (**a**) Data sources; (**b**) methods; and (**c**) tools used in shoreline change analysis and detection (1968–2022). *NI (Not Indicated) shows number of studies that did not report data sources (**a**), methods (**b**), and tools used (**c**). *Multiple shows number of studies that utilized more than 1 data sources (**a**), methods (**b**), and tools (**c**).

3.5. Thematic Progression Analysis

Figure 6 depicts the main research topics based on the global scientific publication of the subject matter of data sources and tools for shoreline change analysis and detection. Placing emphasis on relevant degrees (centrality) (horizontal axis) and development degrees (density) (vertical axis), a four-topic quadrant is identified [64]. It is worth noting that the sizes of the circles in the individual quadrants are relative to the number of documents and are equal to each keyword.



Figure 6. Thematic progression of data sources and tools for shoreline change analysis and detection globally (1968–2022).

Topics found in the upper-right quadrant (motor themes) reveal the hot topics and indicate greater density and stronger centrality. Topics in this quadrant are highly noticeable concepts that are relevant and related directly to other conceptual topics. Topics found in the lower-right quadrant (basic themes) depict important keywords in the data sources and tools for shoreline change analysis and detection as a research area but are not advanced. Again, topics in the upper-left quadrant (niche/specialized themes) are highly engaged and show highly improved internal links but slight external links. Additionally, topics located in the lower-left quadrant (emerging or declining themes) describe themes as less advanced with minimal centrality and density. Coastal erosion is observed as the hot topic on the subject. This topic has higher density and stronger centrality and relates well with other conceptual themes. Basic topics on data sources and tools for shoreline change analysis and detection studies include erosion and shoreline change. Niche topics comprise shoreline evolution and coastal management, while remote sensing is recognized as an emerging topic.

3.6. Direct Citation Analysis

Figure 7 depicts the intellectual structure portrayed through a historical direct citation network. As reiterated by Borgman and Furner [65], the historical direct citation denotes a sequential map of the most important citations arising from a bibliographic database. Relevance in this sense is not only given to the authors, but also the topics of interest on the subject and the related discussion that researchers bring up. A summary of data sources and tools for shoreline change analysis and detection is displayed in Supplementary Material Table S3. From Figure 7, 9 clusters are identified, and these show the articles that have direct citation. A thorough review of the historical direct citation was undertaken to trace the subject's information. The 3 earliest and the 3 latest publications in the clusters are reported. For some clusters, however, either the earliest or the latest publication was reported depending on the number of direct citations in that cluster.

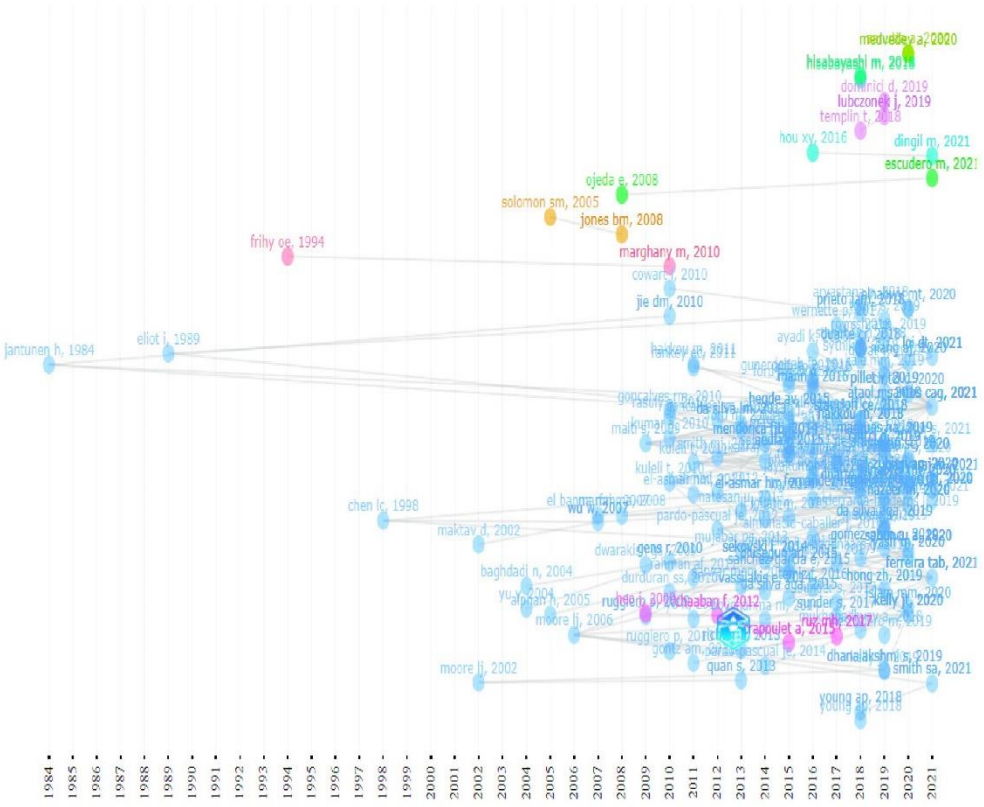


Figure 7. Historical direct citation network of data sources and tools for shoreline change analysis and detection (1968–2022). Note: 129 studies are involved in the blue cluster; 4 studies in the pink; 3 studies in the purple; and 2 studies each in the red, brown, green, light blue, light green, and light brown clusters.

As shown in Figure 7, a direct citation in the field emerged in 1984 (blue colored cluster) by the work of Jantunen and Raitala [66]. The study used multitemporal Landsat data to locate shoreline changes in the Porttipahta Finland water reservoir. Three other studies directly cited this study (Figure 7; 3 direct lines), and it was also cited afterwards by Eliot and Clarke [67] and Chen [68]. Generally, the studies' central focus was on shoreline change detection. Works in this cluster employed diverse approaches, such as remote

sensing techniques (multitemporal Landsat satellite data) used by Jantunen and Raitala [66] to locate shoreline changes in the Porttipahta Finland water reservoir, the use of beach survey records to evaluate temporal and spatial bias in the estimation of shoreline rate of change statistics from beach survey information by Eliot and Clarke [67], the use of remote sensing (multi-temporal satellite images-SPOT) to detect shorelines changes for tideland areas by Chen [68], the use of field measurements and remote sensing (Landsat images) to analyze the influence of climatic variations on river delta hydrodynamics and morphodynamics by da Silva et al. [69], the utilization of remote sensing and GIS (RapidEye images and DSAS) to evaluate sedimentary balance and morphological changes observed in Pecém Port in Brazil by Duarte et al. [70], and remote sensing and GIS (Landsat images, DSAS) to observe a bimodal climate control of shoreline change by Kelly et al. [71]. The works in this cluster stated varying outcomes including the importance of using digital Landsat data to generate information about environmental changes in reservoir areas, variations in the trends of short term beach surveys (5-year records), detection of error in sand barriers tests, greater changes occurring westwards from the Parnaíba river delta, anthropogenic activities seriously changing coastal morphology and the natural elements, and the phase of the Interdecadal Pacific Oscillation (IPO) determining the bimodal climate control of shorelines.

The work of Frihy, et al. [72] in 1994 led the second (red colored cluster) and was directly cited by 1 other study (Figure 7; 1 direct line). The study employed remote sensing techniques (Landsat- MSS and aerial photograph) to analyze the pattern of shoreline changes (beach erosion) in the northwestern Nile delta. The key finding in this was the detection of the longshore pattern or the sequence of beach erosion and accretion [72].

The work of Solomon [73] in 2005 led the third (brown colored cluster) and was directly cited by Jones et al. [74]. This study analyzed the spatial and temporal variability of shoreline change in the Beaufort-Mackenzie region of Canada. Aerial photographs and GPS surveys were the data sources used, whereas the Geographic Resources Analysis Support System (GRASS) was the tool used. The key finding was the dominance of shoreline retreat with mean annual retreat rates (-0.6 m/yr) [73].

Again, the work of Ojeda and Guillén [75] in 2008 led the fourth (green colored cluster). This work was directly cited by 1 other study (Figure 7; 1 direct line). The study monitored shoreline dynamics and beach rotation of artificial embayed beaches in the city of Barcelona [75]. Data sources utilized in this study included cameras (Argus video systems), surveys using the differential Global Position System (dGPS), and the Intertidal Beach Mapper software as the main tools. The main finding in this study was a general retreating trend with displacements of the shorelines, which resulted from the oblique wave incidence during strong storm phenomena [75].

The fifth (pink colored cluster) was also led by the work of Heo et al. [44] in 2009. This work received a direct citation from 1 other study. This was followed by Chaaban et al. [76] in 2012, which received 3 direct citations from other studies. Largely, the studies in this cluster focused on proposing methodologies and data sources in estimating shoreline change. Methods (data sources) used in this study were the utilization of remote sensing (Corona) [44], GIS (aerial photographs) [76], remote sensing (LiDAR) [77], and field surveying (LiDAR and GPS survey) [78]. Key findings from this cluster included the reliability in the use of the buffering and non-linear least square in shoreline change estimation [44], the identification of retreat (82%) in shorelines between 1947 and 2005 [76], significant declines in shorelines [77], and the advancement of the sea towards the coast since the 16th century [78].

In addition, the work of Hou, et al. [79] in 2016 was essential and led the sixth (light blue colored cluster). This work received a direct citation from 1 other study. The study examined coastline changes in China [79]. The study used remote sensing, GIS, and field survey approaches and data sources such as topographic maps and Landsat Thematic Mapper (TM)/Landsat Enhanced Thematic Mapper Plus (ETM) +/Operational Land Imager (OLI). The key finding was the dramatic change in the coastline structure of

mainland China because of coastline artificialization caused by sea reclamation and coastal engineering [79].

Furthermore, the seventh (purple colored cluster) was led by the study of Templin et al. [80] in 2018 and afterwards by Dominici et al. [43] in 2019. Both studies were directly cited by 1 other study. The study of Templin et al. [80] described the application of low-cost fixed-wing UAVs for inland lake shorelines, while that of Dominici et al. [43] found high resolution satellite images for instantaneous shoreline extraction using algorithms. Both studies employed remote sensing approaches, with the addition of algorithms in the case of [43]. UAV by [80] and satellite- WorlView-2 images by Dominici et al. [43] were the data sources utilized in both studies. The findings were that a low-cost UAV is an excellent tool for estimating shallow changes in lake shorelines [80] and the detection of greater accuracy in the Active Connections Matrix (ACM) algorithms for testing satellite images for shoreline extraction [43].

Moreover, the eighth (light green colored cluster) was led by the work of Hisabayashi et al. [45] in 2018. This work received a direct citation from 1 other study. The study examined shoreline change in Funafuti Atoll through the usage of satellite images [45]. A remote sensing approach was used with data sources originating from satellite images such as QuickBird-2, WorldView-2, WorldView-3, and Landsat-OLI data. Tools used were CLASlite software and Terrset-IDRISI. The finding from this study was a decrease (0.13%) in net island area [45].

The final (light brown colored cluster) was led by Zanutta et al. [28] in 2020. This work was cited directly by 1 other study. The study evaluated UAV and ground surveys as a mapping tool for monitoring shoreline and beach changes [28]. This study utilized the remote sensing and field survey approaches. Relevant data were LiDAR data, Digital Terrain Models (DTMs), orthophotos, and UAV (DJI Matrice 600 and Spark) images. The Agisoft Metashape Professional Edition 1.5.5, Agisoft LLC, the RTKLIB v. 2.4.3 software, and QGIS software were the tools employed in the study. The key finding was that low-cost, professional, and commercial UAVs are good tools to produce maps and detect topographical changes.

In general, this review has indicated that the research field focuses on changes along coasts (coastlines/shorelines), riverbanks, deltas and lake shorelines. It is interesting to note that the research field has witnessed significant transformations in terms of methodologies (data sources) and tools used. Since the utilization of low-resolution aerial photographs and historical maps in the interpretation of shorelines between capes Hatteras and Fear in North Carolina by El-Ashry and Wanless [17], there has been an advancement in the quality of data used for shoreline change analysis and detection. The work of Herbich and Hales [81], which was presented at the Third Annual Offshore Technology Conference by the American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., held in Houston, Texas, was essential to this research area. In their work, they talked about remote sensing techniques and the available instruments used in determining changes in coastlines [81]. The works of Dolan et al. [8], which questioned the reliability of aerial photographs in shoreline change measurements was also important. From this point, researchers in the field began exploring more advanced techniques. The work of Jantunen and Raitala [66] was, thus, the first study in this field to utilize multitemporal high resolution satellite- Landsat data to analyze shoreline change. From this point, researchers started using high-resolution satellite images, including aerial photographs.

The growth in remote sensing approaches and the utilization of high-resolution satellite images was challenged with the appropriate tools for shoreline quantification. This challenge was addressed in the 1990s. Thieler and Danforth [82] developed the DSMS/DSAS, a powerful tool used for estimating shoreline rates of change and uncertainties. This era saw the integration of remote sensing and GIS techniques in shoreline change analysis and detection (e.g., Cetin et al. [83] and Williams [84]). The 2000s comprised reviews in the techniques used for shoreline mapping. The work of Moore [85], which provided an overview of errors related with shoreline mapping and the suggested factors like choosing the most appropriate method for shoreline mapping and using GPS over topographical sheets to

establish control, etc. (see Moore [85] for more details) was essential to the research field. Additionally, the work of Boak and Turner [9], which revisited shoreline definition and detection, was important in this time. Their work provided better explanations, especially on shoreline indicators and data sources [9].

Beginning from the mid-2000s, the research field suffered massive transformation with respect to approaches and data sources. While remote sensing, GIS approaches, and DSAS tool still dominate, there has been an increasing utilization of models, algorithms (machine learning), and new software in the research field (e.g. the ACM algorithms by Dominici et al. [46], the buffering and non-linear least square model by Heo et al. [47], CLASlite and Terrset-IDRISI software by Hisabayashi et al. [48], and the GRASS software used by Solomon [79]). It is interesting to note that there has been a shift towards the use of low-cost UAVs (e.g. Zanutta et al. [28], Templin et al. [80], Łubczonek et al. [86], and Medvedev et al. [87]) even though the use of satellite images still dominates the field.

In summary, the research field of shoreline change has seen advancements, especially, in the data sources, approaches, and tools. The field began with the detection of shoreline positions through historical maps, aerial photographs, and now through high resolution satellite images. The remote sensing approach (see Figure 5b) dominates the field. It is interesting to note that field measurements and surveys through the employment of GPS has consistently been utilized in the research field. Researchers use GPS surveys to establish control. GPS surveys are also used to validate remote sensing data. The DSAS has remained an important tool in the research field and shows dominance. However, there has been an increasing utilization of other software such as the QGIS, GRASS, Terset-IDRISI, ERDAS, CoastSat, AMBUR, etc. for coastal variation analysis. The increasing utilization of models, algorithms, and programming environments for research in the field has, therefore, provided room for machine learning (see Figure 5c) in the shoreline change analysis and detection field. It is interesting to note that some of the studies that lead to a cluster are related to one direct citation. There is, however, the chance that these studies could be cited by many more papers. This review believes that papers citing these studies are not indexed in the databases used for the document search in the present study, which could result in their inability capture papers directly citing them.

3.7. Viewpoints of Shoreline Change Analysis and Detection through Machine Learning Tools

The scientific mapping which covers five decades on the research field (see Section 3.1) indicates one major viewpoint, that is, progression from observation and interpretation (qualitative description) of historical maps to spatio-temporal analysis (quantitative and/or computational analysis) of high-resolution satellite images employing geospatial techniques (remote sensing). It is worth noting that the field has benefited from both the observational and spatio-temporal analyses.

With the combined progression of qualitative description and improved quantitative and/or computational analysis, intelligent (machine learning) shoreline change analysis and detection tools have been developed. In this review, machine learning makes up 81, or 5.1% of all the documents (1578) analyzed (Figure 8). As the global shorelines continue to change, an indirect average production of about two scientific documents employing machine learning tools occur yearly. This shows the low utilization of the machine learning tools despite the consistent growth in the field.

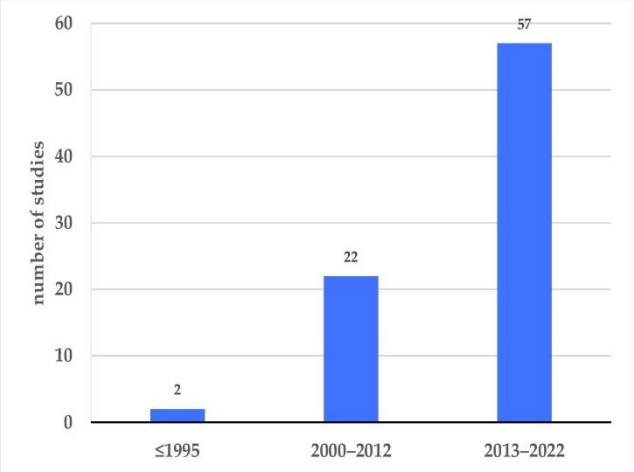


Figure 8. Development in machine learning tools in shoreline change analysis and detection studies.

4. Discussion

The review has revealed the increasing publication trends and the advancement of information on the subject. Although the first Landsat satellite was released in 1972, it was first utilized as a data source for shoreline change analysis and detection in 1984 by Jantunen and Raitala [66] as revealed in this review. Landsat, together with remote sensing and DSAS, have, thus, remained the most utilized data source, method and tool, respectively, on the subject. Researchers in the field choose diverse sources to publish their work. The Journal of Coastal Research (JCR) (Education & Research Foundation) and Remote Sensing (MDPI AG) have been the two most influential in this regard. JCR is based in the U.S.A. and had its first year of publication in 1985. Its long period of establishment and country of publication could be the reason for its prominence. As shown in the review, the majority of the documents in the field were produced in the U.S.A. It could also be due to the journal's scope, which covers all coastal research and subjects relevant to the natural and engineered environment (https://meridian.allenpress.com/jcr, accessed on 15 March 2022). This review believes that the increasing utilization of the remote sensing methods, Landsat as a data source, and machine learning have contributed to the prominence of Remote Sensing. Remote Sensing, having its first year of publication in 2009, publishes original research papers, reviews, technical notes, and communications in remote sensing science. It publishes new, advanced methods of remote sensing (https://mjl.clarivate.com/journal-profile, accessed on 15 March 2022). It is, however, interesting to note that the first scientific article on the subject by El-Ashry and Wanless [17] with regard to this review was published in Marine Geology.

The review has also revealed that several countries contributed to the research development in the field. As shown in Figure 3, the U.S.A. is the country with the most contributions (267 articles; 16.3%), followed by India (191; 11.6%) and China (179; 10.9%), with a tie between Poland (20; 1.2%) and Portugal (20; 1.2%) for the last position among the top 20. A critical analysis among the top 20 from Figure 3 shows that more contributions on the subject are undertaken by the developed countries (65%) (e.g., the U.S.A. Turkey, France, Italy, Australia, Spain, South Korea, Canada, UK, Japan, Germany, Greece, Poland, and Portugal). Notwithstanding, works from the developing countries are encouraging (35%). For instance, India, China, and Brazil were the second, third, and fourth most productive countries on the subject, respectively. On average, bigger clusters and stronger links were observed for the developed countries in the country collaboration analysis as against the developing countries. The high dominance of the developed countries in this field could be due to the well-established research institutions and the level of economic development,

which results in their stronger collaborations. This assertion has been reiterated in the study of Liverpool [88]. This notwithstanding, Zhang, Y, Liu, Y, and Li, X correspondingly, are the first three most relevant authors on the subject. It is interesting to note that these authors are based in a developing country (China) [89]. Again, it must be stated that the contributions from the developing countries are higher in Asia (India and China), South America (Brazil), and North Africa (Egypt) (see Figure 2). Little or no contribution is observed in Sub-Saharan African (SSA) countries. In SSA, Ghana has contributed a total of 14, or 0.9% articles on the subject, followed by Nigeria (6; 0.4%), with a range of 0, or 0.0% to 3, or 0.1% for the rest of the countries. The low research contributions in SSA could be due to low levels of economic development (less funding) and less established research institutions. It could also be due to difficulties obtaining data, as the research field in recent times uses high resolution spatial-temporal satellite images. Some satellite images are expensive, but some others are free. There are other difficulties in obtaining data, such as expensive measuring equipment or lack of historic long-term field data, etc.

The thematic progression of the subject can be linked to the growth in multi-temporal high resolution satellite data (remote sensing). Shoreline change analysis and detection rise above simple observation (description) to high resolution satellite data analysis with the employment of geospatial tools such as remote sensing, GIS, and machine learning approaches. This study believes that the subject's continuous advancement is due to the negative impacts of climate change and variability (sea level rise, temperature, and precipitation, extreme events) and anthropogenic activities (urbanization), which pose risks to coastal zones and their environments. These zones and their communities have, therefore, become vulnerable to inundation and erosion [90]. It is no wonder coastal erosion, shoreline change, climate change, sea level rise, vulnerability, and coastal zone management are the hot topics within the subject. This also reflects the highly utilized keywords on the subject, such as coastal erosion, shoreline change, remote sensing, and DSAS. This, therefore, makes shoreline change (erosion) the fundamental problem most researchers in the field are addressing (see Figure 6).

Found research gaps (see Table S3) were mostly addressed by the researchers themselves. For example, SAR utilization for shoreline change modelling was identified and addressed by Marghany and Hashim [91]. Other found gaps were also addressed in other studies. For instance, reliable methodologies for estimating shoreline recession identified by Heo et al. [44] was addressed by Chaaban et al. [76], while the shoreline mapping accuracy and problems identified by Łubczonek et al. [86] were addressed by Zanutta et al. [28]. It must be stated that some gaps have still not been addressed, especially the ones that have emerged from the recent work, for instance, that of Escudero et al. [92]. These gaps on the subject show the current state of knowledge and indicate potential research directions. This review, therefore, gives a summary of the current state of knowledge and the data sources and tools to be utilized for future research.

The study accepts the possibility of the omission of important scientific papers considering the selection criteria employed. Therefore, there could be a bias in the present results due to the search criteria here employed. The pioneer works by authors such as R.A. Holman, N.G. Plant, T. Lippmann in the late 1980s and 1990s using video imagery for shoreline detection are not included. For instance, the document search in the present study did not capture the study of Holman et al. [93] on the application of video image processing to the study of nearshore processes. Again, the search did not include the study of Plant and Holman [94] on intertidal beach profile estimation using video images, and that of Lippmann and Holman [95] on the quantification of sand bar morphology using a video technique on wave dissipation.

5. Conclusions

The global production of data sources (methods) and tools for shoreline change analysis and detection has been investigated. Due to the negative impacts of climate change/variability and anthropogenic activities, it is pronounced that there has been an

increase in data sources (methods) and tools for shoreline change analysis and detection studies globally. This review concludes that shoreline change analysis and detection studies have progressed from using simple observation (description) from historical maps and topographical maps to employing high-resolution multi-temporal satellite images with remote sensing and GIS approaches for a better understanding of the subject.

This review asserts that the potency of geospatial approaches and tools such as remote sensing, GIS, and machine learning have not been completely discovered. There is a need for more utilization considering their enormous benefits. This review establishes that machine learning (models and algorithms) for shoreline change analysis and detection is an emerging theme. The introduction of machine learning could offer suitable tools and techniques required for the growth of automatic shoreline extraction globally.

The analysis on countries' collaborations revealed less extensive cooperation in comparison to the research network on the subject globally. Greater collaborations are observed among the developed countries as against the developing countries. Additionally, more documents on the subject are produced by the developed countries, reflecting their ability to plan adaptations to and mitigate the subject's problem. Although the contributions and collaborations from the developing countries are encouraging, they have not been evenly represented. There is, therefore, the need for a collaborative and supportive research network to ensure the continuous global development of the research field. It must be stated that there is the likelihood that in the selection process, one or more important scientific papers might be omitted due to the selection criteria. There could, therefore, be a bias in the present results due to the search criteria used.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14094895/s1, Table S1: procedure followed in merging Scopus and WoS databases; Table S2: list of all the studies (1578) used for the analysis carried out in the present study; Table S3: summary of scientific publications with direct citation of data sources (methods) and tools for shoreline change analysis and detection (1968–2022).

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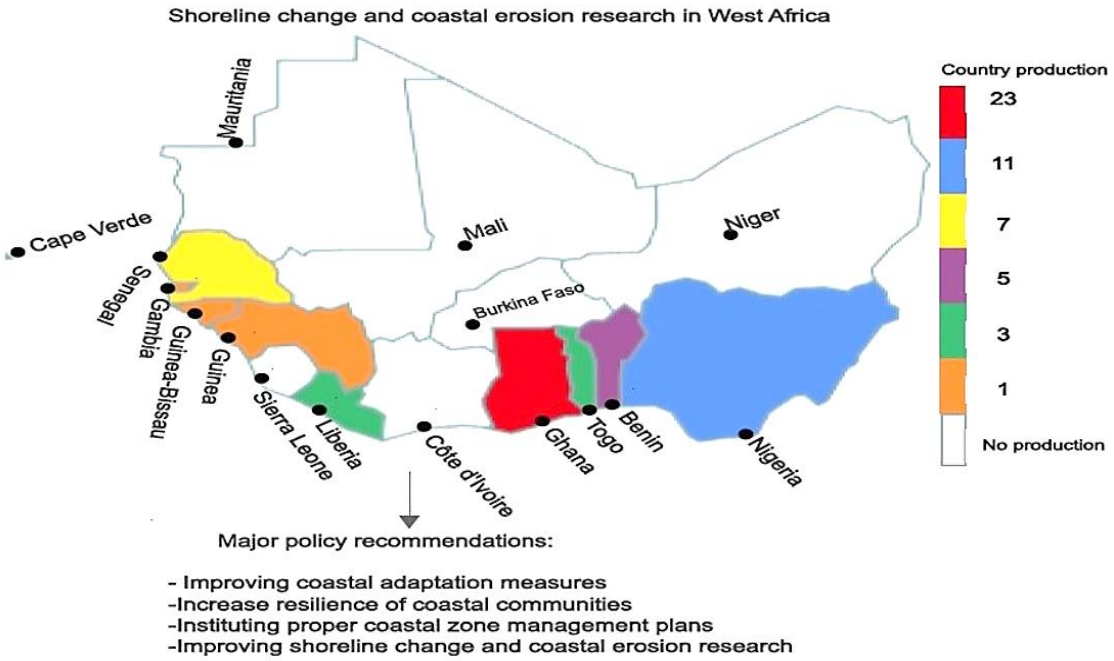
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1.2.11. Shoreline Change and Coastal Erosion in West Africa: A Systematic Review of Research Progress and Policy Recommendation

Paper 4



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Review

Shoreline Change and Coastal Erosion in West Africa: A Systematic Review of Research Progress and Policy Recommendation

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Abstract: Shoreline change and coastal erosion resulting from natural events such as sea level rise and negative anthropogenic activities continue to be problems in many of the world's coastal regions. Many coastal socio-ecological systems have become vulnerable as a result, especially in developing countries with less adaptive capacity. We utilized the systematic method to understand the research progress and policy recommendations on shoreline change and coastal erosion in West Africa. A total of 113 documents were retrieved from Scopus and the Web of Sciences databases, and 43 documents were eligible following established criteria. It was revealed that research on shoreline change and coastal erosion has progressed substantially since 1998, with most research studies originating from the Ghanaian territory. Again, most of the shoreline change and erosion problems in West Africa result from natural events such as sea level rise. However, there was evidence of anthropogenic influences such as sand mining, dam construction, and human encroachment causing shoreline change and erosion in the region. Research in the region has also progressed in terms of methodological approaches. Since 2004, researchers have utilized remote sensing and GIS techniques to source and analyze shoreline change and erosion. However, a combination of remote sensing and field observation approaches is required to clearly depict the erosion problems and aid policy direction. The overall call to action regarding policy recommendations revolves around improving coastal adaptation measures and the resilience of communities, instituting proper coastal zone management plans, and improving shoreline change and coastal erosion research. To protect lives and property, policymakers in the region need to set up good coastal zone management plans, strengthen adaptation measures, and make coastal communities more resistant to possible risks.

Keywords: shoreline change; coastal erosion; sea level rise; coastal zone management; West Africa

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1. Introduction

The global climate has changed, and this has several impacts on both human and natural systems [1]. Coastal zones have widespread socio-ecological systems and remain one of the most affected by the negative impacts of climate change [2]. Global temperatures have increased, which has resulted in the expansion of ocean waters and the melting of glaciers [3]. This process increases the ocean's water volume, thereby resulting in sea level rise [4,5]. Sea level rise poses several threats to coastal systems, especially on the adjacent shoreline and nearby coasts and beaches [6–10], which leads to coastal erosion [11].

Leatherman et al. [7] stressed that a continued rise of 10 cm in sea level could result in 15 m of shoreline erosion along the east coast of the United States. Luijendijk et al. [8] also reiterate that 24% of the global sandy beaches are eroding at rates exceeding 0.5 m/year, whereas 28% and 48% are accreting and stable, respectively. In addition to the natural process of sea level rise as a significant factor for shoreline change and the possible erosion

of coasts and beaches, negative anthropogenic activities on the coast are found to have an equal effect [12–14]. As indicated by Nicholls et al. [15], the long-term erosion of coasts, beaches, and changing shorelines is a well-recognized phenomenon at the local, regional, and global scales. While negative anthropogenic activities reduce sediment supply to the coast [6,16–19], sea level rise alters the sediment budget in all areas [12,20]. Erosion of the coasts and beaches and related shoreline will increase [21,22], especially as the future sea level is projected to rise under human-induced climate change [23]. This, therefore, requires effort to combat the negative impacts the process may have on the coastal systems.

Several efforts have been dedicated to the understanding of the dynamics of the global shorelines and the erosion processes of coasts and beaches. These efforts are essential considering the current negative anthropogenic activities and the projected future rise in sea level [23]. Several research studies on shoreline change and erosion of coasts and beaches have been conducted at all levels across the different continents of the world (e.g., [13,14,17,24–45]).

As the number of original research studies on shoreline change and erosion of coasts and beaches increases across coastal regions of the world, the number of literature reviews that portray the state-of-the-art research stance and policy direction on the subject has also increased (e.g., [10,35,46–54]). While the number of literature review studies on the subject increases in many regions of the world, the research progress and policy stance on the subject in question remain limited in the West African region, although original research exists (e.g., [13,55–63]). While the original research keeps increasing in the region, it is equally important to understand the state-of-the-art stance and progress on the subject in the region and the policy directions recommended. As far as we are aware, no comprehensive review of shoreline change and coastal erosion exists in the region, indicating the need for one. Alves et al. [64] made efforts in a similar conceptual domain. However, their study was limited to coastal erosion and flood risk in the West African region and did not consider the dynamics of shoreline change. Their study was desk-based without a specified time frame or an approach, and it focused on coastal management practices. The authors also did not attempt to understand the policy recommendations offered by researchers on the shoreline change and coastal erosion problems along the West African coast. Research of this nature is imperative, especially considering the vulnerable nature of the region to the negative impacts of climate change [65,66]. To respond to this knowledge gap, it is essential to use a methodology that can show the state-of-the-art stance on the subject. In this regard, this study utilized the systematic review technique to understand the research progress and policy recommendations on shoreline change and erosion along the West African coast.

Therefore, in this study, we systematically reviewed the research progress on shoreline and erosion from coastal Mauritania to coastal Nigeria (i.e., from the northwest coast to the Bight of Benin) between 1998 and 2022 in 43 journals. The main question that drives this study is: How has research on shoreline change and coastal erosion progressed in West Africa? Considering the current increased anthropogenic and natural threats in the world's coastal regions, a systematic review of the research progress and policy recommendations on shoreline change and coast erosion is crucial.

1.1. West Africa: Location and Geomorphology

West Africa is one of the regions of Africa and is made up of countries such as Mauritania, Cape Verde, Senegal, Gambia, Guinea-Bissau, Guinea, Sierra Leone, Liberia, Mali, Burkina Faso, Cote d'Ivoire, Ghana, Togo, Benin, Niger, and Nigeria. Apart from Mali, Burkina Faso, and Niger, which are landlocked countries, the remaining countries form the West African coast. Based on geo-environmental characteristics and meteo-oceanographic driving forces, the West African coastline can be grouped into three [64,67]. These include the northwest section from Mauritania to Guinea Bissau, the muddy and sandy west coast from Guinea Bissau to Sierra Leone, and the Gulf of Guinea from Liberia to Nigeria [64,67]. Figure 1 shows the map of West Africa. The West African coastline covers approximately

6000 km [64,67,68]. The coastline is highly dynamic and comprises sandy and rocky beaches, sand spits, estuaries, mud, and mangrove forests [64,67–69].

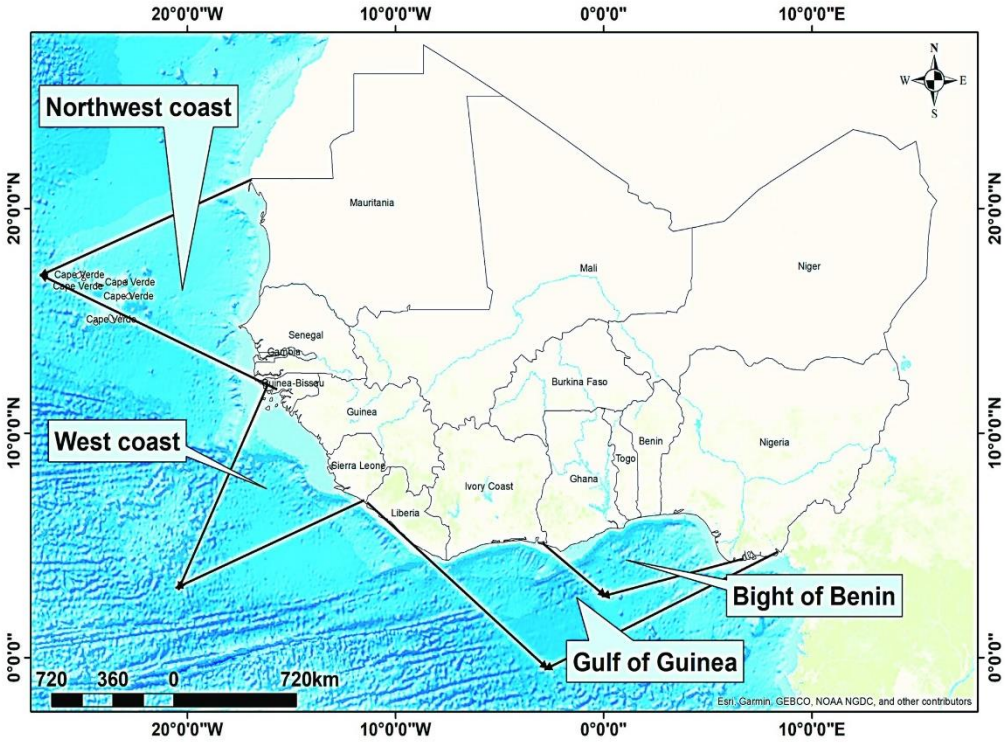


Figure 1. Map showing the division of the West African coast based on geomorphology.

1.1.1. Geo-Environmental Characteristics

The coastline in the northwest (from Mauritania to Guinea-Bissau) varies from high-energy beaches in Mauritania to mangrove ecosystems along the mouth of the River Senegal [64,68]. Various ecosystem types, such as sandy beaches, estuaries, spits, and barrier beaches, exist in the coastal zones of Senegal and Gambia [64]. Major estuaries in this zone include the Senegal, Gambia, Saloum, and Casamance rivers [64]. Volcanic, rocky beaches can also be found in Cape Verde [64]. Erosion is a common problem in this zone, especially along the low coastlines of Senegal and Gambia. The shoreline in these areas is characterized by accretion, especially between 1968 and 1986 [70]. Notwithstanding, evidence of shoreline recession has been recorded, especially beginning from 1986–2004 and from 2004–2017 [70].

The west coast (stretching from Guinea-Bissau to Sierra Leone) is muddy in nature and supports mangrove development [67]. According to Anthony [67], this zone experiences waves from both the North and South Atlantic. The area does not have major river networks, unlike the northwest and the Gulf of Guinea. Nonetheless, the small number of estuaries present in this zone supports sediment load that results in shoreline accretion [64,67].

The Gulf of Guinea (stretching from Liberia to Nigeria) is dynamic in nature and characterized by both rocky and sand beaches. The coastline along Liberia is low-lying with erosional features such as sandy beaches, estuaries, lagoons, and mangroves [64]. In Côte d'Ivoire, both rock (from Cape Palmas to Fresco) and sandy (from Fresco to the western border with Ghana) shoreline types are observed [71]. Ghana's coastline, which is 540 km long, is subdivided into three sections, the western, central, and eastern [72,73].

The western portion is flat with large beaches and lagoons and has low energy [64]. The eastern portion is sandy in nature with barrier lagoons and spit [72]. The central portion has moderate energy with rocky headlands, sandbars, spits, and lagoons [64,74]. Togo and Benin have uniform coastlines characterized by dune ridges and lagoons. It is situated in the center of the Bight of Benin (a beach-ridge barrier-lagoon system from the coast of Ghana to Nigeria). The sandy beaches along these coastlines are highly dependent on the sediment supply from the Volta and Mono rivers [64]. Beginning in the 1960s, the sediment supply from these rivers decreased due to dam construction, which affected the sediment budget [75]. These areas are characterized by huge erosion, with little accretion occurring in the updrift of port infrastructure [75]. The coastline of Nigeria is about 853 km long and is characterized by four distinct geomorphic features, including the barrier–lagoon complex, the mud coast, the Arcuate Niger Delta, and the Strand coast [68]. Nigeria's coastline is mostly covered with mangroves, swamps, lagoons, beach ridges, and sandbars [64]. Major river networks along the Gulf of Guinea coast include the Niger River Delta, the Volta River Delta, the Ankobra River, the Mono River, the Ramos River, etc.

1.1.2. Meteo-Oceanographic Forcings

The northwest section is characterized by swell that is parallel to the coast of Senegal and moves north–south throughout the year [70,76]. This oblique north–south movement results in the formation of spits and sandy ridges toward the south [64]. The wave direction in this area is from the west-northwest to the north [64]. The wind wave in the area has a greater range [61] and is caused by local tropical winds, which peak in spring and autumn and correspond to the oscillatory movement of the Inter-Tropical Convergence Zone (ITCZ) over Senegal [61,64].

The muddy west coast of Guinea-Bissau to Sierra Leone has a southeast to northwest wave direction and is considered the junction coast in terms of wave climate in the West African region [67]. This area receives swell waves from both the North and South Atlantic Oceans, with northwest waves being of low to moderate energy [64,67].

The Gulf of Guinea coast, which also includes the Bight of Benin, is characterized by two differing wave climate components, including locally formed wind waves and a medium-to-high latitude swell [64,77]. The medium-to-high latitude swell waves in the South Atlantic are common in the Bight of Benin region and the same as the locally formed waves in the tropics [64]. Along the Gulf of Guinea, swell waves are notable in the rainy season. The medium-to-high latitude waves are associated with strong westerly winds, and the subtropical zone is controlled by the south-easterly trade winds from the coast of Namibia [77].

2. Materials and Methods

Here, we present the systematic review approach that was utilized to analyze how research on shoreline change and coastal erosion has progressed in West Africa. Here, we followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [78]. The PRISMA protocol guides systematic reviews by ensuring that a specific research question that allows for a systematic literature search is stated explicitly [78]. It also ensures that studies have clear inclusion and exclusion criteria and that large databases for scientific literature searches are examined in a reasonable amount of time [78].

2.1. Resources and Search Procedure

On 31 October 2022, we searched for studies that showed evidence of shoreline change and coastal erosion in the Scopus and Web of Science (WoS) databases. The Scopus database is one of the most popular for conducting literature searches. It contains over 22,800 peer-reviewed journals from 5000 publishers worldwide and is considered one of the largest abstract and citation databases with diverse subject areas, including social sciences, environmental sciences, agriculture, etc. [79]. The WoS database from Clarivate

Analytics contains over 33,000 journals and covers over 256 disciplines, such as social sciences, environmental studies, interdisciplinary, development, and planning [79]. Thus, WoS contains bibliographic and citation data spanning more than a couple of centuries [79].

After deliberating on the appropriate keywords, we developed a list of terms related to shoreline change and coast erosion, which we then used to search the Scopus and WoS databases for relevant studies. In the Scopus database, the following keywords were used: TITLE-ABS-KEY ((“shoreline chang*” OR “shoreline dynamics” OR “coastline change”) AND (“beach erosion” OR “shoreline erosion” OR “coastal erosion”) AND (“West Africa”)) while the topic function was utilized for the WoS search as: TS = ((“shoreline chang*” OR “shoreline dynamics” OR “coastline change”) AND (“beach erosion” OR “shoreline erosion” OR “coastal erosion”) AND (“West Africa”)). Further searches were performed for the individual coastal territories in the region. This was done to capture relevant studies from each country in West Africa. We maintained the list of terms but replaced the keyword (“West Africa”) with each of the coastal countries, e.g., Benin, Cape Verde, Côte d’Ivoire, Liberia, Ghana, Nigeria, etc. We combined the list of terms with Boolean operators to find more relevant concepts for the topic at hand (e.g., OR, AND). The use of the Boolean operator “AND” shows that the review looked at studies that were based on these ideas. To ensure variant endings for keywords, the asterisk (*) truncation function was used where applicable.

Given the keywords used in the document search and selection procedures as well as the use of only Scopus and WoS databases, there is a possibility that some relevant papers on the subject studied will be missed. However, the two databases used for conducting literature searches are regarded as robust and reliable [80].

2.2. Eligibility Criteria and Selection Process

In this study, we considered all document types and languages (e.g., research articles; books; book chapters; conference and conference proceedings; reviews; etc.). We excluded documents that were unrelated to the subject in question, as well as those from outside the West African region or to which we did not have direct access.

Scopus and WoS searches returned 61 and 52 documents, respectively. We must emphasize that the WoS document search was carried out in the Web of Science Core Collection. The resulting literature citations were imported into the EndNote reference management software (https://endnote.com/ accessed on 1 November 2022) for reference organization. At this point, we first eliminated 65 duplicate records. Following that, 48 documents were exported to Microsoft Excel®, where we independently screened them for eligibility. Through an independent review, we used selection criteria for the titles and abstracts. The criteria were then narrowed to include only studies focusing on shoreline change and coast erosion in the West African region. The study’s exclusion criteria were founded on the inclusion of shoreline change and coastal erosion in West Africa. As a result, only studies that addressed these aspects were included in this review. Throughout this process, we met on a regular basis to resolve and discuss any contrasting issues regarding the studies chosen for review. When we were unable to reach an agreement on a particular study, a third researcher was contacted. At the end of this process, a total of 43 documents were used in the review (Figure 2).

2.3. Data Extraction and Analysis

Publication attributes such as author and year, title, study aim, study location, major finding, conclusion or recommendation, and journal source were collected during the data extraction and analysis phase. Here, we applied the inductive qualitative approach to data analysis to examine the main research findings and policy recommendations from the individual studies. This helped to understand the research progress and policy directions on the subject. Table S1 summarizes the characteristics of the publication, study locations, materials and methods, findings, and conclusions.

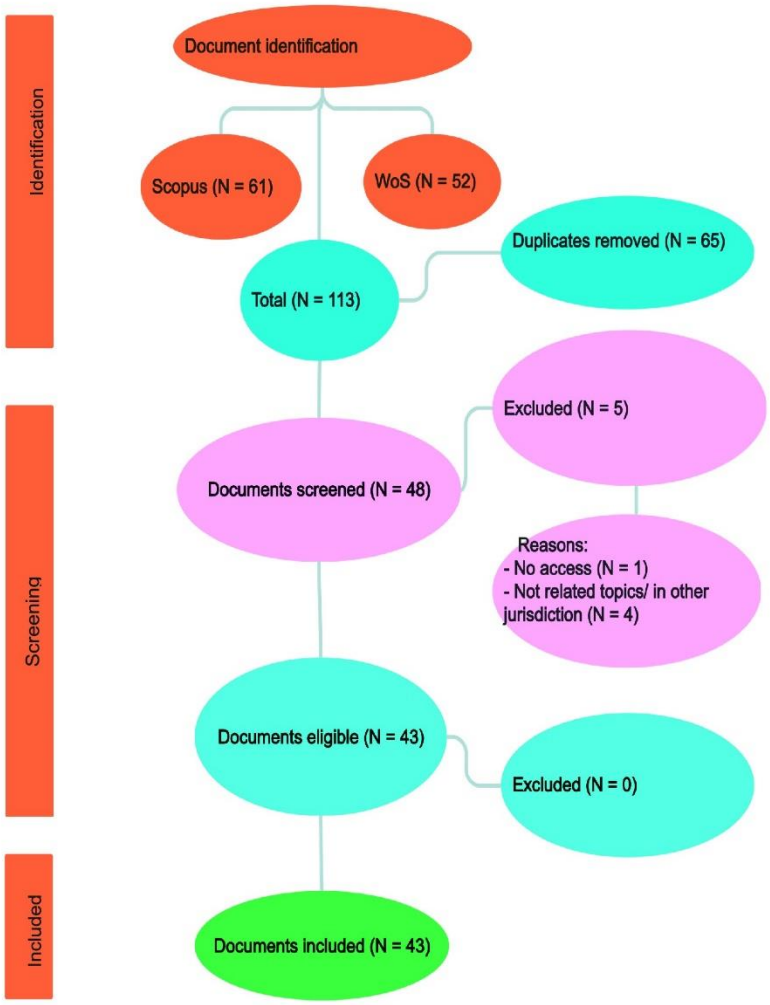


Figure 2. Search and selection process for documents used in the review. Note: N denotes the number of documents.

3. Results

3.1. Publication Characteristics, Study Locations, and Journal Sources

Figure 3a–c show the publication attributes, study locations, and journal sources for the dissemination of research on shoreline change and coastal erosion. From Figure 3a, the most studies (seven) were published in the year 2022, followed by 2021 with six, and the lowest (one) in years such as 1998, 2004, 2012, and 2014. Figure 3a reveals variations in the years of publication. Regarding this review, the first study on the subject occurred in 1998. Following that, interest in the subject declined between 1999 and 2010, with the exception of 2004, when a single study was published. However, interest in the subject has increased since 2011 and particularly since 2021 (Figure 3a). We believe that the decrease in the number of studies between 1998 and 2010 could be due to data challenges, which are a common feature in the region.

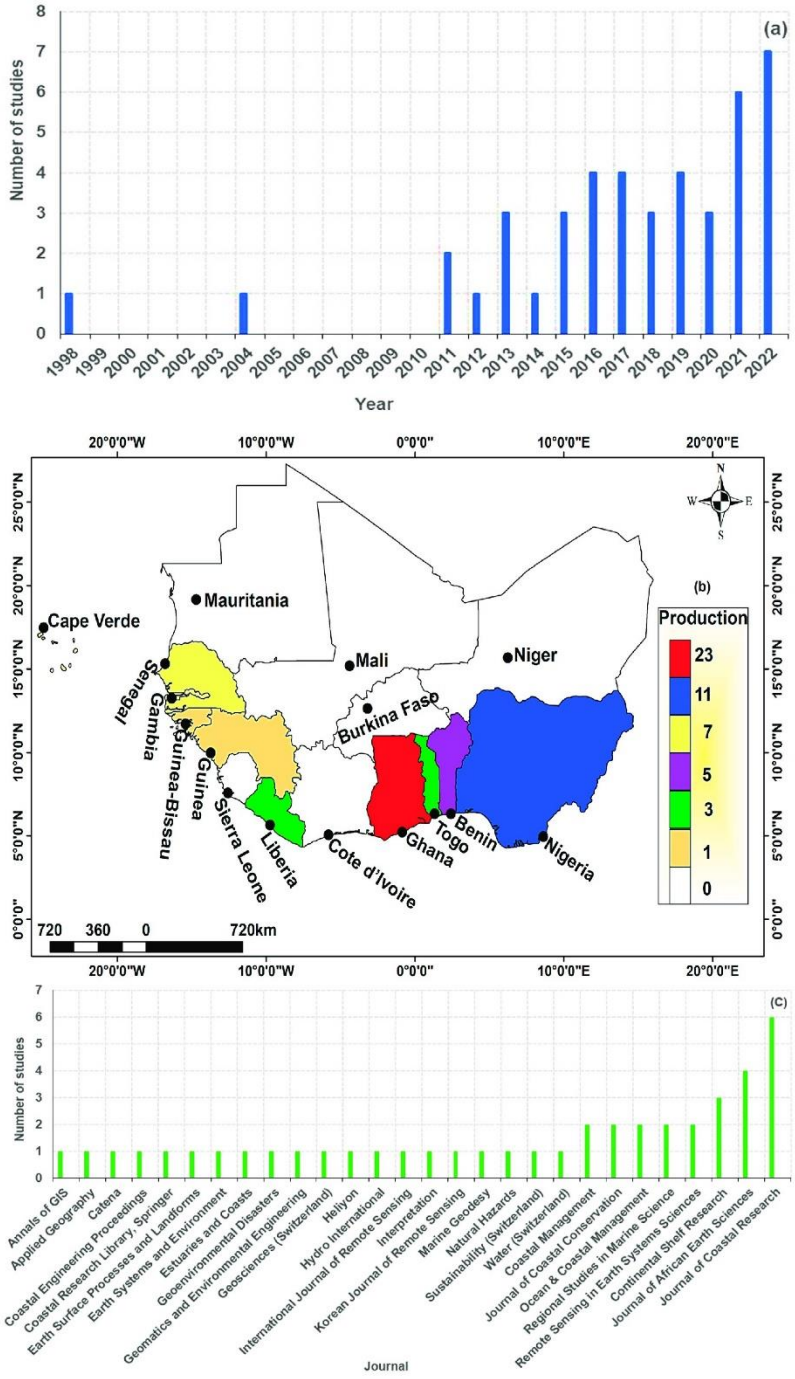


Figure 3. Publication characteristics (**a**), country production (**b**), and journals for research dissemination (**c**) for shoreline change and coastal erosion analysis in West Africa. Note: The year 2022 extends up to the month of October.

From Figure 3b, Ghana is recognized as the country in the West African region with the most [23], followed by Nigeria [11], with no studies in countries such as Côte d'Ivoire, Sierra Leone, and Mauritania. We must state that studies conducted between two or more countries were counted individually for these countries. For instance, studies done along the coast of the Bight of Benin were counted for Ghana, Togo, Benin, and Nigeria. In Figure 3c, the majority (six) of the studies were published in the Journal of Coastal Research, followed by the Journal of African Earth Sciences (four), and the least in journals such as the Annals of GIS and Applied Geography, among others.

3.2. Research Progress on Shoreline Change and Coastal Erosion in West Africa: A Qualitative Analysis of the Literature

Several research studies on shoreline change and coastal erosion have been conducted in the West African territories since 1998. Shoreline change and coastal erosion in the region are the result of natural events such as sea level rise and human-induced actions, as recognized in other regions of the world.

3.2.1. Shoreline Change and Coastal Erosion Due to Natural Events

On the natural causes, Orupabo [81] reported that shoreline retreat at the eroding Victoria Island Bar beach, Nigeria, is about 7.3 m/year, whereas shoreline retreat is on average 1.7 m/year. Kusimi and Dika [82] reported that the Ada Foah shoreline in Ghana has been eroding since 1926 to present times with a mean change of 280.49 m and an average annual rate of 3.46 m/year. Jayson-Quashigah et al. [83] discovered an average erosion rate of 2 m/year $\pm$ 0.44 m along Ghana's Keta coast. Likewise, Appeaning Addo and Lamptey [84] reported that the Accra, Ghana, shoreline has receded at an average rate of 1.13 m/year. Equally, Jonah [13] stated that, between 1974 and 2012, the Elmina, Cape Coast, and Moree coasts in Ghana eroded at a rate of 1.22 m/year $\pm$ 0.16 m. Similarly, Jonah et al. [85] highlighted average shoreline change rates of -1.24 m/year and -0.85 m/year in the medium- and short-term periods along the Elmina, Cape Coast, and Moree coastlines in Ghana. Along the Niger Delta in Nigeria, Dada et al. [86] said that the delta coast is characterized by predominant summer erosion and higher winter accretion. The researchers highlighted that between 2010 and 2012, erosion dominated accretion, with a total of 9.1 km^2 of deltaic land lost to shoreline erosion at an average rate of 4.55 $\pm$ 1.21 km^2/year [86]. Again, Danladi et al. [87] found remarkable erosion along the coastal regions of Lekki, Nigeria.

Moreover, Evadzi et al. [57] pointed out an annual coastal erosion rate of about 2 m/year in Ghana due to sea level rise. Awange et al. [88] indicated more erosion along the Liberian coast between 1998 and 2002. In addition, Gomes et al. [89] highlighted the stable state of the Boavista, Cape Verde shoreline between 1968 and 2010. In addition, Thior et al. [70] stated that the northern lower, Casamance, Senegal, and the southern beaches in Gambia accreted between 1968 and 1986, while higher erosion was observed between 1986 and 2004. Appeaning Addo et al. [90] reported that the eastern and western shorelines of the Volta River estuary in Ghana are eroding at an average rate of 1.94 m/year and 0.58 m/year, respectively. Boye and Fiadonu [91] underlined that in the western region of Ghana, few areas of the shoreline are accreting, while most areas with a rocky shoreline are eroding at varying rates. Moreover, Adeaga et al. [92] indicated that the Lagos, Nigeria, shoreline cumulatively recorded a mean rate change of 0.93 m/year, a mean erosion rate of -1.94 m/year, and a mean accretion rate of 4.84 m/year. The researchers again told us that the Victoria Islands recorded a mean erosion rate of -5.2 m/year and a mean accretion rate of 81.99 m/year over a 20-year period [92].

Brempong et al. [93] reported that in coastal Dzita, Ghana, shoreline changes indicated dominance of erosion at a rate of -7.23 ± 0.23 and -4.85 ± 0.23 m/year between May and December 2018, and June and December 2019. In coastal Rufisque, Senegal, Koulibaly and Ayoade [94] informed us about a serious erosion reaching -19.48 m/year from 1978–1988, about -8 m/year from 1988–1998, -5.88 m/year from 1998–2008, and -6.67 m/year

from 2008–2018. Furthermore, in Togo, Guerrera et al. [58] stated a maximum shoreline retreat rate of 5 m/year. Balle et al. [95] indicated that from 1988 to 2001, a high rate of shoreline accretion was observed at an average rate of 3.46 m/year and an erosion rate of −4.54 m/year from 2001 to 2012 along the Benin shoreline. Osanyintuyi et al. [96] pointed out an average erosion rate of −1.73 m/year and −3.59 m/year and an accretion rate of 0.57 m/year and +4.46 m/year, respectively, for marginal Lagos and Eko city coasts in Nigeria. Yang et al. [97] reported that in Cotonou, Benin, the shoreline revealed accretion of 1.20 km^2, while 3.67 km^2 disappeared due to coastal erosion. Angnuureng et al. [98] informed us about a high erosion rate of about −3 m along the Elmina coast in Ghana. Furthermore, Oloyede et al. [99] highlighted a shoreline change rate of <−2.0 to 1.0 m/year over the entire coastline of Nigeria. Sadio et al. [62] informed us that the average erosion rate for the entire coast along the Saloum River mouth between Diakhanor and Sangomar, Senegal, remains at −3.56 m/year. Komolafe et al. [60] again revealed that approximately 40 km of the shoreline of Ilaje-Ondo State, Nigeria, was accreting with an average of 1.08 m/year and an average erosion rate of −1.40 m/year. Foli et al. [100] also said that the rate of erosion ranged between 1 and 30 m/year for the period 2015–2018 in Ghana, Guinea, Guinea Bissau, Liberia, Nigeria, and Senegal. Figure 4 depicts a graphical representation of the shoreline change rates revealed in the literature for each West African coastal country, while Table 1 summarizes the rates of shoreline change caused by natural events.

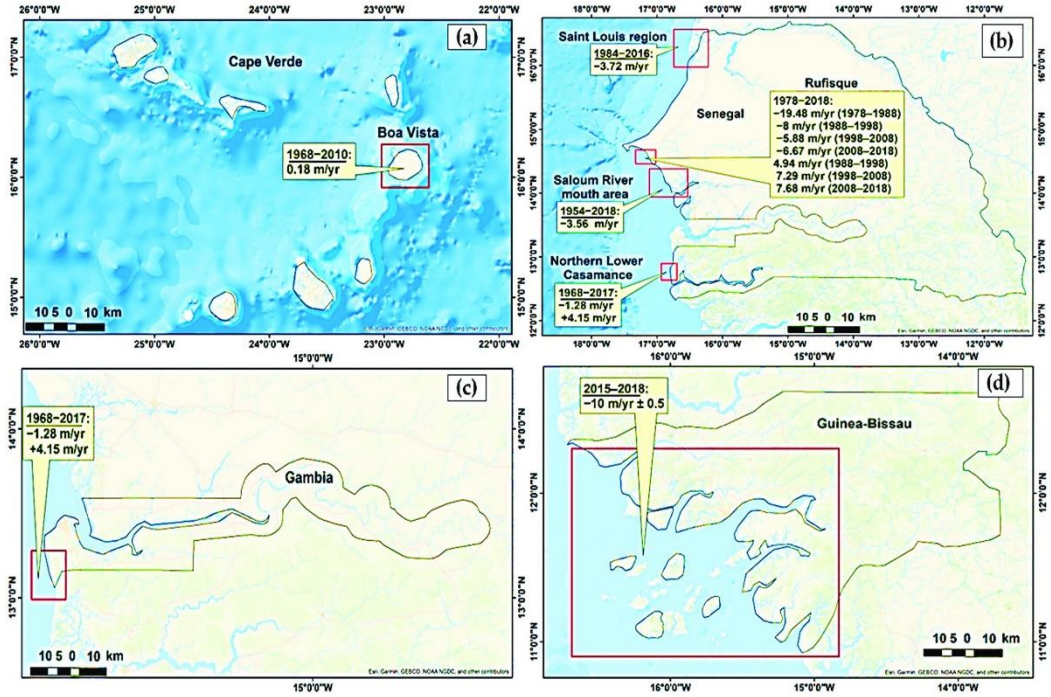


Figure 4. *Cont.*

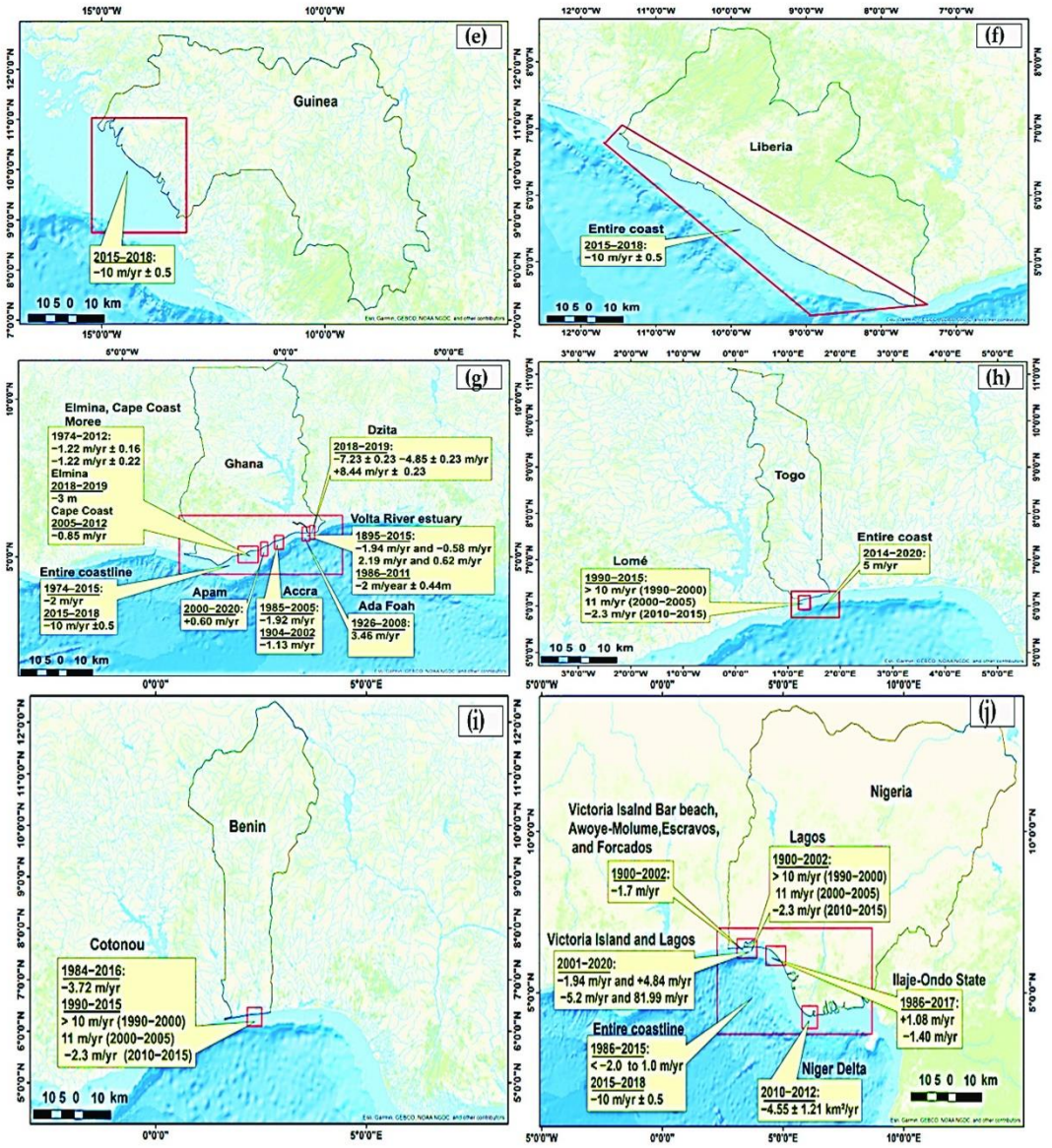


Figure 4. A graphical representation of the shoreline change rates found in the literature for Cape Verde (**a**), Senegal (**b**), Gambia (**c**), Guinea-Bissau (**d**), Guinea (**e**), Liberia (**f**), Ghana (**g**), Togo (**h**), Benin (**i**), and Nigeria (**j**). Note: Erosion and accretion are represented by the negative and positive values, respectively. The sign (±) indicates the degree of uncertainty. The red, rectangular box denotes the areas of application mentioned in the literature used in this review.

Table 1. Shoreline change rates along the West African coast.

Country	Specific Location	Length	Shoreline Change Rates: Erosion (−), Accretion (+), and Uncertainty (±)	Reference
Ghana	Elmina, Moree, Cape Coast	1974–2012	−1.22 m/year ± 0.16	Jonah [13]
Ghana	Ghana	1974–2015	−2 m/year	Evadzi et al. [57]
Togo	Coast of Togo	2014–2020	5 m/year	Guerrera et al. [58]
Nigeria	Ilaje-Ondo State	1986–2017	+1.08 m/year and −1.40 m/year	Komolafe et al. [60]
Senegal	Saloum River mouth between Diakhanor and Sangomar	1954–2018	−3.56 m/year	Sadio et al. [62]
Gambia	southern beaches in Gambia	1968–2017	−1.28 m/year and +4.15 m/year	Thior et al. [70]
Senegal	Northern Lower Casamance	1968–2017	−1.28 m/year and +4.15 m/year	Thior et al. [70]
Nigeria	Victoria Isalnd Bar beach, Awoye-Molume, Escravos and Forcados	1900–2002	−1.7 m/year	Orupabo [81]
Ghana	Ada Foah	1926–2008	3.46 m/year	Kusimi and Dika [82]
Ghana	Volta estuary to Blekusu east of Keta	1986–2011	−2 m/year ± 0.44 m	Jayson-Quashigah et al. [83]
Ghana	Accra	1904–2002	−1.13 m/year	Appeaning-Addo and Lamptey [84]
Ghana	Elmina, Moree, Cape Coast	1974–2012	−1.22 m/year ± 0.22	Jonah et al. [85]
Nigeria	Niger Delta	2010–2012	-4.55 ± 1.21 km^2/year	Dada et al. [86]
Cape Verde	Boavista	1968–2010	0.18 m/year	Gomes et al. [89]
Ghana	Volta river estuary	1895–2015	−1.94 m/year and 0.58 m/year (western side) and 2.19 m/year and 0.62 m/year (marine side)	Appeaning Addo et al. [90]
Nigeria	Victoria Island and Lagos	2001–2020	−1.94 m/year and +4.84 m/year (for Lagos shoreline) and −5.2 m/year and 81.99 m/year (Victoria Island)	Adeaga et al. [92]
Ghana	Dzita	2018–2019	-7.23 ± 0.23 and -4.85 ± 0.23 m/year, and +8.44 m/year ± 0.23	Brempong et al. [93]
Senegal	Rufisque	1978–2018	−19.48 m/year from 1978–1988, close to −8 m/year from 1988–1998, −5.88 m/year from 1998–2008 and −6.67 m/year from 2008–2018, and 4.94 m/year for 1988–1998, 7.29 m/year from 1998–2008 and 7.68 m/year during the period 2008–2018	Koulibaly and Ayoade [94]
Benin	Grand-Popo area	1988–2018	−4.54 m/year and 7.98 m/year	Balle et al. [95]
Nigeria	Lagos Lagoon Barrier coast	1973–2019	−1.73 m/year and +4.46 m/year. −11.79 m/year from 1986 to 1999 (serious erosion). +92.16 m/year and −6.50 m/year at Lekki peninsula	Osanyintuyi et al. [96]
Ghana	Elmina	2018–2019	−3 m	Angnuureng et al. [98]
Nigeria	Entire coastline of Nigeria	1986–2015	<−2.0 to 1.0 m/year	Oloyede et al. [99]
Senegal, Guinea-Bissau, Guinea, Liberia, Nigeria, and Ghana		2015–2018	−10 m/year ±0.5	Foli et al. [100]

3.2.2. Shoreline Change and Coastal Erosion due to Human Activities

On the human-induced actions, Nairn et al. [101] presented a summary of the key aspects of the Keta Sea defense project in Ghana and reported that the undeveloped area of the coast will erode up to 60,000 m^3/year. Appeaning Addo [55] informed us that in Accra, Ghana, human activities including dam construction, sand mining, and engineering interventions have resulted in a sediment deficit that has exacerbated coastal erosion in the area. Again, in Accra, Ghana, Appeaning Addo [56] stated that the estimated total area of land lost by human encroachment on the coast is about 242,139.7 m^2. The researcher stated further that the rate of erosion of the Accra coast is 1.92 m/year [56]. Similarly, Jonah [13] pointed out that the widespread practice of beach sand mining along the Elmina, Cape Coast, and Moree coasts in Ghana has significantly contributed to the erosion of the sections of coastline. In addition, Jonah et al. [102] highlighted that tipper truck-based sand mining activities alone account for the loss of about 285,376 m^3/year along the Cape Coast coastline, which results in erosion. Equally, Ndour et al. [61] reported that after the construction of the Nangbéto Dam on the Mono River in 1987 in Benin, the Bouche du Roi river outlet has exhibited marked instabilities, with an eastward migration exceeding 700 m/year. In addition, the researchers noted that human interventions, such as the construction of seaports and groins, have had a significant impact on shoreline evolution and contributed to shoreline erosion near Cotonou. Table 2 summarizes the natural and human-induced shoreline changes and coastal erosion.

Table 2. A summary of shoreline change and coastal erosion caused by natural events and human activities.

Author	Study Location	Methods (Data Sources/Tools)	Findings
		Natural Events	
Jonah [13]	Elmina, Cape Coast and Moree, Ghana	GIS, field survey (orthophoto, ArcGIS/ArcMap, DSAS, GPS tracking survey)	The Elmina, Cape Coast, and Moree coasts in Ghana eroded at a rate of 1.22 m/year ± 0.16 m between 1974 and 2012
Evadzi et al. [57]	Ghana	Remote sensing and GIS (Landsat images, orthophotos, DEM data, aerial photograph, ArcGIS, DSAS)	An annual coastal erosion rate of about 2 m/year in Ghana due to sea level rise
Guerrera et al. [58]	Coast of Togo	Remote sensing, field observation (Landsat images	A maximum shoreline retreat rate of 5 m/year along the Togo coastline
Komolafe et al. [60]	Ilaje-Ondo State, Nigeria	Remote sensing and GIS (Landsat images, ArcGIS/ArcMap, DSAS,)	The results show that approximately 40 km of the shoreline of Ilaje-Ondo State, Nigeria, was accreting with an average of 1.08 m/year and an average erosion rate of −1.40 m/year
Sadio et al. [62]	Saloum River mouth between Diakhanor and Sangomar, Senegal	Remote sensing and GIS (DSAS, ArcGIS/ArcMap, aerial photograph, Corona satellite photograph, Landsat satellite images)	The average erosion rate −3.56 m/year for the entire coast
Thior et al. [71]	Northern Lower Casamance-Senegal and southern beaches in Gambia	Remote sensing and GIS (Landsat images, aerial photograph, Google Earth images, ArcGIS/ArcMap, DSAS)	The northern lower, Casamance, Senegal, and the southern beaches in Gambia accreted between 1968 and 1986, while higher erosion was observed between 1986 and 2004
Orupabo [81]	Victoria Bar Beach, Awoye-Molume, Escravos and Forcados, Nigeria	Remote sensing (Aerial photograph)	According to the findings, the current rate of areal shoreline retreat at the eroding Victoria Island Bar Beach is put at 7.3 m/year, while shoreline retreat is on average 1.7 m/year.
Kusimi and Dika [82]	Ada Foah, Ghana	Remote sensing, GIS, and survey (Landsat images, ArcGIS/ArcMap, DSAS)	Since 1926 to the present, the shoreline in Ada Foah, Ghana has eroded with a mean change of 280.49 m and an average annual rate of 3.46 m/year.

Table 2. *Cont.*

Author	Study Location	Methods (Data Sources/Tools)	Findings
Jayson-Quashigah et al. [83]	Volta estuary to Blekusu east of Keta, Ghana	GIS (Landsat images, ASTER data, ArcGIS/ArcMap, DSAS)	The Keta coast in Ghana has an average erosion rate of 2 m/year ± 0.44 m
Appeaning Addo and Lamptey [84]	Accra, Ghana	Remote sensing, GIS, and field survey (Aerial photograph, bathymetric map, topographic map, ArcGIS, DSAS, GPS survey	The Accra, Ghana, shoreline has receded at an average rate of 1.13 m/year
Jonah et al. [85]	Elmina, Cape Coast and Moree, Ghana	GIS, field survey (topographic map, orthophotos, ArcGIS, DSAS, GPS survey)	Results showed average shoreline change rates of −1.24 m/year and −0.85 m/year in the medium- and short-term periods along the Elmina, Cape Coast, and Moree coastlines in Ghana.
Dada et al. [86]	Niger Delta, Nigeria	Remote sensing, photo interpretation (Landsat images, ERA-Interim)	Between 2010 and 2012, erosion dominated accretion, with a total of 9.1 km^2 of deltaic land lost to shoreline erosion at an average rate of 4.55 ± 1.21 km^2/year
Danladi et al. [87]	Coastal regions- Lekki, Nigeria	Remote sensing and GIS (ASTER GDEM, Google Earth images, ArcGIS/ArcMap, CorelDraw)	The results revealed remarkable erosion along the coastal regions of Lekki, Nigeria
Awange et al. [88]	The coast of Liberia	Remote sensing, GIS, and field survey (Landsat images, Sentinel-2 data, GPS survey)	More erosion along the Liberian coast between 1998 and 2002
Gomes et al. [89]	Boavista, Cape Verde	Remote sensing and GIS (Aerial photograph, orthophoto map, ArcGIS/ArcMap)	A stable state of the Boavista, Cape Verde shoreline between 1968 and 2010
Appeaning Addo et al. [90]	Volta river estuary, Ghana	Remote sensing and GIS (Landsat satellite images, orthophoto, topographic maps, DSAS, ArcGIS/ArcMap	The eastern and western shorelines of the Volta River estuary in Ghana are eroding at an average rate of 1.94 m/year and 0.58 m/year, respectively
Boye and Fiadonu [91]	Coastal towns in the Western region of Ghana	GIS and Field survey (topographic maps, geological map, orthophotos, ArcGIS/ArcMap, DSAS, GPS survey)	In the western region of Ghana, few areas of the shoreline are accreting, while most areas with a rocky shoreline are eroding at varying rates
Adeaga et al. [92]	Eti-Osa Local Government Area of Victoria Island-entire Lagos, Nigeria	Remote sensing and GIS (Google Earth images, QGIS, AMBUR-R programming)	The Lagos, Nigeria, shoreline cumulatively recorded a mean rate change of 0.93 m/year, a mean erosion rate of −1.94 m/year, and a mean accretion rate of 4.84 m/year
Brempong et al. [93]	Dzita, Ghana	Remote sensing and GIS (UAV, ArcGIS)	Results showed that in coastal Dzita, Ghana, shoreline changes indicated dominance of erosion at a rate of −7.23 ± 0.23 and −4.85 ± 0.23 m/year between May and December 2018, and June and December 2019
Koulibaly and Ayoade [94]	Rufisque, Senegal	Remote sensing, GIS, and Field visit (Landsat images 3, 5, 7, 8, ArcGIS/ArcMap, DSAS)	A serious erosion reaching −19.48 m/year from 1978–1988, about −8 m/year from 1988–1998, −5.88 m/year from 1998–2008, and −6.67 m/year from 2008–2018
Balle et al. [95]	Benin	Remote sensing, GIS, and field survey (SPOT, Sentinel-2, ArcGIS/ArcMap, DSAS, GPS survey)	Results shows that from 1988 to 2001, a high rate of shoreline accretion was observed at an average rate of 3.46 m/year and an erosion rate of –4.54 m/year from 2001 to 2012 along the Benin shoreline

Table 2. *Cont.*

Author	Study Location	Methods (Data Sources/Tools)	Findings
Osanyintuyi et al. [96]	Lagos Lagoon Barrier coast, Nigeria	Remote sensing and GIS (Landsat images 1–5, 7, ArcGIS/ArcMap, DSAS)	An average erosion rate of −1.73 m/year and −3.59 m/year and an accretion rate of 0.57 m/year and +4.46 m/year, respectively, for marginal Lagos and Eko city coasts in Nigeria
Yang et al. [97]	Cotonou, Benin	Remote sensing and GIS (Google Earth images, QGIS)	The shoreline revealed accretion of 1.20 km^2, while 3.67 km^2 disappeared due to coastal erosion
Angnuureng et al. [98]	Elmina, Ghana	Remote sensing (dumpy level and GPS survey, UAV-drone, video camera system, ARCGIS/ArcMap, satellite images-CoastSat, GEE, sentinel, ERA-5)	A high erosion rate of about −3 m along the Elmina coast in Ghana
Oloyede et al. [99]	Nigeria	GIS (DSAS)	A shoreline change rate of <−2.0 to 1.0 m/year over the entire coastline of Nigeria
Foli et al. [100]	Guinea, Nigeria, Liberia, Senegal, Guinea Bissau and Ghana	Remote sensing (Sentinel-1)	The rate of erosion ranged between 1 and 30 m/year for the period 2015–2018 in Ghana, Guinea, Guinea Bissau, Liberia, Nigeria, and Senegal
		Human activities	
Jonah [13]	Elmina, Cape Coast and Moree, Ghana	GIS, field survey (orthophoto, ArcGIS/ArcMap, DSAS, GPS tracking survey)	The widespread practice of beach sand mining along the Elmina, Cape Coast, and Moree coasts in Ghana has significantly contributed to the erosion of the sections of coastline
Appeaning Addo [55]	Accra, Ghana	Remote sensing, GIS, and Field survey (topographic map, wave data, site visits)	Human activities, including dam construction, sand mining, and engineering interventions in Accra have resulted in a sediment deficit that has exacerbated coastal erosion in the area
Appeaning Addo [56]	Accra, Ghana	Remote sensing (Aerial photographs, orthomaps, GIS, DSAS)	The estimated total area of land lost by human encroachment on the coast is about 242,139.7 m^2 and the rate of erosion of the Accra coast is 1.92 m/year
Ndour et al. [61]	"Langue de Barbarie," sand spit in Saint-Louis Region, Senegal, and Mono River, the "Bouche du Roi," Cotonou, Benin	Remote sensing and GIS (Landsat 4,5,7,8 satellite images, aerial photograph, ArcGIS, ArcMap, DSAS)	After the construction of the Nangbéto Dam on the Mono River in 1987 in Benin, the Bouche du Roi river outlet has exhibited marked instabilities, with an eastward migration exceeding 700 m/year
Nairn et al. [101]	Victoria Bar Beach, Awoye-Molume, Escravos and Forcados, Nigeria	Remote sensing (Aerial photograph)	The undeveloped area of the Keta sea defense system will erode to make up the remaining 60,000 m^3/year deficit between the transport through the project area and the potential rate downdrift of the sea defense system
Jonah et al. [102]	Cape Coast, Ghana	GIS, field survey (ArcGIS, DSAS, orthophotos, GPS survey)	Tipper truck-based sand mining activities alone account for the loss of about 285,376 m^3/year along the Cape Coast coastline, which results in erosion

3.2.3. Policy Recommendation by Research Studies on Shoreline Change and Coastal Erosion in West Africa

Several policy recommendations have been suggested by researchers in the West African region based on the shoreline change and coastal erosion problems identified. For instance, Orupabo [81] advised the coastal authorities in Nigeria of the need to establish relevant infrastructure to collect, compute, and manage meteo-ocean data along the country's

coastline. Kusimi and Dika [82] suggested to the coastal planners of Ada Foah, Ghana, the need for a sea defense project such as sand nourishment and groins to protect the shoreline from erosion. Appeaning Addo [56] recommended to authorities the need to create setback lines along the Accra coast in Ghana to protect lands for the shoreline's cyclic activities. In addition, Jonah [13] suggested to coastal managers in Elmina, Cape Coast, and Moree in Ghana the need for the adoption of a proactive and coordinated shoreline management plan for Ghana's coast like those of the United Kingdom shoreline management plan due to the numerous known benefits. Similarly, Evadzi et al. [57] advised policymakers on the need to intensify research into the anthropogenic factors that account for approximately 69% of the annual erosion rate in coastal Ghana.

Along the Elmina coast in Ghana, Angnuureng et al. [98] advised coastal managers of the Elmina beach in Ghana that, in addition to the hard engineering structures to fight erosion, more soft measures such as beach nourishment will counter erosion and eventually build the beach. Likewise, Ndour et al. [61] suggested to the coastal authorities in Senegal and Benin the need to improve the adaptation strategies along the coasts of the countries. Similarly, Sadio et al. [62] emphasized the need for improved adaptation measures along the shoreline of Senegal due to the projected rise in sea level by 2050 and 2100. Along the Volta River estuary in Ghana, Appeaning Addo et al. [90] suggested to authorities the need for effective management approaches such as developing disaster risk reduction strategies as well as increasing the resilience and adaptive capacity of the communities along the estuary. Similarly, in Lekki, Nigeria, Danladi et al. [87] alluded to policymakers about the need for continuous inspection of the entire Lekki coast and the construction of environmentally friendly coastal defenses like dune barriers and sand replenishment. Again, in the Eti-Osa local government area of Victoria Island, Nigeria, Adeaga et al. [92] mentioned to authorities the need to institute appropriate land use and land cover management plans for the area. Considering the serious nature of shoreline change and coastal erosion in Nigeria, Oloyede et al. [99] suggested to coastal planners the practicability of their study in identifying the vulnerable portions of the Nigerian coast and subsequently aiding in the development of appropriate adaptation and mitigation plans. Moreover, Osanyintuyi et al. [96] said that the current coastal management policies and plans in Lagos State, Nigeria, need to be changed so that the coastal zone can be used in a sustainable way.

Koulibaly and Ayoade [94] also advised authorities in coastal Rufisque, Senegal, to concentrate coastal protection facilities and to include a community dimension in local and national plans for adaptation to sea level rise and related impacts such as coastal erosion. Guerrera et al. [58] advised coastal authorities in Togo to develop urgent measures to mitigate the problem of shoreline change and coastal erosion, as well as the need to include effective solutions in the 2018–2022 national development plan. Moreover, Yang et al. [97] suggested to the coastal managers of Cotonou, Benin, the need to maximize the effectiveness of groins along the shoreline of the area. In addition, Foli et al. [100] advised coastal authorities in Ghana, Guinea, Guinea-Bissau, Liberia, Nigeria, and Senegal to increase dialogue and consultations in the policy- and decision-making process to be able to achieve the blue economy agenda. Table S1 in the Supplementary Material summarizes the key findings and policy recommendations from all the studies used in this review.

4. Discussion

The research progress on shoreline change and coastal erosion and the policy recommendations in West Africa have been systematically appraised. The review shows that research on shoreline change and coastal erosion has made a lot of progress in West Africa, where scientists are committed to studying the topic.

Regarding this review, it was revealed that the first study on the subject appeared in 1998 in Ghana by Nairn et al. [101]. Notwithstanding, their study focused on the human-induced causes of shoreline change and coastal erosion and employed only numerical modeling techniques and not remote sensing or GIS approaches. Between 1999 and 2010,

excluding 2004, the interest in the subject dropped greatly as no study was conducted, and this could be attributed to factors such as low economic development (insufficient funding), less established research institutions, and data challenges [46]. Still, this claim could be questioned, especially when it comes to the lack of data, because in 2004, Orupabo used the remote sensing method and analyzed aerial photos to estimate changes in the Nigerian shorelines of Victoria Bar Beach, Awoye-Molume, Escravos, and Forcados [81].

Since 2011, interest in the subject has increased, especially beginning in 2021, when more studies emerged. As negative anthropogenic activities keep increasing and sea level is projected to rise [23], more research is expected from the region. As indicated in the review, most of the shoreline change and coastal erosion problems in the region were the result of natural events like sea level rise. However, there is evidence of greater anthropogenic influence, for example, along the shoreline of Accra, Ghana [55,56], in the sections of the Elmina, Cape Coast, and Moree shorelines in Ghana [13], and in coastal Benin [61]. This, thus, supports the assertion that human-induced factors and sea level rise are the major causes of shoreline change and coastal erosion made elsewhere [12,14]. Sand mining, dam construction (which can have both positive and negative effects), and human encroachment are all negative human activities that can be found along most of the region's shorelines.

As research progresses in the region, researchers have made efforts to suggest appropriate policy recommendations to authorities in their respective areas of jurisdiction. The overall call to action regarding policy recommendations revolves around improving coastal adaptation measures and the resilience of communities, instituting proper coastal zone management plans, and improving shoreline change and coastal erosion research. Researchers have used the Journal of Coastal Research and the Journal of African Earth Sciences, among others, the most to share their research findings.

One other thing worth mentioning as progress for the region is the increasing use of remote sensing and GIS approaches for shoreline change and coastal erosion analysis (see Table S1 in the Supplementary Material). Since 2011, most researchers have employed the techniques. Most data are sourced from satellite images (Landsat, Corona, Google Earth, etc.), aerial photographs, video camera systems, and unmanned aerial vehicles (drones), while tools such as ArcGIS/ArcMap, the digital shoreline analysis system (DSAS), QGIS, and the global positioning system (GPS) have been employed to analyze shoreline change and coastal erosion in the region. This supports the global analysis of data sources and tools for shoreline change analysis by Ankrah et al. [46]. While the above techniques are appropriate and highly recommended, it is equally important for researchers in the region to integrate these techniques with field survey and observation approaches. From the review, few studies employed the combined approaches (e.g., [13,55,58,61,83,90,98,102]). We believe that a combination of remote sensing and field observation can show (through pictures) the problems with coastal erosion in a way that can help policymakers figure out what needs to be done.

5. Conclusions

The study utilized the systematic review approach to analyze the research progress on shoreline change and coastal erosion in West Africa. The main conclusion from this review is that shoreline change and coastal erosion research in West Africa has progressed substantially, reflecting the increasing concerns of scientists in the region. According to the research, Ghana has the most studies [23] on the subject, followed by Nigeria [11], with no studies in countries such as Côte d'Ivoire, Sierra Leone, and Mauritania.

It was established that research on the subject has progressed not only in terms of theory but also in terms of methodological stance. However, a combination of remote sensing and field observation techniques is required. It was revealed that shoreline change and coastal erosion in West Africa are the result of both natural events such as sea level rise and negative anthropogenic activities, thereby supporting the scientific consensus of a combined natural and human-induced factor as the cause of shoreline change and coastal erosion [12,14]. Sand mining, dam construction, and human encroachment (urbanization)

were the negative anthropogenic activities causing shoreline change and coastal erosion in most of the countries in West Africa.

Researchers in the region have made several recommendations on the subject to aid policy directions and interventions. It was established that the most important policy recommendation by researchers in the sub-region has been the need to improve coastal adaptation measures and the resilience of communities, institute proper coastal zone management plans, and improve research on the subject. The review has revealed that the West African shoreline is changing and is highly characterized by erosion. Researchers in the region are committed and have recommended several policy directions to their respective policymakers. As the sea level is expected to rise, it could change shorelines and cause erosion. To protect lives and property, policymakers in the region need to set up good coastal zone management plans, strengthen adaptation measures, and make coastal communities more resistant to possible risks.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/geosciences13020059/s1, Table S1: Summaries of the key findings and policy recommendations from the studies used in this review.

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1.2.12. Climate change and variability problems in Ghana: identifying knowledge gaps and justification for research in the coastal savannah agroecological zone

Ghana is no exception to the increased adverse impacts of climate change and variability that the global community is currently facing. Ghana is grappling with several socioeconomic and environmental challenges, including road accidents, land degradation, and deforestation (Acheampong et al., 2019; Boateng, 2021; Kyere-Boateng & Marek, 2021; Moomen & Dewan, 2017), and the incidence of climate change and variability has increased these challenges (Neville & Mohammed, 2010). As indicated by the Environment Protection Agency (EPA), Ghana's climate substantially changed beginning in the 1960s, especially in its parameters of temperature and rainfall (EPA, 2007). Between 1961 and 2000, the EPA (2007) pointed out a 1 °C increase in temperature with a decline in rainfall of about 20%. Based on scenarios, the EPA (2007) expected temperatures to change by 0.6 °C in 2020, 2.0 °C by 2050, and 3.9 °C by 2080. For rainfall, the EPA (2007) predicted a reduction of 2.8% in 2020, 10.9% in 2050, and 18.6% in 2080. Yaro (2013) argued that rainfall has increased in recent times, despite the anticipated declines by the EPA. Notwithstanding, the findings of Abbam et al. (2018) revealed that Ghana's rainfall has become irregular, with greater variability in distribution. The occurrence of extreme events, including drought and floods, has also become frequent in Ghana (Asante & Amuakwa-Mensah, 2015; Incoom et al., 2020; Yin et al., 2021; Yiran & Stringer, 2016). Based on the records of the EPA (2003), drought events were prevalent in the 1960s, 1970s, 1980s, and 1990s, especially the historic nationwide drought in 1983 and 1984, which negatively affected crop outputs in the country. Several flooding incidences have occurred in the country; however, the greatest, along with a gas explosion, occurred on June 3rd, 2015, in the capital city of Accra, with more than 150 deaths (Yin et al., 2021).

Studies demonstrating the impacts of climate change have increased in Ghana. For instance, in their review on climate change and variability in Ghana, Asante and Amuakwa-Mensah (2015) informed about the projected increase in temperature and decrease in rainfall in the years 2020, 2050, and 2080 and underlined the implications for various sectors, especially agriculture, health, and energy. Again, Kabo-Bah et al. (2016) studied the effects of temperature and rainfall changes on hydropower generation in Ghana and established an increasing trend in annual temperature and increasing and decreasing trends in rainfall in different parts of the country. Additionally, Larbi et al. (2018) examined trends in rainfall and temperature extremes in the Vea catchment area of Ghana and reported a

uniform increase in temperature extremes over the catchment and a high frequency and intensity of rainfall extremes in the southern part of the catchment compared to the middle and the northern parts. In the recent study on rainfall onset, cessation, and length of the growing season in northern Ghana, Atiah et al. (2021) pointed out a significant late and early onset in the east and west areas, respectively, and late cessation and longer growing periods in northern Ghana. Moreover, Cudjoe et al. (2021) examined the effects of climate variability on maize production in the Ejura-Sekyedumase municipality of Ghana and informed about the shorter duration and less predictable nature of rainfall and increased temperatures in the area.

Notwithstanding the insights garnered from the above studies, they focus solely on the understanding of the impacts of climate change and variability at basin and catchment scales and in the agroecological zones in the mid-to-northern half of Ghana (i.e., Sudan Savannah, Guinea Savannah, and the forest and transitional zones). The studies, however, made no attempt to understand the impacts of climate change and variability in the coastal savannah agroecological zone, which is of equal importance. For instance, there is currently a lack of studies on extreme event incidences, especially those that are meteorological in nature, including drought and flood, and their temporal and spatial distribution in the coastal Savannah agroecological zone. No study has also attempted to project the future possible changes in temperature and rainfall in the zone, as well as the understanding of the rainfall variability and how it is being influenced by large-scale natural variability like ENSO and their overall effects on the growing seasons in the coastal Savannah agroecological zone. This understanding of these changes is beneficial to the farmers, especially the smallholder farmers in the zone, as they will enrich their knowledge and improve their agricultural practices and food security in the zone and the country as a whole.

Considering the location of the coastal Savannah agroecological zone, it is being influenced by the interplay between the land and the ocean, which makes it particularly susceptible to the adverse impacts of climate change and variability. The coastal location of the zone further makes it prone to other climate and sea level rise-related impacts, including shoreline change and erosion. A number of studies, such as those of Abdul-Kareem et al. (2022), Angnuureng et al. (2022), Appeaning Addo et al. (2020), Appeaning Addo (2014), Appeaning Addo et al. (2011), Boye et al. (2018), Jayson-Quashigah et al. (2013), Jonah et al. (2016), Jonah (2015), and Mann et al. (2023), have analysed the impacts of shoreline change and erosion on the coastal areas of Ghana. Notwithstanding

the efforts made in these studies, there are limitations that call for a detailed analysis of shoreline change and erosion in the zone. These studies analysed a small segment of the shoreline. For instance, Abdul-Kareem et al. (2022) analysed just a small portion of the Apam beach. Angnuureng et al. (2022) investigated a limited portion of Elmina Bay. Appeaning Addo et al. (2020) analysed the shoreline dynamics of the Volta River estuary, while Mann et al. (2023) investigated a small area of the Keta coast. No efforts have been made to understand the shoreline change and erosion effects along the entire central and eastern coast of Ghana, where the coastal Savannah agroecological zone is located. Moreover, no study has analysed a specific shoreline armouring index (Aybulatov & Artyukhin, 1993) to understand human interventions on the coast. There is also a lack of comprehensive discussion on the specific adaptation strategies implemented either by the local coastal communities or by policy initiatives to address shoreline change and erosion along the coast (Gbedemah, 2023). The analysis of shoreline change and the influence of erosion, coupled with a specific shoreline armouring index along the entire central and eastern coast of Ghana, is necessary to improve policy-making decisions. An analysis of this nature thus serves to aid in the implementation of appropriate adaptation measures for various communities, historic locations, and the ecosystems along the coast, which is beneficial under the present and persistent climate change. As a result, a detailed assessment of the impacts of climate change and variability in the coastal savannah agroecological zone thus requires an interdisciplinary approach, which is currently lacking.

This research, therefore, uses a multimethod and interdisciplinary approach to assess climate change and climate variability impacts in the coastal savannah agroecological zone of Ghana. This research contributes to the scientific literature by providing a conceptual understanding of the impacts of climate change and variability based on empirical findings from the coastal savannah agroecological zone in Ghana. The research also makes a significant methodological contribution by adapting existing research methods in a multimethod and interdisciplinary manner to enhance our understanding of the impacts of climate change and climate variability on the socio-ecological systems in the coastal savannah agroecological zone in Ghana.

1.3. Research goal and objectives

The principal goal of this thesis is to assess the impacts of climate change and variability in the coastal savannah agroecological zone of Ghana, where there is a dearth of knowledge about climate change and variability. The aim is to understand how climate change and

variability are impacting the coastal ecosystems, resources, and livelihoods of people, including farmers and small-scale fishermen. This understanding will serve as a basis for improving policy decision-making in the zone. In order to fulfil this principal goal, the specific objectives are as follows:

1) To evaluate climate change and climate variability in the coastal savannah agroecological zone of Ghana.
2) To project possible future climate change scenarios for the coastal savannah agroecological zone of Ghana.
3) To analyse the influence of El Niño-Southern Oscillation on rainfall variability in the coastal savannah agroecological zone of Ghana.
4) To analyse the impacts of climate change and climate variability on marine and freshwater fish harvest and their effects on the socio-economic livelihoods of the communities in the coastal savannah agroecological zone of Ghana.
5) To analyse the influence of climate change on shoreline change and the impacts of erosion on the ecosystems and their implications on the communities in the coastal savannah agroecological zone of Ghana.

In line with the above aims and objectives, this research seeks to provide an answer to the following fundamental question: How and to what extent have climate change and variability impacted the coastal ecosystems and livelihoods of people, including smallholder farmers and small-scale fishermen located in the coastal savannah agroecological zone of Ghana?

This question is relevant and significant, given the increasing adverse effects of climate change and variability. As reiterated by Easterling (2007), climate change and variability remain one of the greatest challenges of the twenty-first century and have become issues of life and death because of their negative impacts on socio-economic development (FAO, 2017; IPCC, 2018). The changes in parameters like temperature, rainfall, and wind result in severe adverse consequences for agriculture, food security, water resources, health, livelihoods, disruption of ecosystems, and related service provisions (Ahmed et al., 2022; Mohammed et al., 2021; Papa et al., 2023; Rocque et al., 2021). The interactions between the land and the ocean greatly influence the world's coastal zones and their socio-ecological systems, putting them in a dire situation. More research providing evidence on the increasing impacts of climate change and variability across different scales (i.e., local to global) is required to be able to develop appropriate adaptation measures and aid policy

decisions. The research focus on the coastal savannah agroecological zone of Ghana is important considering the diverse socio-economic activities such as agriculture, fishing, trade and commerce, residential, and tourism, all of which are climate-dependent.

1.4. Applied societal, academic (science), and methodological contributions of the research

Using a multimethod and interdisciplinary approach, this research makes several relevant significant societal, academic, and methodological contributions, as follows:

1) It contributes to the scientific discourse surrounding the advancement of assessments on the impacts of climate change and climate variability. These evaluations are applicable across many scales, ranging from local to global. For instance, the discussions about the growing interest in extreme weather and climate events are pertinent to the Global South, especially for the African region and Ghana, to be precise, where the climate significantly influences most economic activities.
2) It contributes to a conceptual understanding of the present and future possible impacts of climate change and climate variability on coastal zones. This is crucial for developing improved adaptation strategies for a variety of impacts on coastal livelihood systems.
3) It contributes to the general awareness, knowledge, and perception of climate change and climate variability risks among coastal small-scale fishing and smallholder farming communities. This emphasises the potential and added value of improved climatological literacy in coastal communities, as well as the importance of informal knowledge in science. Coastal small-scale fishermen and smallholder farmers' improved awareness and proper perception of climate change and climate variability risks is crucial for enhanced adaptation strategies, as less awareness and poor risk perception can result in maladaptation (Barnett and O'Neill, 2010; Johnson et al., 2023).
4) It adds to the scientific literature on the effects of climate change and variability on coastal zones in the Global South, specifically the African region and Ghana. For instance, the systematic literature review on shoreline change and coastal erosion in West Africa contributes to the research progress and methodological stance, which supports the scientific consensus on the subject (see Paper 4).

5) It makes a significant methodological contribution by adapting existing research methods in a multimethod and interdisciplinary manner to enhance our understanding of the impacts of climate change and climate variability on socio-ecological systems. For instance, this research applied Gough's (2008) and Tam et al. (2015) day-to-day variability temperature framework, widely used in Canadian and North American urban areas, to assess day-to-day temperature variability in nine urban areas within Ghana's coastal savannah agroecological zone (see Paper 6). This research has also enhanced our understanding of the impacts of climate variability on coastal livelihoods through qualitative methods. Using qualitative methods, the research argued that while the causes of climate variability require natural science and quantitative measures, the impacts on coastal livelihoods and their effects on different groups of fishermen (small vs. large scale, with differing worldviews and cultures, etc.) often require qualitative methods from the social sciences (see Paper 11).

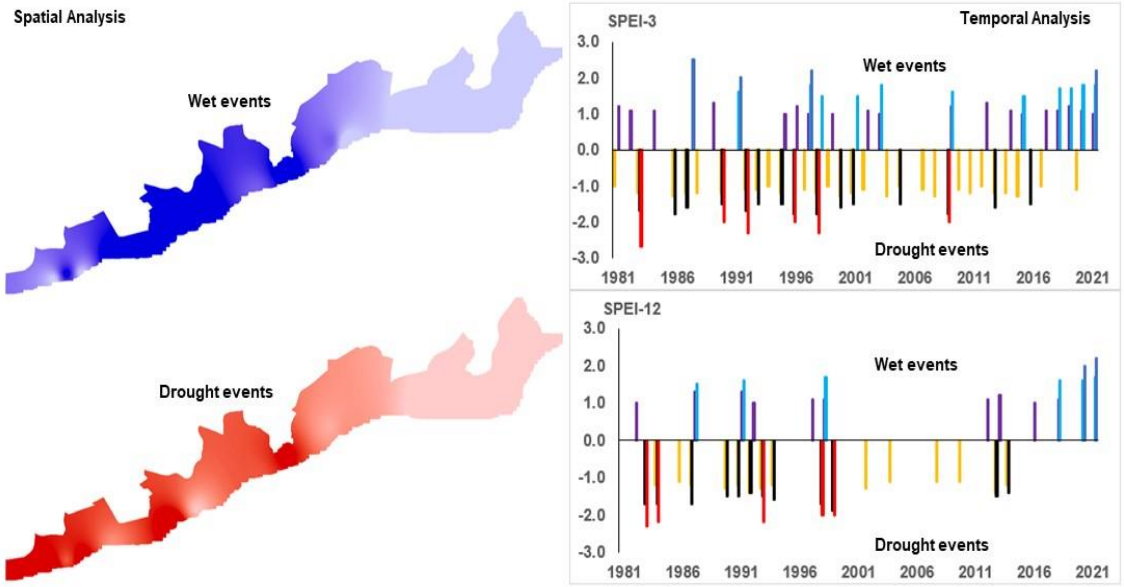
1.5. Organisation of chapters

This thesis is organised into seven chapters that are aligned with the research objectives. Chapter one presents the general introduction, literature review (including four papers), research goals and objectives, and applied societal, academic, and methodological contributions of the research. Chapter two (objective 1) presents the evaluation of climate change and climate variability in the coastal savannah agroecological zone of Ghana and consists of three papers (papers 5, 6, and 7). Chapter three (objective 2) illustrates the projection of possible future climate change scenarios for the coastal savannah agroecological zone of Ghana and comprises one paper (paper 8). Chapter four (objective 3) presents the analysis of the influence of ENSO on rainfall variability in the coastal savannah agroecological zone of Ghana and consists of one paper (paper 9). Chapter five (objective 4) illustrates the analysis of the impacts of climate change and climate variability on marine and freshwater fish harvest and their effects on the socio-economic livelihoods of the communities in the coastal savannah agroecological zone of Ghana and comprises two papers (papers 10 and 11). Chapter 6 (objective 5) analyses the influence of climate change on shoreline change and the impacts of erosion on the ecosystems and their implications on the communities in the coastal savannah agroecological zone of Ghana and consists of one paper (paper 12). Chapter seven presents a conclusion and synthesis of the main findings from the previous chapters and discusses the research's contributions and limitations.

CHAPTER 2: Evaluation of climate change and climate variability in the coastal savannah agroecological zone of Ghana

2.1. Spatiotemporal Characteristics of Meteorological Drought and Wetness Events Across the Coastal Savannah Agroecological Zone of Ghana

Paper 5



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Spatiotemporal Characteristics of Meteorological Drought and Wetness Events across the Coastal Savannah Agroecological Zone of Ghana

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Abstract: Drought and wetness events have become common due to global warming, warranting the need for continuous analysis and monitoring of drought and wet events to safeguard people's livelihoods. In this study, the Standardized Precipitation Evapotranspiration Index (SPEI) was utilized to analyze the spatiotemporal characteristics of drought and wetness events in the coastal Savannah agroecological zone from 1981 to 2021. Climate data from 14 locations across the zone were used to characterize drought and wetness events at the 3 and 12 month timescales. Except for September 1995 and November 2002, when changepoints occurred, the results revealed the homogeneous nature of temperature and rainfall in the zone. More drought events were observed in the dry and minor seasons, while the wet season had more wetness events under both the SPEI-3 and SPEI-12 timescales. The results also showed that, while moderate-to-severe drought events were common for most years, extreme drought events were more typical in the 1980s and 1990s than in the 2000s under both the SPEI-3 and SPEI-12. Furthermore, the 2000s saw more moderate-to-severe wetness events than the 1980s and 1990s, while the greatest number of extreme wetness events occurred in 1987, followed by 1997 and 2021 under the SPEI-3, and a few moderate-to-extreme wetness events occurred in 1987, 1991, 1997–1998, 2012–2013, 2018, and 2020–2021 under the SPEI-12. Under the SPEI-12, only extreme drought events showed a significant positive trend with a small magnitude of change. On the spatial scale, drought and wetness events occurred more frequently in the Central and Volta regions than in the Greater Accra region; however, the intensity and duration of the events were stronger and lasted longer in the Greater Accra and Central regions than in the Volta region. The regular monitoring of drought and wetness events is required to protect the livelihoods of people in the zone.

Keywords: drought; wetness events; SPEI; spatial variation; drought frequency; drought intensity; Ghana

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1. Introduction

Drought continues to be one of the greatest natural disasters facing humanity [1] and has become more frequent in recent times due to global warming [2–4]. As a natural hazard, drought poses threats to agricultural, social, economic, and environmental systems, negatively affecting the livelihood opportunities of many people [5–8]. As has been reported by the International Disaster Database (EM-DAT), 432 natural disasters were recorded in the year 2021, including drought, which affected 101.8 million people with 10,492 deaths and economic damage worth 252 billion United State dollars [9]. In the West African region, the number of significant disasters that occurred from 2000 to 2010 (1975–2011) included flooding (133 (196)), drought (15 (59)), extreme temperatures (1 (3)), earthquakes (0 (1)),

mass movements of moisture (4 (3)), storms (12 (6)), volcanoes (0 (1)), wildfires (1 (5)), and dry landslides (0 (1)) [10].

Indeed, drought is intricate and considered one of the least-understood natural disasters [11]. There are spatial and temporal variations in the frequency, duration, and intensity of drought, as an extreme event [12]. These spatial and temporal variations in drought have given room for various definitions, making it difficult to derive a definite universal definition [12]. Kogan [13] highlighted the need for the identification and incorporation of area variations, such as physiological features, prevailing climatic conditions, economic development, and their effects on livelihoods, when defining and characterizing drought. Nonetheless, drought is inadequately defined and characterized at present, particularly in data-scarce areas, casting doubt on the relevance and appropriateness of relevant drought execution plans [12,14,15]. Drought occurs as a result of negative water imbalances caused by a prolonged lack of precipitation or excess evapotranspiration over a prolonged period [16,17]. Based on the above definition, four distinct types of drought can be recognized, namely, meteorological, agricultural, hydrological, and socio-economic [17–20]. Previous research studies, such as [6,7,12,19,21,22], have defined and explained the various types of droughts. Mishra and Singh [19] advocated for the addition of groundwater drought as a fifth type of drought. Meteorological drought, which is seen as an extreme climate event, plays a significant role in the other types of droughts [23,24].

Considering the intricate and challenging nature of drought characterization [25], there has been increasing interest in the development of appropriate drought indices for drought monitoring, assessment, and the creation of early warning systems [12,26]. As emphasized by Quiring and Ganesh [27], most of these indices use meteorological variables such as variations in precipitation. Such indices include the Drought Severity Index (PDSI) [21], the Standardized Precipitation Index (SPI) [16], and the Standardized Precipitation Evapotranspiration Index (SPEI) [15], among others. These drought indices have been used in numerous research studies [1,15,28–38]. Of course, numerous drought indices exist, as underlined by Liu et al. [39]. Heim et al. [12] classified the numerous drought indices into site-based and remote sensing-based ones. The remote sensing-based drought indices include those such as the Vegetation Condition Index (VCI) proposed by Kogan [13] and the Normalized Difference Water Index (NDWI) by Gao [40], among others. It should be noted that all of these indices have certain strengths and weaknesses.

In the context of global warming, the incidence of extreme events such as droughts and floods is projected to increase in many regions around the world [41]. Thus, significant efforts have been given towards understanding drought dynamics and related impacts, in the quest to develop mitigation measures [41–43]. Notwithstanding these efforts, drought evolution, duration, frequency, and intensity remain a challenge and are not well-realized, due to their intricacies in comparison to other natural disasters [44,45]. Many research studies have been carried out on droughts in many parts of the world in the context of global warming [41,42,46], as scientists wish to understand all the details; for example, in Africa [47–49], Asia [50–52], Australia [53–55], Europe [6,56,57], North America [2,58,59], and South America [60–62]. There has also been drought research at the global level (see, e.g., [42,46,63–65]).

Drought is an intrinsic attribute of the West African climate and is recognized as one of the major causes of associated economic difficulties, migration, and mortality [66]. For instance, the extreme drought events in the West African regions in the 1970s and 1980s caused water shortages for both social and agricultural use [66]. This caused famine, which led to the deaths of between 100,000 and 250,000 people, and about 3.5 million livestock worth $400 million perished [67]. In Ghana, the incidence of extreme drought caused a series of bush fires that led to the loss of properties, human lives, and farmlands [68].

Extreme events such as droughts and floods have increased in Ghana in recent decades, making the country vulnerable [69,70]. Many research studies have been performed to analyze drought in Ghana. For instance, Kasei et al. [71] utilized the SPI to investigate the temporal characteristics of meteorological drought in the Volta basin, in order to

provide support for water resource management. Similarly, Ndehedehe et al. [72] used the SPI, Standardized Runoff Index (SRI), and Standardized Soil moisture Index (SSI) to analyze the spatiotemporal patterns of drought in the Volta river basin for hydrological monitoring. Likewise, Nyatuame and Adodzo [73] employed the SPI to characterize the magnitude, duration, frequency, commencement, and termination of drought and flood in the Tordzie watershed, and they highlighted the possible effects on agriculture and management of water resources. Additionally, Oguntunde et al. [74] utilized the SPI, SPEI, and the Standardized Runoff Index (SRI) to examine drought characteristics in the Volta river basin, and they underlined the impacts on agriculture, water resources, and energy supply. Dovie and Kasei [75] also employed the SPI to highlight the increased drought and flood influence on groundwater recharge and irrigation in the White Volta river basin. In addition, Akurugu et al. [76] studied the groundwater resources in the Densu river basin in south-western coastal Ghana, and they concluded that the basin's recharge rate is at risk of decreasing due to the impacts of climate change and urbanization. Furthermore, Nasirudeen et al. [77] used the SPI and Reconnaissance Drought Index (RDI) to analyze drought patterns in the Tano river basin and found that drought had a negative impact on agricultural production and water supply along the river. Addi et al. [78] used the SPI to study large-scale droughts along the coast of Ghana, in order to obtain better information for early warming and disaster risk management.

The research studies mentioned above were predominantly concentrated in the Volta river basin and the Savannah agroecological zone, with few conducted in equally important locations, such as the coastal areas. Addi et al. [78] attempted to investigate meteorological drought in coastal Ghana; however, they made no attempt to analyze the spatial variations and the incidence of drought and wetness events. Furthermore, most of the studies did not attempt to characterize the frequency, duration, and intensity of the drought and wet events. A detailed drought and wetness event analysis in coastal Ghana is crucial for recognizing and comprehending the complexities associated with these events during the current phase of global warming, which remains challenging.

In this study, we employed the widely applied SPEI [15] to analyze the spatiotemporal characteristics of drought and wetness events based on frequency, duration, and intensity in the coastal Savannah agroecological zone in Ghana in 1981–2021. In addition, we performed a homogeneity test on the temperature and rainfall time-series data and analyzed the monthly variations in drought and wetness events in the zone, as well as the temporal evolution and trends in drought and wetness events in the zone. The findings of the present study provide important insights regarding the analysis of drought and wetness events, which can support the decision-making process of smallholder farmers and water resource managers in the coastal Savannah agroecological zone of Ghana.

2. Materials and Methods

2.1. Study Area

Ghana is in West Africa, with a latitude of 4°44′ N to 11°11′ N and a longitude of 3°11′ W to 1°11′ E [79]. Ghana has a tropical climate, with both dry and wet seasons, which is strongly influenced by the West African Monsoon (WAM) and the Intertropical Discontinuity (ITD) [78]. Ghana is divided into six major agroecological zones, based on climate, vegetation, and soil, as follows: Coastal Savannah, Rain Forest, Deciduous Forest, Transition Zone, Guinea Savannah, and Sudan Savannah [79].

This study focuses on the coastal Savannah agroecological zone (Figure 1). The elevation of the coastal Savannah agroecological zone ranges from the lowest point of −3.8 m on the coast to the highest point of 641.2 m inland (Figure 1a). This zone is the driest in the country [80,81], with a maximum and minimum mean annual temperature of 27.9 °C and 26.6 °C, respectively (Figure 1b). Despite having a bimodal rainfall regime, it is the zone that receives the lowest rainfall [82,83]. The average annual rainfall ranges from a low of 978.4 mm to a high of 1339.9 mm (Figure 1c). The major rainfall season in the zone begins from April to July, and the minor season occurs from September to early November,

while the dry season commences from late November to March [84]. Major towns in this zone (Figure 1a) include Elmina, Cape Coast, Moree, Saltpond, Apam, Winneba, Bortianor, Accra, Tema, Prampram, Ada Foah, Anloga, Keta, and Denu. The zone's primary economic activities include fishing, agriculture, and trading [78].

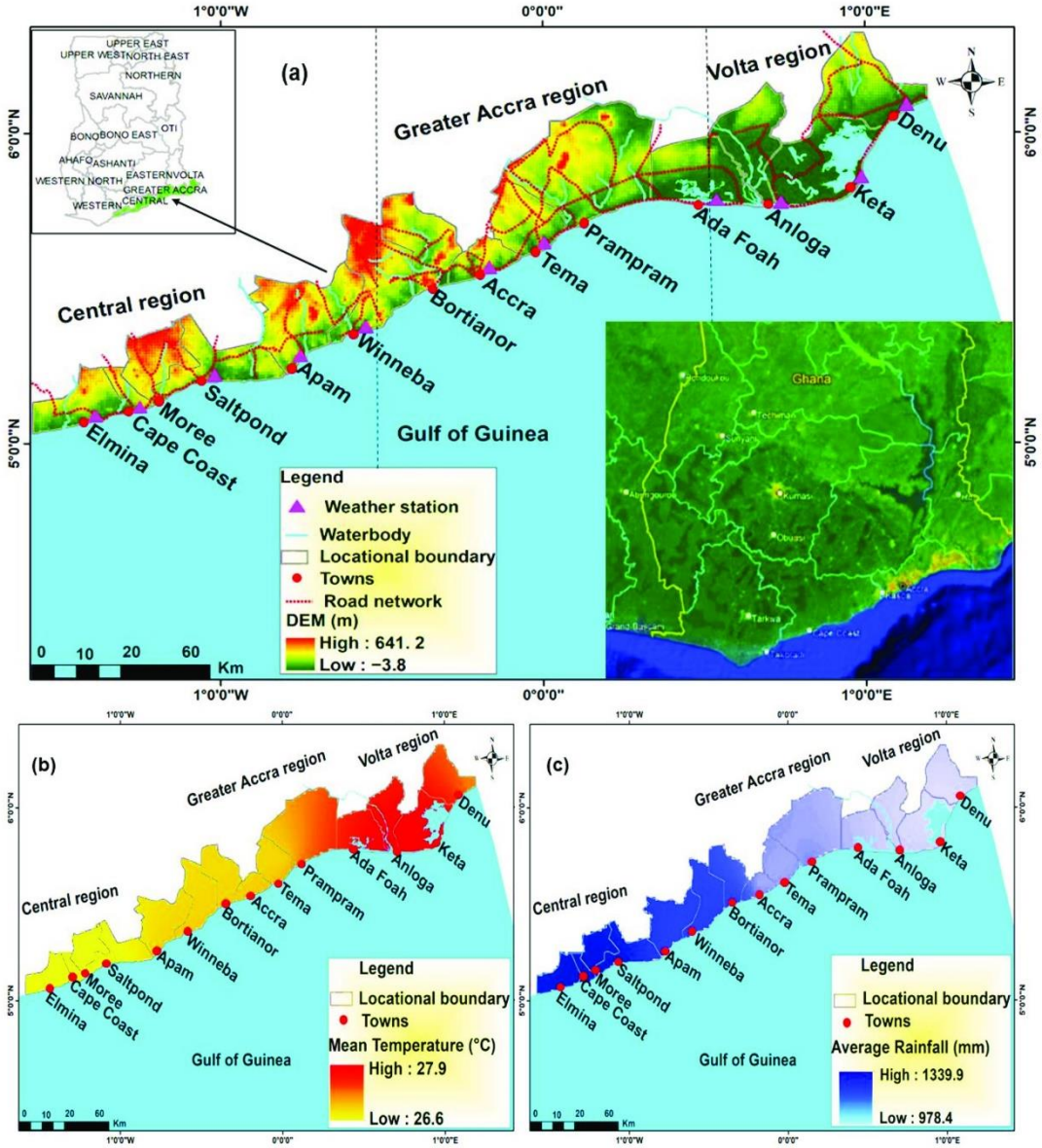


Figure 1. Map showing the location of the coastal Savannah agroecological zone, elevation, major towns, and measurement stations (**a**); average annual rainfall (from 1981 to 2021) (**b**); mean annual temperature (from 1981 to 2021) (**c**).

2.2. Data Sources and Quality Control

Monthly climatological data for 14 locations (Figure 1b) from 1981 to 2021 were obtained, in order to characterize drought and wet events in the Coastal Savannah agroecological zone. The data utilized included monthly rainfall and maximum and minimum temperatures acquired from the Ghana Meteorological Agency (GMet) and the National Aeronautics and Space Administration/Prediction of Worldwide Energy Resources (NASA/POWER) [85]. From GMet, we obtained data for eleven synoptic stations—Elmina, Cape Coast, Saltpond, Apam, Winneba, Accra, Tema, Ada Foah, Anloga, Keta, and Denu—whereas those for Moree, Bortianor, and Prampram were acquired from NASA/POWER.

GMet is the representative agency for climatological data provision in Ghana, while NASA/POWER is a satellite-based data set that provides global weather and agroclimatology data at 1° latitude and longitude resolution [86]. NASA/POWER satellite data have been widely utilized [86–88] and are considered suitable and dependable, especially for filling data gaps in data-scarce regions such as developing countries [86].

The R-Instat (version 0.70) software [89] was used to check for missing gaps in the rainfall and temperature data sets from the eleven synoptic stations. Here, the missing gaps in each data set were less than 2%. Following the advice of Monteiro et al. [86], the NASA/POWER satellite data were used to fill in these gaps.

2.3. Methods

2.3.1. Homogeneity Tests of the Observed Temperature and Rainfall Time-Series Data

In this study, we performed three homogeneity tests to detect shifts or breaks (inhomogeneities) in the observed monthly temperature and rainfall time-series data. These tests included the Pettitt test [90], the Buishand range test [91], and the Standard Normal Homogeneity Test (SNHT) [92]. These tests are highly recommended for detecting homogeneity in a given time-series data set [93,94]. The tests can recognize shifts in the time-series to detect changepoints and their corresponding years of change [94]. Furthermore, the Pettitt test and the Buishand range test can identify changepoints in the middle of the time-series, while the beginning and end of the time-series were the cases assessed by the SNHT [93,94]. The Pettitt test is a non-parametric test and does not require the assumption of a normally distributed time-series; the opposite is true for the Buishand range test and the SNHT [93–95].

Criteria for Homogeneity Analysis

In this study, we used the method of Winingaard et al. [93] to detect changepoints in climate variables. A series is said to be homogeneous (HG) if the calculated p-value of all three tests is greater than the significance level alpha of 0.05. If the estimated p-value of at least two of the three tests is less than the significance level alpha of 0.05 and at least two of the three tests have the same year of change, there is considered to be a changepoint (CP) in the series. In addition, if each of the three tests identifies a changepoint in different years, the series is considered uncertain (U). This method was successfully utilized in the earlier studies of Yildirim and Rahman [94] and Jaiswal et al. [95].

2.3.2. Computation of SPEI

As described earlier, the SPEI uses the climatic water balance, which is calculated from the difference between precipitation and potential evapotranspiration (PET) [15]. The SPEI, thus, has the capability to portray the variations in drought and wet conditions through changes in water supply and demand [47]. The SPEI was computed using the SPEI package in R. A detailed computation procedure for the SPEI has been provided by Vincente-Serrano et al. [15], as follows:

$$D_i = P_i - \mathrm{PET}_i, \quad (1)$$

where D_i is the moisture deficit in millimeters for month i, P_i denotes the precipitation in millimeters for month i, and PET_i denotes the potential evapotranspiration in millimeters for month i. The Hargreaves method [96] was used to compute the PET, considering the usage of only maximum and minimum temperatures [97].

The estimated D_i values were summarized at different timescales. The difference $D^k_{i,j}$ between a particular month j and year i was determined according to the selected timescale k. As indicated in the study of Vincente-Serrano et al. [15], the accumulated difference, for example, for one month in a given year i with a 12 month timescale, is estimated as follows:

$$X^k_{i,j} = \sum_{l=13-k+j}^{12} D_{i-1,l} + \sum_{l=1}^{j} D_{i,l}, \text{ if } j < k \text{ and} \quad (2)$$

$$X^k_{i,j} = \sum_{l=j-k+1}^{j} D_{i,l}, \text{ if } j \geq k, \quad (3)$$

where $D_{i,l}$ is the $P-$PET difference in the first month of year i, in millimeters.

The probability density function of a three-parameter log-logistic distribution was employed to normalize the D series, in order to obtain the SPEI, as shown below:

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1}\left[1+\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right]^{-2}, \quad (4)$$

where α, β, and γ denote the scale, shape, and origin, correspondingly, for D values in the range ($\gamma > D < \infty$).

Based on the log–logistic distribution, the probability distribution function of the D series is given by

$$F(x) = \left[1+\left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right]^{-1}. \quad (5)$$

The computation of the SPEI is obtained through the standardized values of $F(x)$ as follows:

$$SPEI = W - \frac{C_0 + C_1 W + C_2 W}{1 + d_1 W + d_2 W^2 + d_3 W^3}, \quad (6)$$

where

$$W = \sqrt{-2\,\mathrm{In}(p)}, \quad (7)$$

$C_0 = 2.5155$, $C_1 = 0.8028$, $C_2 = 0.0203$, $d_1 = 1.4327$, $d_2 = 0.1892$, and $d_3 = 0.0013$. When $p \leq 0.5$, $W = \sqrt{-2\,\mathrm{In}(p)}$; when $p > 0.5$, $W = \sqrt{-2\,\mathrm{In}(1-p)}$.

As the SPEI is based on the SPI, negative and positive values indicate drought and wetness, respectively [98]. Based on this, we followed the classification of SPEI by Alley [14]. Here, the SPEI value indicates either extreme (SPEI ≤ -2.00), severe (-1.50 to -1.99), moderate (-1.00 to -1.49), or mild (-0.00 to -0.99) drought; likewise, it also can denote extreme (SPEI $\geq +2.00$), severe (+1.50 to +1.99), moderate (+1.00 to +1.49), or mild (+0.00 to +0.99) wetness. The frequency, duration, and intensity of drought and wetness events are characterized based on these SPEI values.

2.3.3. Computation of Drought/Wetness Characteristics

To compute the drought and wetness characteristics in the coastal Savannah agroecological zone of Ghana, thresholds of SPEI ≤ -1.00 and $\geq +1.00$ were used to capture drought and wetness events, respectively. We must emphasize that these events were also taken in terms of months. The recent studies of Ayugi et al. [47] on the evaluation of meteorological drought and flood scenarios over Kenya, East Africa, and that of Polong et al. [99] on the temporal and spatial evolution of the SPEI in the Tana River Basin, Kenya,

have employed similar thresholds. We adapted the definition of Ayugi et al. [47] to compute the frequency, duration, severity, and intensity of drought and wetness events.

Frequency indicates the number of occurrences of drought and wetness events in a given period, and is expressed as the ratio of the number of drought incidences in a month to the total number of months over the given period, calculated as follows:

$$F = \frac{n_k}{N_K} \times 100\%, \tag{8}$$

where F is the frequency of occurrence of a drought/wetness event/month, n_k indicates the number of drought (SPEI ≤ -1.00) and wetness (SPEI $\geq +1.00$) events, and N_k denotes the total number of months in the study period.

Duration (D) indicates the length of time (i.e., number of months) from the beginning to the end of drought or wetness events [6]. It is the sum of all drought and wetness event durations divided by the number of drought and wetness events [34], as expressed below, and is achieved by adding all the drought and wetness event periods and dividing by the number of droughts (in the case of drought events), and the same is done for wetness events.

$$D = \frac{\sum_{i=1}^{n} i}{K_S} \tag{9}$$

Here, D denotes the duration of drought/wetness events, n is the upper limit of the of drought/wetness duration events/months, i is the sum of drought/wetness duration events/months, and Ks is the number of drought/wetness events/months.

Severity (S) indicates the aggregate sum of the SPEI values, based on the duration amount, as expressed below:

$$\mathrm{S} = \sum_{i=1}^{\mathrm{D}} \mathrm{SPEI_i}, \tag{10}$$

where D is the duration, i is the month, and denotes the SPEIi value in month i.

The intensity (I) reveals the severity of a drought or wetness event over the duration of the drought or wetness event, and is computed by dividing severity in Equation (10) by the duration in Equation (9), as follows:

$$\mathrm{I} = \frac{\mathrm{S}}{\mathrm{D}}. \tag{11}$$

2.3.4. Trend Analysis

Mann–Kendall Test and Theil–Sen Slope Estimator

To analyze temporal trends in drought and wet events, the Mann–Kendall [100,101] (MK) test was conducted. The MK is a non-parametric test that compares the presence of a trend in a time-series to the null hypothesis that there is no trend [102]. The WMO strongly recommends the MK test when examining meteorological and hydrological variables [102,103], and it has been widely used in environmental research for temporal trend analysis [102,104]. The significance of the trends was tested in this study at the $\alpha = 0.05$ significance level. The Sen [105] slope estimator was employed to calculate the magnitude of the trend.

2.3.5. Spatial Interpolation

We employed the ordinary Kriging interpolation method to characterize drought and wetness events in the coastal Savannah agroecological zone of Ghana. The ordinary Kriging method is an effective surface interpolation technique that is based on spatially dependent variance and is normally expressed as a semivariogram [106,107]. The changes in 3 and 12

month SPEI values were examined by adapting the linear regression analysis with ordinary least squares and the slope trend analysis method [108], as follows:

$$S = \frac{l \times \sum_{p=1}^{l} a \times y_a - \sum_{p=1}^{l} a \sum_{p=1}^{l} y_a}{l \times \sum_{p=1}^{l} a^2 - \left(\sum_{p=1}^{l} a\right)^2}, \quad (12)$$

where S is the slope, which shows the trend of annual 3 and 12 month SPEI data; l is the length of the of the time-series; y_a reveals the mean value of SPEI at time i. Slopes greater than 0 (positive) and less than 0 (negative) indicate increasing and decreasing trends in drought and wetness events in the coastal Savannah agroecological zone, respectively.

3. Results

3.1. Changepoint Analysis

Table 1 shows the results of the changepoint analysis for temperature and rainfall for the study locations and the entire zone. Here, we employed the Pettitt, SNHT, and Buishand range homogeneity tests following the developed criteria (see Section 2.3.1). Table S1 provides a summary of the statistical results of the Pettitt, SNHT, and Buishand range homogeneity tests, and Figure S1 is a graphical depiction of the changepoints in the study region.

The overall results of the analysis in Table 1 reveal the homogeneous nature of both temperature and rainfall data. Notwithstanding, changepoints exist in most of the study locations. From Table 1, rainfall is more homogenous in the region than temperature. For instance, changepoints in temperature occurred in the years 1995, 1996, and 2002 in Accra and Tema, while a changepoint in rainfall occurred only in 2002. Again, in 1997, 2004, 2010, and 2012, changepoints were observed for temperature in Ada Foah, Anloga, and Keta, whereas rainfall was homogenous throughout the period. A similar case was observed in the locations of Cape Coast, Elmina, Moree, and Saltpond; the same is true for Apam, Bortianor, and Winneba (Table 1). From Table 1, the overall results for the entire zone reveal the homogeneous nature of both temperature and rainfall throughout the year for the period under analysis, except for September 1995 and November 2002 (for temperature and rainfall, respectively). Figure 2a,b show the changepoint occurrences in September 1995 for temperature and November 2002 for rainfall for the entire zone. Here, the results for the entire zone were obtained by averaging the results at individual locations.

Table 1. Changepoint analysis for temperature and rainfall. Note: * *HG* Homogeneous, * *CP* Change point, * *U* Uncertain.

Location	Month	Temperature		Rainfall	
		Nature of Series	Year of Change	Nature of Series	Year of Change
Accra, Tema	Jan	HG	–	HG	–
	Feb	HG	–	HG	–
	Mar	CP	1996	HG	–
	Apr	HG	–	HG	–
	May	HG	–	HG	–
	Jun	HG	–	HG	–
	Jul	HG	–	HG	–
	Aug	HG	–	HG	–
	Sep	CP	2002	HG	–
	Oct	CP	1995	U	–
	Nov	HG	–	CP	2002
	Dec	HG	–	HG	–
	Annual	HG	–	HG	–

Table 1. *Cont.*

Location	Month	Temperature		Rainfall	
		Nature of Series	Year of Change	Nature of Series	Year of Change
Ada Foah, Anloga, Keta	Jan	HG	–	HG	–
	Feb	HG	–	HG	–
	Mar	HG	–	HG	–
	Apr	HG	–	HG	–
	May	HG	–	HG	–
	Jun	CP	2010	HG	–
	Jul	CP	1997	HG	–
	Aug	CP	2012	HG	–
	Sep	CP	2004	HG	–
	Oct	HG	–	HG	–
	Nov	HG	–	U	–
	Dec	HG	–	HG	–
	Annual	HG		HG	–
Cape Coast, Elmina, Moree, Saltpond	Jan	HG	–	HG	–
	Feb	HG	–	CP	2002
	Mar	CP	1996	HG	–
	Apr	HG	–	HG	–
	May	CP	1997	HG	–
	Jun	HG	–	HG	–
	Jul	HG	–	HG	–
	Aug	HG	–	HG	–
	Sep	CP	2002	HG	–
	Oct	CP	1996	HG	–
	Nov	CP	1996	U	–
	Dec	HG	–	HG	–
	Annual	CP	1997	HG	–
Apam, Bortianor, Winneba	Jan	HG	–	HG	–
	Feb	HG	–	HG	–
	Mar	HG	–	HG	–
	Apr	HG	–	HG	–
	May	HG	–	HG	–
	Jun	HG	–	HG	–
	Jul	HG	–	HG	–
	Aug	HG	–	HG	–
	Sep	CP	2002	HG	–
	Oct	CP	1995	U	–
	Nov	HG	–	CP	1999
	Dec	HG	–	HG	–
	Annual	HG	–	HG	–
Prampram	Jan	HG	–	HG	–
	Feb	HG	–	HG	–
	Mar	HG	–	HG	–
	Apr	HG	–	HG	–
	May	HG	–	HG	–
	Jun	HG	–	HG	–
	Jul	HG	–	HG	–
	Aug	HG	–	HG	–
	Sep	CP	1995	HG	–
	Oct	HG	–	HG	–
	Nov	HG	–	CP	2002
	Dec	HG	–	HG	–
	Annual	HG	–	HG	–

Table 1. *Cont.*

Location	Month	Temperature		Rainfall	
		Nature of Series	Year of Change	Nature of Series	Year of Change
Denu	Jan	HG	–	HG	–
	Feb	HG	–	HG	–
	Mar	CP	1997	HG	–
	Apr	HG	–	HG	–
	May	HG	–	HG	–
	Jun	HG	–	HG	–
	Jul	CP	2005	HG	–
	Aug	HG	–	HG	–
	Sep	CP	2002	HG	–
	Oct	U	–	HG	–
	Nov	CP	1994	U	–
	Dec	HG	–	HG	–
	Annual	HG	1997	HG	–
Entire zone	Jan	HG	–	HG	–
	Feb	HG	–	HG	–
	Mar	HG	–	HG	–
	Apr	HG	–	HG	–
	May	HG	–	HG	–
	Jun	HG	–	HG	–
	Jul	HG	–	HG	–
	Aug	HG	–	HG	–
	Sep	CP	1995	HG	–
	Oct	HG	–	HG	–
	Nov	HG	–	CP	2002
	Dec	HG	–	HG	–
	Annual	HG	–	HG	–

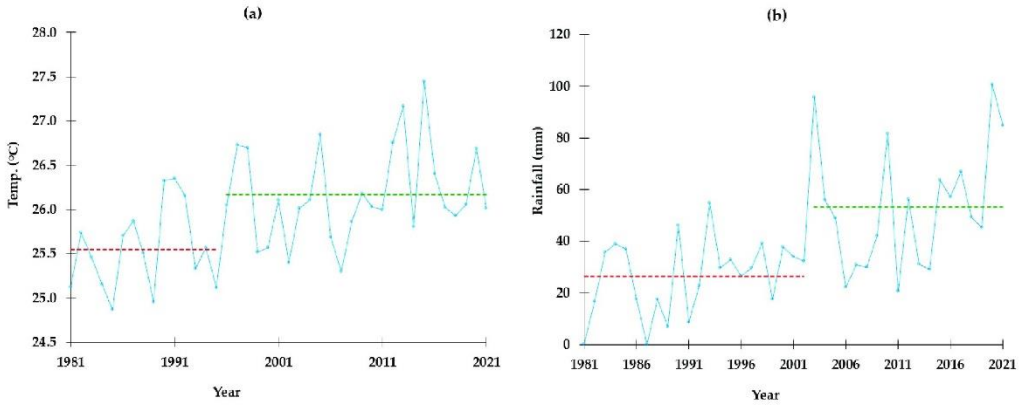


Figure 2. Changepoints in September temperature (**a**) and November rainfall (**b**) for the coastal Savannah agroecological zone of Ghana.

3.2. Monthly Variations in Drought and Wetness Events

Figure 3a–d show the mean monthly variations in SPEI-3 and SPE-12 drought and wetness events over the coastal Savannah agroecological zone of Ghana from 1981 to 2021. Here, we analyzed the monthly variations in moderate, severe, and extreme drought events (Figure 3a,b) and wetness events (Figure 3c,d) for SPEI-3 and SPEI-12 based on the thresholds of ≤ -1.00 (drought) and $\geq +1.00$ (wetness). Table 2 shows the results of the Mann–Kendal test and Sen's slope estimate for the monthly variations in moderate-

to-extreme drought and wetness events under the SPEI-3 and SPEI-12 timescales. From Figure 3a, it can be observed that extreme drought events were more common in the dry season (late November–March) than in the wet season (April–July) under the SPEI-3 timescale. Notwithstanding, moderate-to-severe drought events occurred throughout the season, except for June and July, when no moderate drought events occurred. The SPEI-12 timescale (Figure 3b) revealed that extreme drought events are typical throughout the season, except for the months of June and July, while moderate-to-severe drought events occurred across the season.

From Figure 3c,d, it can be seen that the zone experienced moderate-to-extreme wetness events throughout the months under the period of analysis. Notwithstanding, moderate-to-extreme wetness events were stronger in the wet season (April–July) than in the minor season (September–early November) and the dry season (late November–March), under both the SPEI-3 and SPEI-12 timescales.

The results of the Mann–Kendall test revealed a positive significant trend (alpha: 0.05, *p*-value: 0.042), but a weak magnitude of change (Sen's slope estimate: 0.000) only in moderate drought throughout the months in the zone under the SPEI-12 (Table 2). Among the seasons, a significant positive trend (alpha: 0.05, *p*-value: 0.037), but a weak magnitude of change (Sen's slope estimate: 0.010), only existed in the dry season for severe wetness under the SPEI-3, with the others being non-significant (Table 2).

The incidences of drought and wetness events in the coastal savannah agroecological zone tended to follow the seasonal patterns in temperature and rainfall in the zone. While extreme drought event occurrences were greater in the month of January (values of −2.7 and −2.3, for SPEI-3 and SPEI-12, respectively), the corresponding extreme wetness event incidences were greater in June (2.6 and 2.3 for SPEI-3 and SPEI-12, correspondingly) during the wet season and in October (2.3 under both SPEI-3 and SPEI-12) for the minor season.

Table 2. Mann–Kendall trend test and Sen's slope estimate for seasonal drought and wetness events from 1981–2021.

Index	Drought/Wet Events	MK Stat (S)	Var (S)	Kendall's Tau	*p*-Value	Sen's Slope
			All months			
SPEI-3 (SPEI-12)	Moderate drought	13 (19)	186.333 (87.667)	0.229 (0.510)	0.341 (0.042 *)	0.000 (0.000)
	Severe drought	7 (21)	146.333 (198.333)	0.144 (0.349)	0.563 (0.136)	0.000 (0.017)
	Extreme drought	7 (4)	15.667 (114.000)	0.738 (0.099)	0.077 (0.708)	0.065 (0.000)
	Moderate wet	12 (18)	164.667 (164.667)	0.228 (0.342)	0.350 (0.161)	0.000 (0.000)
	Severe wet	24 (13)	193.333 (139.667)	0.410 (0.281)	0.084 (0.271)	0.013 (0.000)
	Extreme wet	−9 (−4)	151.667 (145.333)	−0.181 (−0.083)	0.465 (0.740)	0.000 (0.000)
			Wet season			
SPEI-3 (SPEI-12)	Moderate drought	5 (?)	7.667 (?)	0.913 (?)	0.071 (?)	0.083 (?)
	Severe drought	5 (5)	7.667 (7.667)	0.913 (0.913)	0.071 (0.071)	0.100 (0.100)
	Extreme drought	*NA* (?)	*NA* (?)	*NA* (?)	*NA* (?)	*NA* (?)
	Moderate wet	4 (1)	8.667 (5.000)	0.667 (0.236)	0.174 (0.655)	0.083 (0.000)
	Severe wet	3 (0)	7.667 (2.667)	0.548 (0)	0.279 (1.000)	0.067 (0.000)
	Extreme wet	3 (3)	7.667 (7.667)	0.548 (0.548)	0.279 (0.279)	0.042 (0.067)
			Minor season			
	Moderate drought	2 (?)	2.667 (?)	0.816 (?)	0.221 (?)	0.050 (?)
	Severe drought	*NA* (−2)	*NA* (2.667)	*NA* (−0.816)	*NA* (0.221)	*NA* (−0.050)
	Extreme drought	1 (0)	1.000 (2.667)	1 (0)	0.317 (1.000)	0.050 (0.000)
SPEI-3 (SPEI-12)	Moderate wet	0 (2)	2.667 (2.667)	0 (0.816)	1.000 (0.221)	0.000 (0.050)
	Severe wet	1 (?)	3.667 (?)	0.333 (?)	0.602 (?)	0.050 (?)
	Extreme wet	0 (0)	2.667 (2.667)	0 (0)	1.000 (1.000)	0.000 (0.000)
			Dry season			
	Moderate drought	1 (5)	13.000 (13.000)	0.120 (0.598)	0.782 (0.166)	0.000 (0.012)
	Severe drought	0 (7)	8.000 (13.000)	0 (0.837)	1.000 (0.052)	0.000 (0.021)
SPEI-3 (SPEI-12)	Extreme drought	4 (4)	8.667 (14.667)	0.667 (0.447)	0.174 (0.296)	0.066 (0.011)
	Moderate wet	4 (4)	8.000 (14.667)	0.632 (0.447)	0.157 (0.296)	0.000 (0.010)
	Severe wet	8 (5)	14.667 (13.000)	0.894 (0.598)	0.037 * (0.166)	0.012 (0.010)
	Extreme wet	−1 (−1)	5.000 (5.000)	−0.236 (−0.236)	0.655 (0.655)	0.000 (0.000)

Note: * Significant at 0.05, Reject H_o if *p*-value is < 0.05 or accept H_o if *p*-value is > 0.05. *NA* Not applicable, or the event did not appear in a specific index or season. ? The event could not be computed as some sequences were constant.

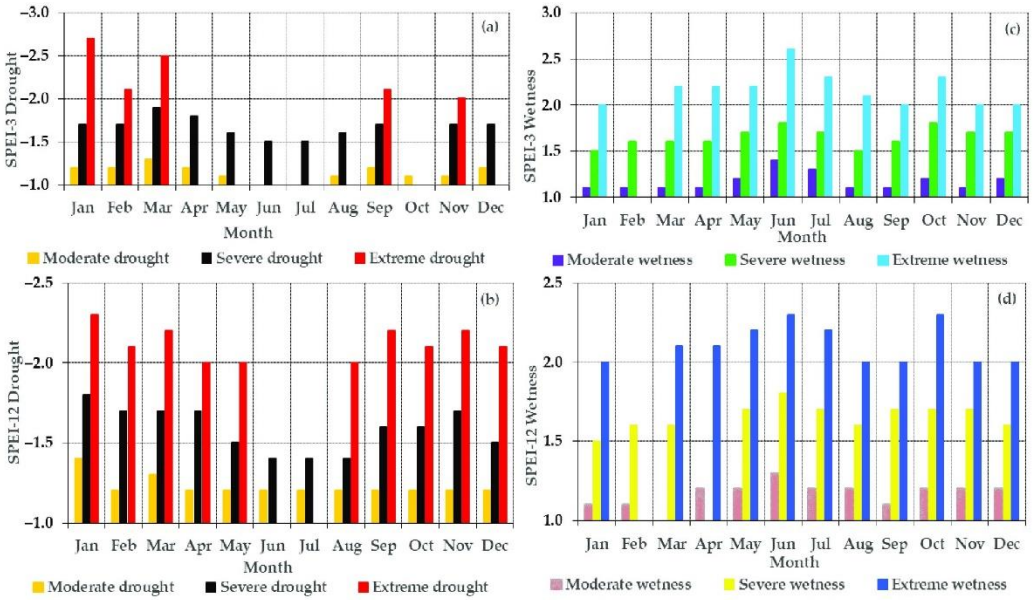


Figure 3. Temporal evolution of the mean monthly SPEI-3 and SPEI-12 for moderate, severe, and extreme drought (**a**,**b**) and wetness (**c**,**d**) from 1981–2021 over the coastal Savannah agroecological zone in Ghana.

Temporal Evolution and Trends in Drought and Wetness Events

Figure 4a–e show the temporal evolution of drought and wetness events over the coastal Savannah agroecological zone of Ghana from 1981 to 2021. We analyzed the temporal developments in moderate-to-extreme drought (Figure 4a,b) and wetness (Figure 4c,d), as well as all drought and wetness events (Figure 4e) for SPEI-3 and SPEI-12, following the thresholds of ≤ -1.00 (drought) and $\geq +1.00$ (wetness). All drought and wetness events in the zone were calculated using the averages of moderate-to-extreme drought and wetness events. It should be noted that the normal drought and wetness categories were not considered in this study, based on the established thresholds. It is apparent, from Figure 4a,b, that the study region has suffered moderate-to-extreme drought events, notwithstanding the wet event incidences (Figure 4c,d). For instance, in Figure 4a, the SPEI-3 detected moderate-to-extreme drought events in the 1980s and 1990s and moderate-to-severe in the 2000s, except for the year 2009, when an extreme event happened. Under the SPEI-3 timescale, extreme drought events occurred in the years 1983 (value: −2.7), 1990 (−2.0), 1992 (−2.3), 1996 (−2.0), 1998 (−2.3), and 2009 (−2.0). Similar drought events were also detected under the SPEI-12 timescale (Figure 4b). However, the moderate-to-extreme and moderate-to-severe drought event incidences were higher for the SPEI-3 data. For example, extreme drought events under SPEI-12 appeared only in the 1980s and 1990s, and not in the 2000s, as was the case with SPEI-3. Here, the extreme drought years occurred in 1983 (value: −2.3), 1984, 1993 (−2.3), and 1998 and 1999 (−2.0).

The study region also observed moderate-to-extreme wetness events on both the SPEI-3 and SPEI-12 timescales (Figure 4c,d). In Figure 4c, the SPEI-3 recorded moderate-to-extreme wetness events in the 1980s and 1990s and moderate-to-severe ones in the 2000s, excluding the year 2021, when an extreme wetness event ensued. Extreme wetness events occurred in 1987 (value: 2.5), 1991 (2.0), and in 1997 and 2021 (2.2). The SPEI-12 timescale also recorded moderate-to-severe wetness events in the 1980s and 1990s and moderate-to-extreme wetness events in the 2000s, with the years 2021 (value: 2.2) and 2020 (2.0) recording extreme wetness events.

From Figure 4e, it is evident that drought and wetness events are common in the zone. The years 1983 and 1999 recorded the greatest drought incidences, with the highest values (−2.0) under the SPEI-12 timescale, while the lowest (−1.0) occurred in 1981, 1994, 2012, and 2017 under the SPEI-3 timescale (Figure 4e). The year 1987 recorded the highest value (2.5) of a wetness event under the SPEI-3 timescale, followed by 2021 (2.0) for the SPEI-12 timescale, and the lowest (1.0) occurring in 1982 and 1992 (under SPEI-12) and 1995 and 1999 (under SPEI-3). Under the SPEI-12 timescale, a low value (1.0) followed in 2016. Figure S2 depicts the results of the temporal developments in drought and wetness events for the individual study locations.

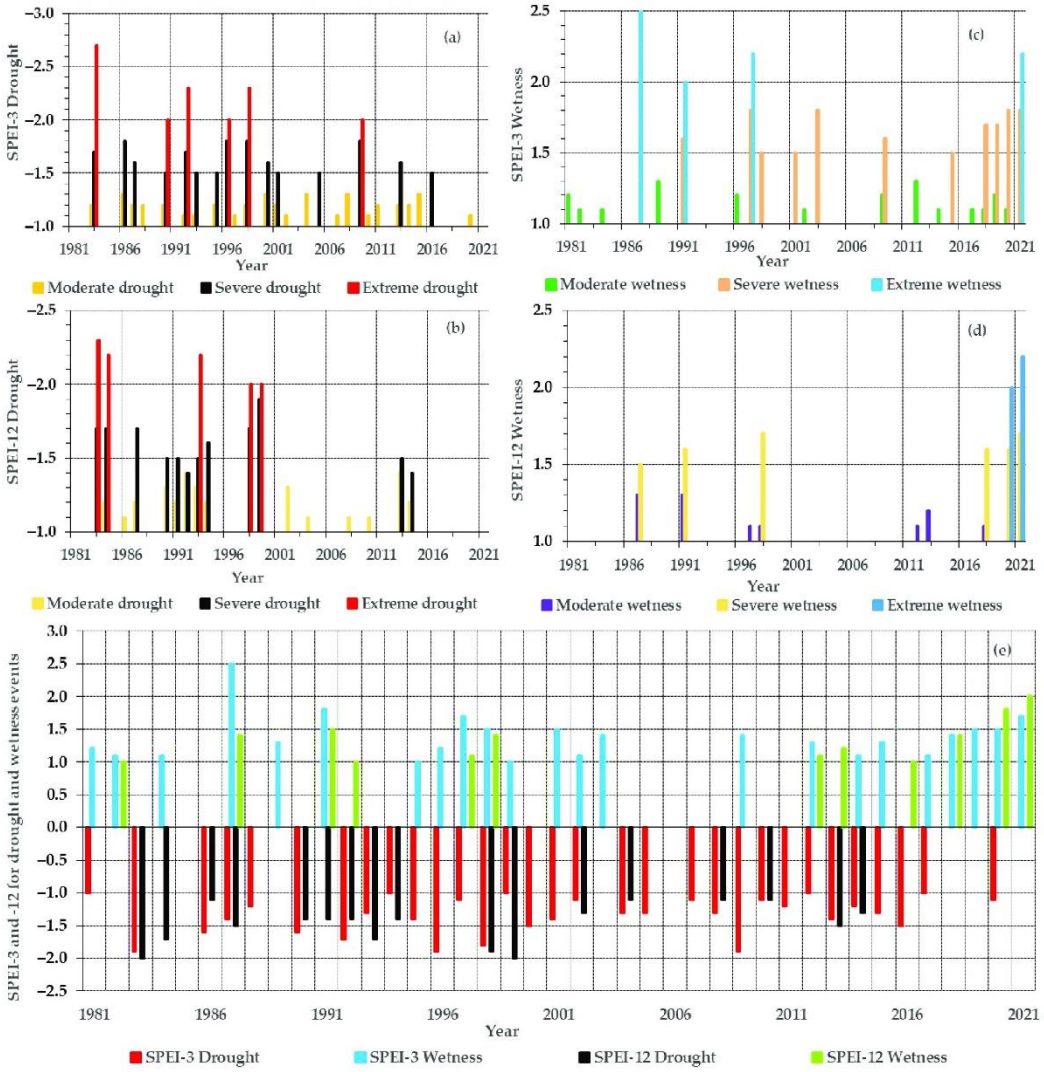


Figure 4. Temporal evolution of the mean annual SPEI-3 and SPEI-12 for moderate-to-extreme drought (**a**,**b**), wetness (**c**,**d**), and all drought and wet events (**e**) from 1981–2021 over the coastal Savannah agroecological zone in Ghana.

The results of the Mann–Kendall test (Table 3) showed a significant positive trend (alpha: 0.05, *p*-value: 0.037) in the extreme drought events in the zone. However, the magnitude of change was weak (Sen's slope estimate: 0.017). No significant trends were observed in the other drought groups, and the same was true for all drought and wetness events (Table 3).

Table 3. Mann–Kendall trend test and Sen's slope estimate for annual drought and wetness events from 1981–2021.

Index	Drought/Wetness Event	MK Stat (S)	Var (S)	Kendall's Tau	*p*-Value	Sen's Slope
SPEI-3 (SPEI-12)	Moderate drought	13 (1)	2347.667 (303.667)	0.039 (0.012)	0.788 (0.954)	0.000 (0.000)
	Severe drought	16 (13)	366.667 (194.333)	0.175 (0.220)	0.403 (0.351)	0.000 (0.002)
	Extreme drought	5 (8)	23.667 (14.667)	0.389 (0.894)	0.304 (0.037 *)	0.018 (0.017)
	Moderate wetness	−16 (−3)	734.667 (111.667)	−0.108 (−0.076)	0.555 (0.776)	0.000 (0.000)
	Severe wetness	16 (7)	150.667 (23.667)	0.325 (0.545)	0.192 (0.150)	0.007 (0.003)
	Extreme wetness	−−1 (1)	7.667 (1.000)	−0.183 (1)	0.718 (0.317)	−0.004 (0.200)
SPEI-3(SPEI-12)	All drought	91 (38)	33,993.667 (568.000)	0.206 (0.297)	0.118 (0.111)	0.008 (0.011)
	All wetness	32 (23)	1398.000 (204.333)	0.133 (0.369)	0.392 (0.108)	0.005 (0.012)

Note: * Significant at 0.05, Reject H_o if *p*-value is < 0.05 or accept H_o if *p*-value is > 0.05.

3.3. Spatial Evolution of SPEI

Figure 5a–h shows the spatial evolution of the occurrences of extreme and severe drought and wetness events in SPEI-3 and SPEI-12 over the coastal Savannah agroecological zone. At this point, an analysis was conducted to identify the distribution of extreme and severe drought and wetness events across the study region, following the earlier analysis. Here, the analysis was carried out following the region classification (see Figure 1). Notably, extreme dry events have SPEI values of ≤ -2.00 and represent the worst drought events in the region, whereas severe dry events have SPEI values ranging from -1.50 to -1.99, indicating intense drought conditions. In Figure 5a,b, the SPEI-3 recorded a high occurrence (2.03) of extreme drought events in most parts of Central and Greater Accra and a low occurrence (0.61) in Volta. According to the SPEI-12, there were both high (3.64) and low (0.20) occurrences of extreme drought in the Central and Greater Accra, with a low value in Volta. A dissimilar pattern was observed regarding severe drought events over the study region. Here, high incidences of severe drought events (Figure 5c,d) appeared in the Volta under the SPEI-3 and SPEI-12 (7.52 and 9.15, respectively). Both SPEI-3 and SPEI-12 were able to detect severe drought events in some parts of Central and Greater Accra.

Regional variations were also observed regarding the extreme and severe wetness events (Figure 5e–h). In Figure 5e, the SPEI-3 identified the maximum (2.64) incidence of extreme wetness events in the Central and some areas of Greater Accra and Volta, while the minimum (1.22) occurred for Greater Accra and Volta. Under the SPEI-12 (Figure 5f), a greater (3.46) occurrence of extreme wetness was observed in Central, with moderate-to-extreme events in Greater Accra, and the lowest occurrence (0.20) in Volta. In Figure 5g,h, high occurrences of severe wetness events occurred in Volta and some parts of Greater Accra (8.33 and 6.91, respectively), and low occurrences (2.85 and 3.05) were observed in Central.

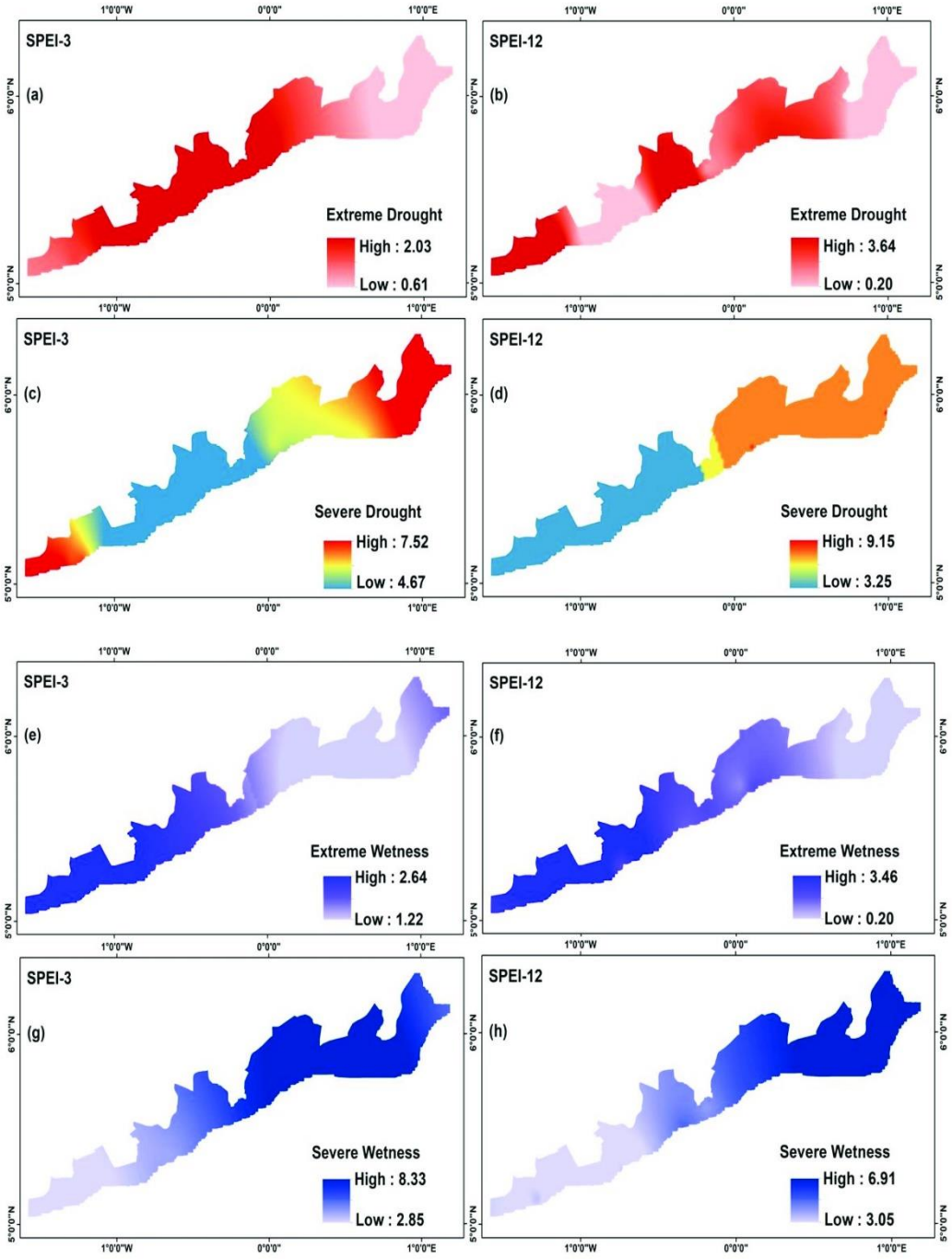


Figure 5. Spatial distribution of the average values for SPEI-3 and SPEI-12 for extreme drought (**a**,**b**), severe drought (**c**,**d**), extreme wetness (**e**,**f**), and severe wetness (**g**,**h**) events in the coastal Savannah agroecological zone of Ghana from 1981 to 2021.

3.4. Spatial Distribution of Drought and Wetness Characteristics

Considering the definitions provided in Section 2.3.3, we characterized drought and wetness events in the coastal Savannah agroecological zone of Ghana based on their frequency, duration, and intensity (Figure 6a–l). In terms of percentage, high values (20.9) occurred in the areas of Volta and some parts of Central, while a low one (17.3) appeared in Greater Accra and Central under the SPEI-3 (Figure 6a). A similar pattern was observed with the SPEI-12, where the highest frequency (21.3) was seen in Volta and some parts of Central and Greater Accra, with the lowest (15.0) also occurring in the latter two regions (Figure 6b). In the corresponding wetness frequency (Figure 6g,h), the maximum (19.9) and minimum (16.9) were distributed across the regions for the SPEI-3 (Figure 6g). As can be seen from Figure 6h, while the greatest value (19.9) occurred across the regions, it was superior in Volta, compared to the other two. The lowest (13.8) occurred in most parts of Central.

In Figure 6c,d, the drought duration varied across the regions. Drought duration was much longer in Central and Greater Accra than in Volta under both SPEI-3 (a high of 1.44) and SPEI-12 (1.57), as shown in Figure 6c,d. For SPEI-3 (Figure 6i), a high (1.47) and a low (1.39) duration of wetness events occurred across the zone. However, in SPEI-12, the greatest (1.54) wetness duration appeared for the Central portion, with the lowest (1.37) occurring for the other two regions (Figure 6j). The intensity of the drought (Figure 6e,f) and wetness (Figure 6k,l) followed a similar pattern to that of the duration. For example, in Figure 6e,f, the intensity of the drought cuts across the regions with the highest intensities of 1.50 and 1.64 under the SPEI-3 and SPEI-12 timescales, respectively. The intensity of wetness events identified by SPEI-3 (Figure 6k) was also distributed across the regions, while that of SPEI-12 (Figure 6l) was more intense in the Central region than the other two. A clear local variation was also observed in the drought and wetness frequencies, durations, and intensities across the zone.

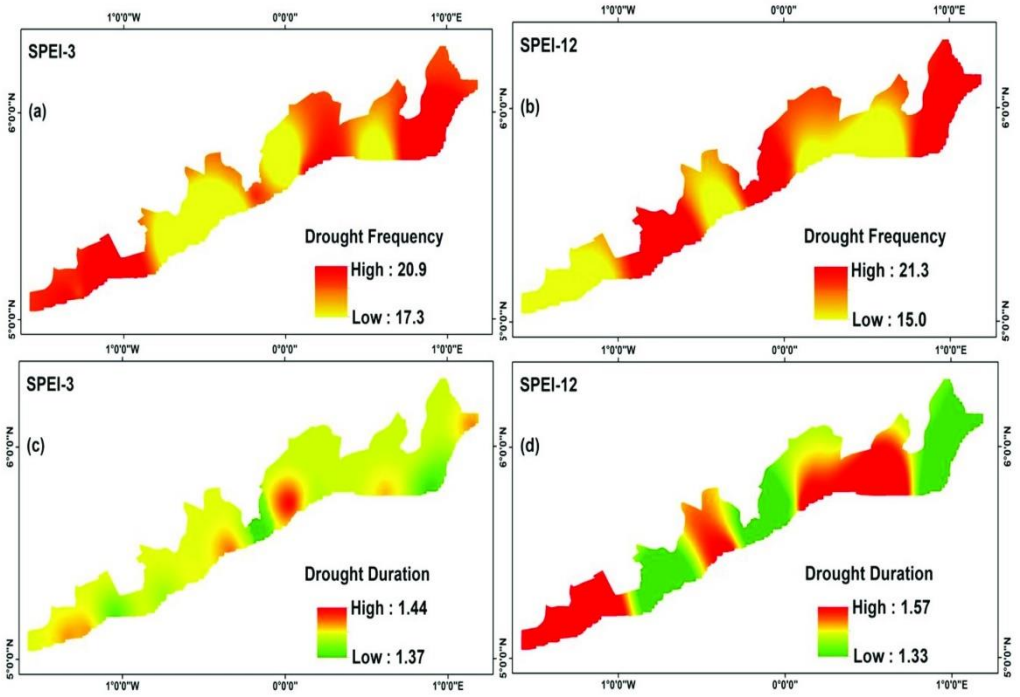


Figure 6. *Cont.*

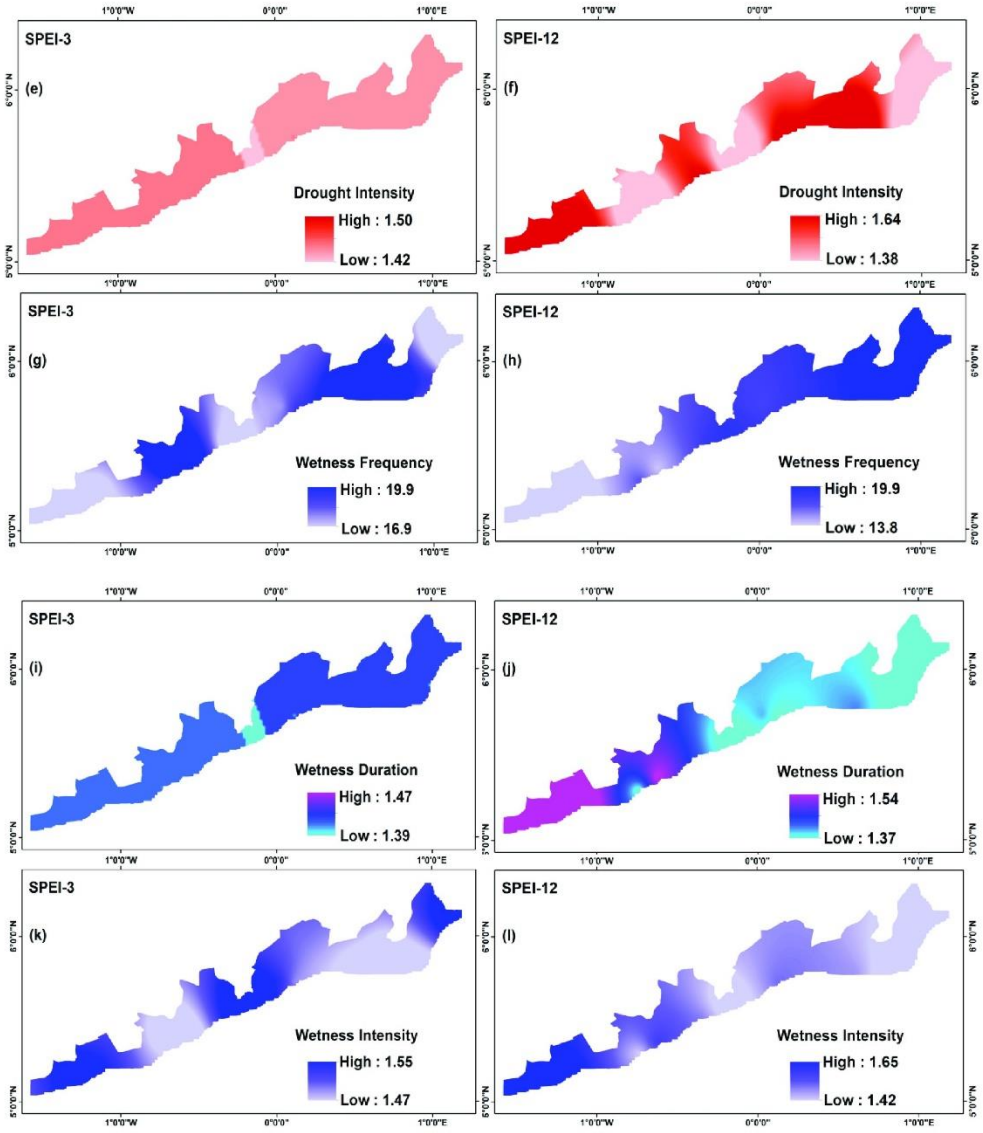


Figure 6. Spatial distribution of drought and wetness characteristics at SPEI-3 and SPEI-12 timescales in the coastal Savannah agroecological of Ghana from 1981–2021: Drought frequency (**a**,**b**) SPEI-3 and SPEI-12; drought duration (**c**,**d**) SPEI-3 and SPEI-12; drought intensity (**e**,**f**) SPEI-3 and SPEI-12; wetness frequency (**g**,**h**) SPEI-3 and SPEI-12; wetness duration (**i**,**j**) SPEI-3 and SPEI-12; wetness intensity (**k**,**l**) SPEI-3 and SPEI-12.

3.5. Spatial Distribution of Drought and Wetness Trends

Figure 7a–d show the spatial distribution of drought and wetness trends in the coastal Savannah agroecological zone of Ghana from 1981 to 2021 for SPEI-3 and SPEI-12 timescales using linear regression analysis with ordinary least squares. For SPEI-3 (Figure 7a), the drought trends were greater (0.157) in the Central and Volta areas and less (−0.000) for Greater Accra. Under SPEI-12, high (0.043) trends appeared for the Central region and were low (−0.027) for the other two regions (Figure 7b). In Figure 7c, maximum (0.040) wetness trends occurred in the Central and Greater Accra areas, while a minimum (0.002) was observed in the Volta under SPEI-3. For SPEI-12 (Figure 7d), higher (0.056) wet trends were observed in the Greater Accra area and some parts of the Central region.

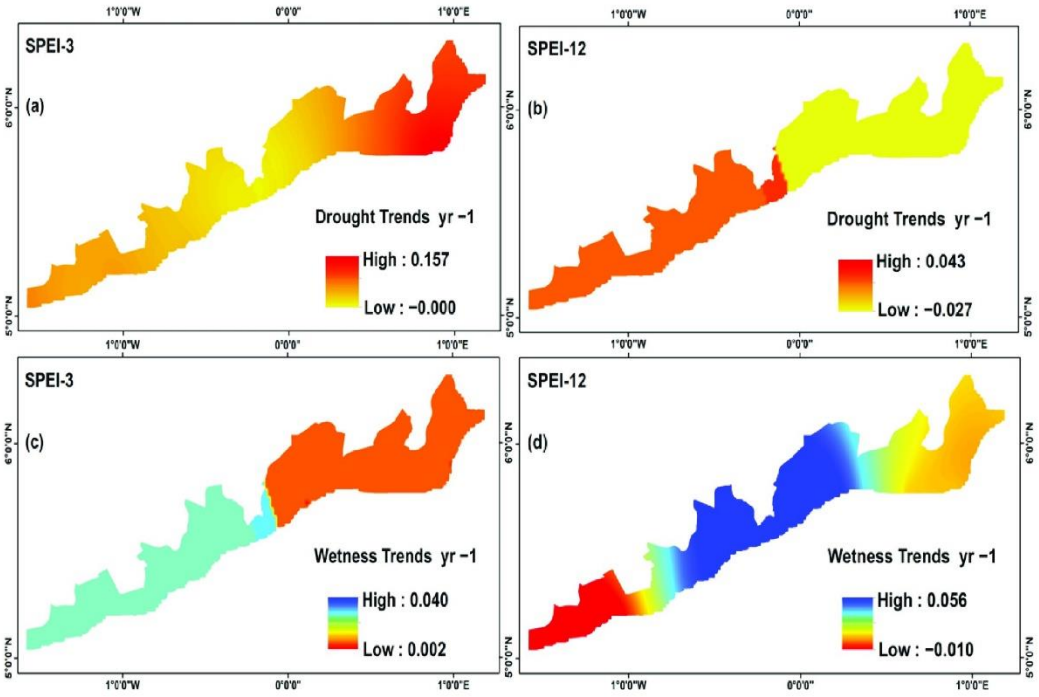


Figure 7. Spatial distribution of drought/wetness trends in the coastal Savannah agroecological zone of Ghana: Drought trends under (**a**) SPEI-3 and (**b**) SPEI-12 timescales; wetness trends under (**c**) SPEI-3 and (**d**) SPEI-12 timescales.

Drought in the zone increased from Central to Volta during the period of analysis. While the corresponding wetness followed a similar pattern, the increase was greater in the Greater Accra area. Here, it is important not to disregard the local variations in drought and wet trends across the regions.

4. Discussion

The occurrence of extreme events, such as droughts and wetness, has become common in many regions of the world due to anthropogenic-induced global warming [41]. Of course, large-scale natural variability, such as the El Niño Southern Oscillation (ENSO), also has an impact on the occurrence of extreme climatic events [109,110]. However, the evidence of harmful anthropogenic activities and related greenhouse gas emissions is apparent, as has been reiterated by the IPCC [41]. Variability has become a common characteristic of the climates of many countries, especially in the parameters of temperature and precipitation.

Variations in these climatic parameters are possibly the cause of drought and wet events in the coastal Savannah agroecological zone of Ghana, taking into consideration the role of rainfall and temperature on evapotranspiration. As has been highlighted by Thiaw and Kumar [66], extreme events and natural disasters are inherent elements of the West African climate, and Ghana's in particular.

The results of the changepoint analysis revealed the homogeneous nature of rainfall and temperature in the study region. Nonetheless, there were significant temperature changes between the mid-1990s to 2012. The changepoints in the climate variables could be attributed to the increased industrial and commercial activities in the zone, especially in the capital city (Accra) and Tema. The above finding is consistent with earlier studies conducted elsewhere, such as in southeast Australia [94], Raipur (the capital city of Chhattisgarh state, India) [95], and in Umbria, Italy [111].

Despite the corresponding wetness incidences, our findings clearly established the frequency and intensity of drought events. These findings support previous studies conducted in different regions of the world [99,112–115]. For instance, Wang et al. [112] have reported an increased frequency and intensity of drought events in the Yellow River Basin in China. An et al. [113] have reported a significant increase in the frequency and intensity of droughts in Inner Mongolia. Similarly, Ge et al. [114] have revealed aggravated drought frequency, intensity, and duration in the northern and eastern Indian plains. The study region's combined drought and wetness events may endanger the livelihood opportunities of many people. For instance, while the extreme drought events in the 1980s and 1983 in particular were so extreme, the flood occurrences in 2013 in the study region (and Accra, to be precise) negatively affected the livelihoods of the people and led to related mortalities [116]. Undoubtedly, the immense consequences for agriculture cannot be ignored, especially considering the rainfed nature of agriculture in the study region. There is significant evidence of the impacts of drought on agriculture in the scientific literature. Research studies such as [117–123] have reported the dire impacts of drought on agriculture. Smallholder farmers in the zone are, thus, vulnerable to these extreme events. Despite the fact that wetness events in the study region have recently increased, there is evidence of significant losses to the livelihoods of smallholder farmers in the region caused by floods [124]. The ongoing drought and wetness events will have implications for food security in the study region, and Ghana as a whole. This is obvious, especially given the frequency of moderate-to-extreme and moderate-to-severe drought/wetness events in the short-term timescale (SPEI-3; see Figure 4), indicating that drought/wetness events have a greater impact on agriculture during the growing season than on hydrological and water resources in the study region [19,125].

The monthly variations revealed that drought and wetness event incidences follow the seasonal pattern in temperature and rainfall in the zone. While moderate-to-severe drought and wetness events were common throughout the season, extreme drought event occurrences were greater in the dry season, especially in January, while the corresponding extreme wetness event values were higher in June and October. The results emphasized short- and long-term variations in drought and wetness events across the study region. In both the short- and long-term timescales, the incidence of extreme drought or wetness events was higher in the Central and Greater Accra areas than in Volta (see Figure 5), despite local variability across the regions. This was similar, in terms of the duration and intensity of drought or wet events (see Figure 6). Drought or wetness events increased from the Central region to the Volta. The above finding is in line with the earlier study by Santos et al. [126] conducted in Portugal, which reported the increased occurrence of more frequent cycles of drought and wet events in the south of Portugal, compared to the north. The finding also supports the study of Zhao et al. [127], who observed increased wetter and fewer drought conditions in the western upstream part of the Yangtze River Basin, China. The variations in drought or wetness events across the study region are possibly the result of the atmosphere–ocean–land connections, or due to the differences in topography and landscape dynamics. For instance, the changes in drought and wetness events in

the study region (and Ghana in general) have been linked to the seasonal movements in the Intertropical Discontinuity (ITD) and the West African Monsoon winds [78]. The ITD develops when the dry northeast trade winds (originating from the Sahara Desert) meet the moist southwest (originating from the South Atlantic Ocean) trade winds. The movement of the ITD is responsible for the seasonal rainfall patterns in Ghana. The seasonal movement of the ITD from the north to the south (and vice versa) results in more drought and wetness events, respectively. Furthermore, ocean–atmosphere dynamics, evidenced by abnormal sea surface temperatures and related large-scale teleconnection factors, such as the ENSO and the North Atlantic Oscillation (NAO), are related to the occurrences of extreme events in West Africa, and Ghana in particular [78]. Other climate change attribution studies have also stressed the increased incidence of frequent and intense droughts and wetness events. Dai [3] reviewed drought events under global warming and established that drought periods that lasted for years to decades have occurred many times in West Africa, North America, and East Asia. Similarly, Chiang et al. [128] have reported increased drought frequency, intensity, and duration in larger parts of the Americas, Africa, and Asia due to anthropogenic forcing. In addition, Brito et al. [129] have revealed the frequent nature of drought conditions in the semi-arid Northeast region of Brazil. Christidis and Stott [130] further stated that drought conditions are more prevalent in the south of Europe than in the north of Europe, while the opposite is true for wet conditions, due to the influence of anthropogenic climate change. Furthermore, due to the significant temperature rise, increased drought events have occurred in the Mediterranean region, while precipitation has remained stable or decreased [131–133]. Both drought and wetness events are projected to increase as a result of human-induced global warming [134,135].

Although we selected the 3 and 12 month timescales, several research studies, such as [34,136,137], have reported the feasibility of considering other timescales. Drought and wetness analyses can be performed on a variety of timescales, depending on the need.

5. Conclusions

In this study, we employed the SPEI to analyze the spatiotemporal characteristics of meteorological drought and wetness events in the coastal Savannah agroecological zone of Ghana from 1981 to 2021. Our findings support previous scientific evidence regarding the increased frequency and intensity of drought and wetness events.

The changepoint analysis revealed a more homogeneous nature of temperature and rainfall over the entire zone, except for September 1995 and November 2002, when changepoints occurred. The monthly variations revealed that drought and wetness event incidences follow the seasonal pattern of temperature and rainfall in the zone.

The temporal scale showed more moderate-to-extreme drought events in the 1980s and 1990s than in the 2000s, while the opposite is true for wetness events under both the SPEI-3 and SPEI-12 timescales. On the spatial scale, more extreme drought and wetness events occurred in the Central and Greater Accra areas, with severe conditions in the Volta areas. The SPEI-3 outperformed the SPEI-12 in extreme and severe drought and wetness event occurrences, indicating consequences for agriculture during the crop-growing season. Therefore, there is a need for the regular monitoring of drought and wet events to safeguard agricultural activities, especially those of smallholder farmers in the zone, in order to protect their livelihoods.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15010211/s1, Figure S1: Changepoints in temperature and rainfall for the coastal Savannah agroecological zone of Ghana; Figure S2: Temporal evolution of the mean annual SPEI-3 and SPEI-12 for moderate-to-extreme drought and wet events for the individual locations from 1981–2021 in the coastal Savannah agroecological zone in Ghana; Table S1: Changepoint analysis for climatic variables.

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2.2. Temperature variability in coastal Ghana: a day-to-day variability framework

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RESEARCH

Temperature variability in coastal Ghana: a day-to-day variability framework

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Abstract
Day-to-day temperature variability (DTD) is observed to have negative effects on people and their activities. The study assessed DTD in nine areas in coastal Ghana. The study used daily maximum (T_{max}) and minimum (T_{min}) temperatures from 1981–2021, obtained from the Ghana Meteorological Agency (GMet) and the National Aeronautics and Space Administration/Prediction of Worldwide Energy Resources (NASA/POWER). The ERA5 hourly data on single levels from 1940 to present, obtained from the fifth-generation European Centre for Medium-Range Weather Forecasts reanalysis, was further utilised to validate the NASA/POWER and the GMet datasets. The standard deviation (SD), DTD, the ratio of DTD to SD (G), the change in DTD (ΔDTD), threshold exceedances (2 °C and 4 °C), and the linear regression test were the statistical methods applied. Results established that an orderly climate ($G < 1$) exists in the nine areas. The highest monthly averages ΔDTD were observed in Ada Foah, Apam, and Elmina, while the lowest occurred in Denu, Keta, and Saltpond. Throughout the year, Ada Foah had the most exceedances of the 2 °C and 4 °C thresholds in DTD, except for the 4 °C DTD T_{min}, where Cape Coast was higher. Temporal trends increased in both DTD T_{max} and $T_{min.}$ However, improvements in DTD T_{min} were weak. DTD was higher in the dry season (November–March) than in the wet season (May–July) due to higher insolation and seasonal wind developments. A continuous increase in DTD could affect the health of the people in coastal Ghana.

Keywords Day-to-day temperature variability · Climate change · Temporal trends · Coastal Ghana

1 Introduction

Climate change and climate variability continue to be among the most discussed issues in the twenty-first century and have received significant research interest (Guo et al. 2021), especially the dire impacts that result from the day-to-day variability in parameters like temperature (Gough 2008; IPCC 2014). Day-to-day temperature variability thus reflects the events and reactions of humans and other species to a changing climate (Olson and Wallander 2002). Variability from one day to the next is normally caused by surface energy balance, atmospheric fluctuations, and local topography (Gough 2008; Szyga-Pluta 2021). Incoming shortwave radiation influences local temperature variations and resultant insolation (Hertwig et al. 2020). Variability in shortwave radiation is caused by seasonal movement of the Earth's rotational axis, and as reiterated by Gough (2008), this causes higher and lower insolation in summer and winter, respectively. In the Ghanaian setting, higher and lower insolation are thus observed in the dry and wet seasons, correspondingly (Tanu et al. 2021). Consequently, due to seasonal shifts, day-to-day variations in insolation through shortwave radiation are either absorbed or reflected by the Earth's atmosphere (Schwarz et al. 2020). Shortwave radiation is reflected back to space by the atmosphere's cloud cover and the Earth's surface (the Earth's albedo). Also,

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frontal storms or cyclone development have been identified as a major cause of day-to-day temperature variations, especially in the midlatitudes (Catto et al. 2019; Ferreira et al. 2013; Gough 2008). As underlined by Gough (2008), these storms contribute to day-to-day variability through various phases of cyclonic development involving warm and cold fronts. The occurrence of these storms can cause day-to-day temperature changes of more than 10 °C (Ahrens 2003). The topography of areas such as mountains can also cause changes in temperature (Gough 2008; Mohsin and Gough 2010).

Temperature change from one day to the next is essential for understanding the Earth's climate variability (Tam and Gough 2012). The day-to-day variability in temperature can affect agriculture (Wang et al. 2021; Craufurd and Wheeler 2009; Wheeler and Kay 2010), socio-economic development (Linsenmeier 2021), the ecosystem (Pendlebury et al. 2004), and, more importantly, human health (Noelke et al. 2016; Zhou et al. 2014; Zhang et al. 2017, 2018; Song and Yan 2022). Here, strong emphasis is attached to the negative health outcomes, considering the critical role of health in socio-economic development (Weil 2014). Significant research attention has been given to the effects of day-to-day temperature variability on human health (e.g., the effect on emotional well-being in the U.S.A. (Noelke et al. 2016), on mortality in China (Hu et al. 2019; Zhang et al. 2017; Zhou et al. 2014), in Vienna (Matzarakis et al. 2011), in Slovakia (Výberči et al. 2018), in England and Wales (Zhang et al. 2018), on cardiovascular and respiratory diseases in Dhaka, Bangladesh (Rahman et al. 2022), in China (Cao et al. 2009), in Japan (Onozuka and Hagihara 2017), and in Athens, Greece (Nastos and Matzarakis 2006). Variations in day-to-day temperature in extreme cases can thus increase health risks and cause more mortalities, especially for the elderly (Bi et al. 2022; Zhan et al. 2017; Zhou et al. 2020). More often than not, day-to-day temperature variability is followed by extreme weather events such as storms and winds, which can affect traffic situations and related risks in cities (Zhou et al. 2020). This, thus, warrants more research on day-to-day temperature variability and its associated impacts.

As emphasised by Gough (2008), many research studies conventionally use the standard deviation (SD) of daily values in a given month to evaluate day-to-day variability and determine the value and the mean deviation. The SD as a statistical measure has the assumption that a "normal" distribution exists in climate data and that the distribution peaks at the mean are balanced on both edges. The SD also assumes a random distribution in a given climate dataset (Gough 2008). Several questions have been raised about the use of SD as a measure of temperature variability, thereby giving rise to diverse definitions and developments. For instance, Karl et al. (1995), in their analysis of climate variability trends in China, Australia, the U.S.A., and the former Soviet Union, disregarded the SD and instead defined variability as the absolute difference observed between two adjacent discrete time periods. Again, Moberg et al. (2000) defined the absolute difference in temperature anomalies from one day to the next when they compared eight measures of day-to-day temperature variability in Europe. Moberg et al. (2000) indicated in their outcome that the intramonthly SD is a good measure of variability. Additionally, Collins et al. (2000) defined day-to-day variability as the mean inter-daily difference of maximum, minimum, and mean temperatures when they assessed trends in the annual frequencies of extreme temperature events in Australia. Walsh et al. (2005) further defined day-to-day temperature variability as the 1-day lag autocorrelation assessed using the deviations relative to the 31-day running mean temperatures of each year when they analysed the variability of daily temperatures in Alaska and Northern Canada. Gough (2008) followed the definition of Karl et al. (1995) and extended it to include the ratio (Day-to-Day (DTD/SD)) and termed the ratio "*G*." Gough (2008) applied this statistical measure to the cities of Toronto and Calgary, Canada. Gough grouped climates into random, orderly, and oscillatory or reactionary (see Gough 2008 for details). Gough affirmed that the SD as a statistical measure truly represents day-to-day variability when the climate is random (Gough 2008). Wu et al. (2017) and Tian et al. (2019) followed a similar definition of day-to-day variability expressed in terms of the absolute difference in maximum, minimum, and mean temperatures between two-adjacent day periods or two consecutive days. So, we can say that many studies improved upon the definition of Karl et al. (1995).

The aforementioned research studies clearly indicate the progression and development of appropriate statistical measures of day-to-day temperature variability. These developments are essential considering the continued increase in temperature and related impacts, especially those posed to human health. While the present study acknowledges the various statistical measures of day-to-day temperature variability, it adopts those of Gough (2008). The present study agrees with Gough's assertion that the climate could be orderly, oscillatory, or random (Gough 2008). Also, the Gough (2008) statistical measure has been widely applied in different settings, e.g., in Canada (Anderson et al. 2018; Tam and Gough 2012), in China (Gough and Hu 2016), and in North America (Tam et al. 2015). Following this, it is imperative to extend this statistical measure of day-to-day temperature variability to the Ghanaian setting (see Sect. 2.1 for the specific urban areas of application), where no study in this regard has been performed. The present study therefore assessed the day-to-day temperature variability in nine areas in coastal Ghana. Here, Gough's (2008) day-to-day temperature variability framework, which is an improvement on Karl et al. (1995) earlier framework, was used to examine the ratio of DTD to SD "*G*" values for daily maximum

and minimum temperatures; monthly changes in daily maximum and minimum temperatures; threshold exceedances of 2 °C and 4 °C; and temporal trends in daily maximum and minimum temperatures. This study contributes to the existing body of statistical models, such as Gough's (2008), that demonstrate the dynamics of temperature changes between consecutive days.

1.1 Temperature variability in coastal Ghana: a review of the literature

Ghana, like many land regions globally, is susceptible to the adverse impacts of rising temperatures. The World Bank (2010) employed a range of climate scenarios to project a trend of increasing temperatures across all regions of Ghana. The Ministry of Environment, Science, Technology, and Innovation (MESTI) in Ghana provided additional support for the development of a national climate change policy. Based on the findings of the MESTI, it was observed that the country experienced a temperature rise of about 1 °C from 1960 to 2000. Furthermore, future projections indicate a potential increase of approximately 1.7 °C to 2.0 °C (MESTI 2013). The potential consequences of rising temperatures pose a significant risk to the socio-economic development of the country (Asante and Amuakwa-Mensah 2015; Asare-Nuamah and Botchway 2019), particularly in coastal areas that are exposed to the effects of both land and ocean temperature variability (Amoako and Boamah 2015; Ankrah 2018).

The coastal areas of Ghana facilitate a variety of socio-economic activities, including fishing, agriculture, trade and commerce, transportation, leisure, and tourism. These activities play a significant role in improving the country's economy and enhancing the livelihood of its people (Akpalu et al. 2015; Boateng et al. 2018; Danquah et al. 2021). Nevertheless, the increasing temperatures along the coastal areas present an essential threat to the sustainability of the socio-economic activities mentioned above (Asante and Amuakwa-Mensah 2015; Boateng et al. 2020). The studies conducted by Abbam et al. (2018), Adu-Prah et al. (2019), Ankrah et al. (2023), Asare-Nuamah and Botchway (2019), Ayamga et al. (2021), Frimpong et al. (2022), Johnson (2020), and Williams et al. (2019) demonstrated the observed increase in temperature trends and the variability in the coastal areas of Ghana. Abbam et al. (2018) provided information regarding the significant increase in the mean annual temperature of 1.34 °C in the Greater Accra region during the decades from 1900 to 1909 and 2005 to 2014. Their study focused on identifying areas in Ghana that experience climate-related stress by analysing the spatial and temporal variations of rainfall and temperature. In their study, Adu-Prah et al. (2019) reported an increasing trend in both annual maximum (0.2 °C) and minimum (0.8 °C) temperatures in the Greater Accra region. Additionally, they found an increase in maximum (1.0 °C) and minimum (0.8 °C) temperatures in the Central region of Ghana (Adu-Prah et al. 2019). These findings were derived from a detailed analysis of spatiotemporal data, providing valuable insights into the climate variability of Ghana. Similarly, Johnson (2020) informed us about the increasing trends observed in both the maximum and minimum temperatures in coastal Winneba between the years 1980 and 2019. Furthermore, according to the findings of Williams et al. (2019), the Keta municipality experienced variations in its mean annual temperature ranging from 27.4 °C to 28.8 °C during the period from 1997 to 2016. Their study also revealed an increased trend in warming of 0.03 °C (Williams et al. 2019). Besides, Asare-Nuamah and Botchway (2019) reported an increased temperature in the coastal Savannah zone (i.e., the Central, Greater Accra, and Volta regions) when they assessed the characteristics and trends in temperature and rainfall across the agroecological zones of Ghana. In their analysis of annual and intra-annual climate variability and change in the Volta delta, Ayamga et al. (2021) discovered significant temporal increases in annual minimum, maximum, and mean temperatures at both coastal and inland delta stations. Furthermore, the study conducted by Frimpong et al. (2022) found an increase in the frequency of warm days and a general increase in the minimum temperature over the coastal areas of Accra. Also, Ankrah et al. (2023) observed a warming trend in both maximum and minimum temperatures within the coastal Savannah agro-ecological zone of Ghana. Their analysis focused on extreme temperature and rainfall events as well as future climate change projections (Ankrah et al. 2023).

The increased temperature trends and variability have adverse effects on both socio-economic factors and ecosystems in the coastal areas of Ghana. Several studies, such as those of Akpalu et al. (2015), Amekudzi et al. (2014), Atindana et al. (2020), Klutse et al. (2014), Owusu-Sekyere et al. (2011), and Williams et al. (2019), have been undertaken. According to Owusu-Sekyere et al. (2011), there was a decrease in crop yields in the Cape Coast metropolitan area from 1993 to 2008. This decrease was attributed to the gradual variations in climate parameters, such as temperature (Owusu-Sekyere et al. 2011). A study conducted by Amekudzi et al. (2014) provided insights into the prevalence of malaria in coastal cities in Ghana, attributing it to climate-related factors such as increasing temperatures and flooding. Similarly, in their study of climate variables and malaria caseloads in two ecological zones of Ghana, Klutse et al. (2014) discovered a stronger correlation between malaria caseloads and maximum temperature at a two-month lag in coastal Winneba. Again, Akpalu et al. (2015) stressed that the increasing temperature variability in coastal Ghana is decreasing the environmental carrying capacity of fish

stocks. Furthermore, Williams et al. (2019) highlighted the impacts of increasing temperatures on the activities of smallholder horticultural farmers in the Keta municipality. Also, Atindana et al. (2020) revealed the impact of climate variability, evidenced through increasing temperatures, on oyster harvest among coastal-dependent fishing communities in Ghana.

Urbanisation and related changes in land use and land cover have been identified as essential factors that impact temperature variability in the coastal areas of Ghana. Several studies, such as those of Addae and Oppelt (2019), Adua and Baffoe (2013), Asabere et al. (2020), Biney and Boakye (2021), Buo et al. (2021), Kumi-Boateng et al. (2015), Mariwah et al. (2017), Mattah et al. (2018), and Mensah et al. (2019), have been conducted to examine the effects of urbanisation and changes in land use and land cover on urban surface temperatures. The expansion of built-up areas is identified as the main catalyst for urbanisation and changes in land use and land cover, as demonstrated in the aforementioned studies. The expansion identified is attributed to the conversion of marshes, water bodies, vegetation, and forests for the purposes of residential, commercial, and industrial development. This trend is particularly noticeable in metropolitan areas located along the coast, including Tema, Accra, and Takoradi (Addae and Oppelt 2019; Adua and Baffoe 2013; Asabere et al. 2020; Biney and Boakye 2021; Buo et al. 2021; Kumi-Boateng et al. 2015; Mariwah et al. 2017; Mensah et al. 2019). Adua and Baffoe (2013) emphasised an increase in temperatures observed in the city of Sekondi-Takoradi, attributing this phenomenon to changes in land use and land cover as well as urban expansion. Similarly, Kumi-Boateng et al. (2015) reported an increase in surface radiant temperature of 4.3 °C in the Sekondi-Takoradi metropolitan area due to increased urban development. The researchers went on to state that urbanisation affects the monthly and seasonal average temperature changes of the area Kumi-Boateng et al. (2015). Again, Mariwah et al. (2017) discovered that between 1990 and 2010, built-up areas increased greatly to become the most common land cover type in the Tema metropolitan area, which reduced the vegetative cover considerably. The decreased vegetative cover and the increased built-up areas could affect the temperature variations in the metropolis. According to Biney and Boakye (2021), there was a notable 25.93% increase in settlement, accompanied by a decrease of 0.08% in water, 16.0% in vegetation, and 9.86% in bare land in the Sekondi-Takoradi metropolitan area. The researchers went further to state that between 1991 and 2018, the metropolis experienced urban sprawl, resulting in changes to the land cover stratum (Biney and Boakye 2021). This finding supports the previous studies conducted by Adua and Baffoe (2013) and Kumi-Boateng et al. (2015), which reported increased temperature variability in the area. According to the findings of Bou et al. (2021), there is evidence of an increased intensity of urban heat islands in the city of Accra. This phenomenon can be attributed to the expansion of built-up areas within the city, coupled with the presence of bare lands and limited vegetation. These factors collectively contribute to an increase in surface temperatures in the urban environment.

The increased temperature variability due to rapid urbanisation and related changes in land use and land cover create several socio-economic and environmental challenges in coastal Ghana. For instance, in a study undertaken by Mattah et al. (2018), it was revealed that increased urbanisation and a decrease in vegetative cover and land-use patterns in the metropolitan areas of Accra and Sekondi-Takoradi have led to a rise in mosquito populations and environmental degradation. The changing land-use patterns and a decrease in vegetation cover have considerable impacts on the large water bodies located along the coast of Ghana, such as the Odaw River, Keta Lagoon, Pra River, Ankobra River, and Volta River, which disrupt their ability to reduce nighttime cooling effects (Ackom et al. 2020; Awotwi et al. 2019; Duku et al. 2021; Kutir et al. 2022). The rapid urbanisation and changes in land use and land cover in coastal Ghana thus reflect the link between day-to-day temperature variability and climate change and related impacts on food security and livelihoods (Akpalu et al. 2015; Atindana et al. 2020; Owusu-Sekyere et al. 2011), diseases (Amekudzi et al. 2014; Klutse et al. 2014; Williams et al. 2019), and the functioning of hydrological systems (Ackom et al. 2020; Awotwi et al. 2019; Duku et al. 2021; Kutir et al. 2022) along coastal Ghana.

The adverse impacts of day-to-day temperature variability and climate change in coastal Ghana are further exacerbated by urbanisation and related changes in land use and land cover. Nevertheless, it is worth noting that the studies reviewed in this analysis focused mainly on examining temperature variability based on monthly and annual averages while neglecting the examination of daily averages. The effects of day-to-day temperature variations have been observed to have substantial consequences in many areas, including agriculture (Wang et al. 2021; Wheeler and Kay 2010), socio-economic development (Linsenmeier 2021), ecosystem dynamics (Pendlebury et al. 2004), and human health (Zhang et al. 2018; Zhou et al. 2020). Elsewhere, previous studies have demonstrated the existence of day-to-day temperature variability and the related effects of urbanisation in various metropolitan areas, such as Canada (Anderson et al. 2018; Tam and Gough 2012), China (Gough and Hu 2016), and North America (Tam et al. 2015). The extension of such analysis to the Ghanaian setting, where a study of this nature has not been undertaken, is essential. The choice of coastal Ghana as the study area was influenced by the

presence of numerous metropolitan areas and the increased level of economic activity in the area.

2 Materials and method

2.1 Study area

Ghana is in West Africa, with latitudes of 4° 44′ N and 11° 11′ N and longitudes of 3° 11′ W and 1° 11′ E (Asare-Nuamah and Botchway 2019). Ghana has a tropical climate with both dry and wet seasons, which is strongly influenced by the West African Monsoon (WAM) and the Inter Tropical Discontinuity (ITD) (Addi et al. 2021). The coast of Ghana is divided into three sections: western, central, and eastern. In terms of climate and vegetation characteristics, the western portion is termed as rain forest (wet equatorial) and is considered the wettest zone in Ghana, while the central and eastern portions are termed as coastal savannah (dry equatorial) and are seen as the driest region in Ghana (Addi et al. 2021; Bessah et al. 2022; Dickson and Benneh 2001). Here, nine urban areas were selected from the central and eastern portions. The study was conducted in nine urban areas in coastal Ghana from three administrative regions, namely the central, Greater Accra, and Volta regions. These regions fall under the Coastal Savannah agroecological zone (CSAZ) of Ghana. The nine urban areas studied were Accra, Cape Coast, Elmina, Saltpond, Ada Foah, Keta, Tema New Town, Apam, and Denu (Fig. 1 shows the study locations). Table 1 shows the specific coordinates and locations of the study locations.

2.2 Data and quality control

The study used daily maximum (T_{max}) and minimum (T_{min}) temperatures (period from 1981–2021) obtained from the Ghana Meteorological Agency (GMet) and the National Aeronautics and Space Administration/Prediction of Worldwide Energy Resources (NASA/POWER) (https://power.larc.nasa.gov/). The study also used ERA5 hourly data on single levels from 1940 to present, acquired from the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF)

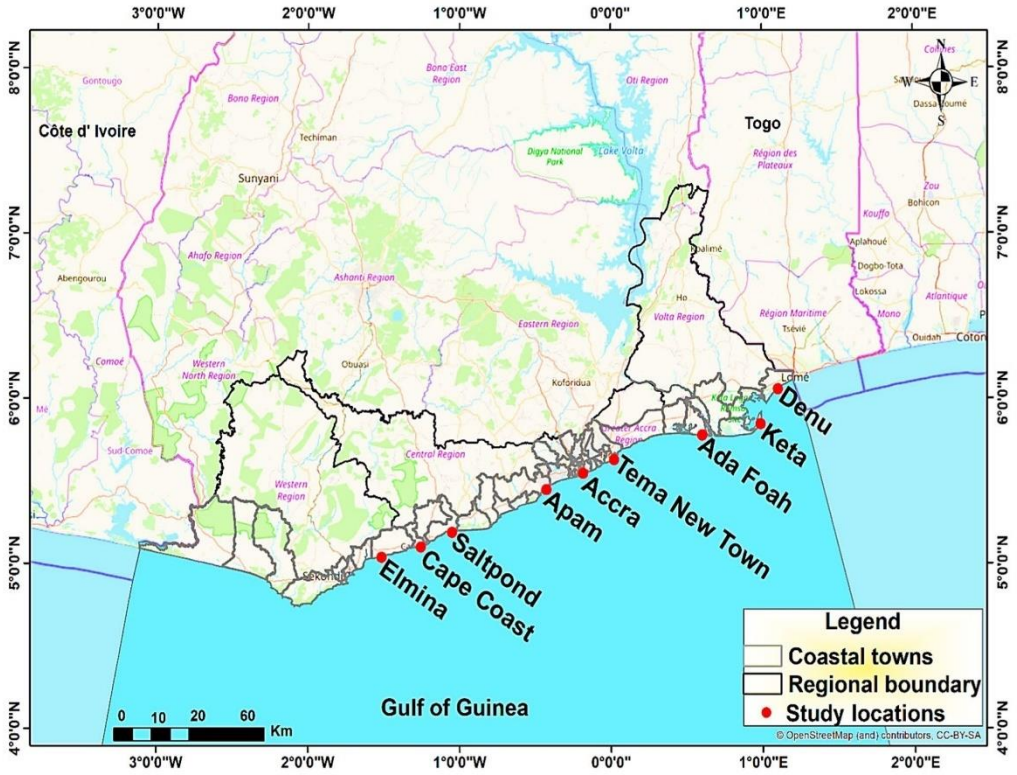


Fig. 1 Map showing the study locations

Table 1 Coordinates and population of the study locations. Note: Population is based on the 2021 Census

Location	Latitude	Longitude	Population
Accra	5° 60′ N	0° 18′ W	284,124
Ada Foah	5° 46′ N	0° 37′ E	76,411
Cape Coast	5° 06′ N	1° 15′ W	189, 925
Elmina	5° 05′ N	1° 20′ W	166,017
Saltpond	5° 20′ N	1° 05′ W	168,905
Apam	5° 17′ N	0° 44′ W	129,512
Keta	5° 45′ N	0° 30′ E	78,862
Denu	6° 03′ N	1° 11′ E	253,122
Tema New Town	5° 39′ N	0° 01′ E	177,924

***Source*:** Ghana Statistical Service (2021)

reanalysis (ERA5) (Hersbach et al. 2023). This dataset was employed to validate the GMet and NASA/POWER datasets.

The GMet is the official agency for climate data provision in Ghana. It was established in 1937 after the Second World War and was formally handed over to the Communication Ministry of Ghana in 1957. Currently, the GMet has 22 synoptic stations with approximately 310 meteorological stations operating every 24 h and reporting measurements of temperature, rainfall, humidity, and winds, among others (https://www.meteo.gov.gh/gmet/achievements-milestones/). The NASA/POWER data set provides global weather and climatological data at 1° latitude and longitude (Monteiro et al. 2018; White et al. 2008). Several research studies have employed the NASA/POWER satellite data and indicated its suitability and reliability (e.g., in Brazil (Monteiro et al. 2018), in Africa (Van Wart et al. 2015), in North America (Mourtzinis et al. 2017), in Europe (Van Wart et al. 2013), in Asia (Bai et al. 2010), and in Oman (Marzouk 2021), especially for filling missing data gaps in data scarce regions such as the developing countries (Monteiro et al. 2018). The GMet provided daily data for Accra (Station code: 23016ACC), Cape Coast (23048CAP), Ada-Foah (23002ADA), Apam (23061APA), Elmina (23024ELE), Saltpond (23022SAL), and Keta (23015KET), while the NASA/POWER satellite database provided data for Denu and Tema New Town.

The daily T_{max} and T_{min} obtained from the GMet were subjected to a quality control check in R-Instat (version 0.70) (http://r-instat.org/About.html) to check the percentage of missing values. In this analysis, the percentage of missing values in each dataset was less than 2%. Following the suggestion of Monteiro et al. (2018), the study used the NASA/POWER data to fill in the missing values. This made the dataset full.

2.3 Climatic variable performance analysis at the study locations

Although it is generally advised to use reanalysis datasets to address missing data gaps, particularly in data-scarce regions (Monteiro et al. 2018), it is important to validate these datasets given their coarser spatial resolution. It is strongly recommended to validate these datasets against observed datasets, especially in coastal regions, as the presence of oceanic air masses has a significant impact (Ngoungue Langue et al. 2023). The ERA5 reanalysis dataset was used for the purpose of validating the NASA/POWER and station datasets. The ERA5 dataset demonstrates a greater representation of spatial variability in both T_{max} and T_{min} compared to the NASA/POWER dataset, as indicated in Online Resource 1. The ERA5 reanalysis grid boxes covered a larger extent of the study location than the NASA/POWER dataset, which suggests that the ERA5 reanalysis data has better spatial resolution.

The analysis of correlation between the station and reanalysis datasets in Table 2 demonstrated a very low strength of positive and negative correlations observed among the various study locations. However, a high positive correlation was identified between the ERA5 and the NASA/POWER reanalysis datasets at various locations. This observation indicates a strong correlation between the NASA/POWER data and ERA5 grid points, despite the disparity in their spatial resolutions. The graphical representations depicting the correlation analysis between the

Table 2 Correlation analysis between stations, ERA5 reanalysis, and NASA/POWER datasets

Location	Variable	Correlation	
		T_{max}	T_{min}
Accra	Station and NASA/POWER	0.35	−0.24
Ada Foah	Station and ERA5	−0.22	−0.14
	Station and NASA/POWER	−0.01	−0.16
	ERA5 and NASA/POWER	0.63	0.81
Cape Coast	Station and NASA/POWER	−0.26	−0.08
Elmina	Station and NASA/POWER	−0.26	−0.08
Saltpond	Station and ERA5	0.26	0.09
	Station and NASA/POWER	0.21	0.16
	ERA5 and NASA/POWER	0.82	0.85
Apam	Station and ERA5	0.00	0.10
	Station and NASA/POWER	0.01	0.09
	ERA5 and NASA/POWER	0.68	0.82
Keta	Station and ERA5	0.11	0.39
	Station and NASA/POWER	0.14	0.53
	ERA5 and NASA/POWER	0.86	0.78
Denu	ERA5 and NASA/POWER	0.86	0.80
Tema New Town	ERA5 and NASA/POWER	0.86	0.75

station data and the two reanalysis datasets can be found in Online Resource 2.

2.4 Statistical computations

As already mentioned, this study adopted Gough's (2008) statistical measure of day-to-day variability, which followed and expanded those defined by Karl et al. (1995). Following this, the study computed the SD, the ratio of DTD to SD (*G*), the day-to-day variability (DTD), the change that occurs in the DTD (ΔDTD), which was applied in the earlier work of Tam and Gough (2012) and formally introduced in Tam et al. (2015), and the threshold exceedances.

The SD, as indicated by Gough (2008), can be computed as:

$$\mathrm{SD} = \left[\sum \left(T - T_{avg}\right)^2/(N-1)\right]^{1/2} \quad (1)$$

where:

N shows the number of data components; *T* is temperature; T_{avg} reflects the monthly mean temperature; and ∑ indicates the sum of *N*.

The DTD can also be calculated as:

$$\mathrm{DTD} = \sum_i \left|T - T_{i-1}\right|/(N-1) \quad (2)$$

where:

N shows the number of days in a given month, | | indicates the absolute value, *T* represents either the daily maximum (T_{max}) or minimum (T_{min}) temperature, *i* reflects the counting in days of a given month, and ∑ is the summation of all the *N* data values.

The *G* is defined as the following ratio:

$$G = \mathrm{DTD}/\mathrm{SD} \quad (3)$$

According to the research conducted by Gough (2008) and further supported by Tam and Gough (2012), the *G* can be categorised into three distinct types: orderly, oscillatory/reactionary, and random, as outlined in Table 3. The *G* was computed for the individual months, and the values were averaged for the entire period of analysis.

The study further computed the ΔDTD following Tam et al. (2015) as:

$$\Delta\mathrm{DTD} = \mathrm{DTD}_{Tmax} - \mathrm{DTD}_{Tmin} \quad (4)$$

where:

Δ is change, *DTD* shows day-to-day variability, T_{max} is maximum temperature, and T_{min} is minimum temperature. As underlined by Tam et al. (2015), a positive change shows larger variability in the day, and a negative change indicates larger variability in the night.

The threshold exceedances were computed by counting the frequencies of change in temperature from one day to the next, exceeding a particular limit within a given month (Gough 2008). A threshold exceedance of 2 °C and 4 °C was used in this study.

The study applied a linear regression statistic to the ΔDTD, the 2 °C threshold exceedances, and the time series analyses in the DTD. The linear regression test fits a straight line in the form ($y = a + bx$) *to a* data series and determines the slope, which may be significantly different from zero or not. The test statistic (*t*) as utilized in the study of Jaiswal et al. (2015) is calculated as:

$$a = \bar{y} - b\bar{x} \quad (5)$$

$$b = \frac{\sum \left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sum \left(x_i - \bar{x}\right)^2} \quad (6)$$

$$\sum \varepsilon^2 = \sum \left(y_i - \bar{y}\right)^2 - b \sum \left(x_i - \bar{x}\right)^2 \quad (7)$$

$$S_b = \frac{\varepsilon_i^2}{(n-2)\sum \left(x_i - \bar{x}\right)^2} \quad (8)$$

$$t = \frac{b}{S_b} \quad (9)$$

where *a* is the intercept and *b* is the slope of fitted the line, $\sum \varepsilon^2$ is the sum of squares of residuals or errors, and S_b is the standard error of *b*.

Table 3 G value, climate type, and meaning according to Gough (2008) and Tam and Gough (2012)

G value	Climate type	Description
$G < 1$	Orderly	Overestimation of variability by the SD
$G > 1$	Oscillatory/reactionary	Underestimation of variability by the SD
$G \sim 1$	Random	SD reveals similar estimations to those of the DTD

3 Results

3.1 G values for daily maximum (GT_{max}) and minimum (GT_{min}) temperatures

Figures 2a–i show the monthly averages of $G\ T_{max}$ and $G\ T_{min}$ values for Accra, Ada Foah, Apam, Cape Coast, Denu, Elmina, Keta, Saltpond, and Tema New Town (study locations). G values for all study locations range between 0.2 and 0.4, indicating an orderly climate ($G < 1$) and data clustering. From Figs. 2a–i, a greater degree of changeability can be seen in $G\ T_{max}$ throughout the years for the study locations. Among the study locations, the maximum monthly average $G\ T_{max}$ value of 0.5 °C occurred in Ada Foah (Fig. 2b) in March and Apam (Fig. 2c) in March and April, while the minimum $G\ T_{max}$ value of 0.2 °C was recorded in the other locations. A smaller degree of changeability is observed in the $G\ T_{min}$ values. The highest monthly average $G\ T_{min}$ value of 0.4 °C was observed in Ada Foah and Apam, and the lowest (0.1 °C) was recorded in the other locations.

3.2 Monthly averages of ΔDTD

Figures 3a–i and 3j–r show the monthly averages of DTD T_{max}, DTD T_{min}, and the ΔDTD for the study locations, respectively. Table 4 shows the linear regression analysis

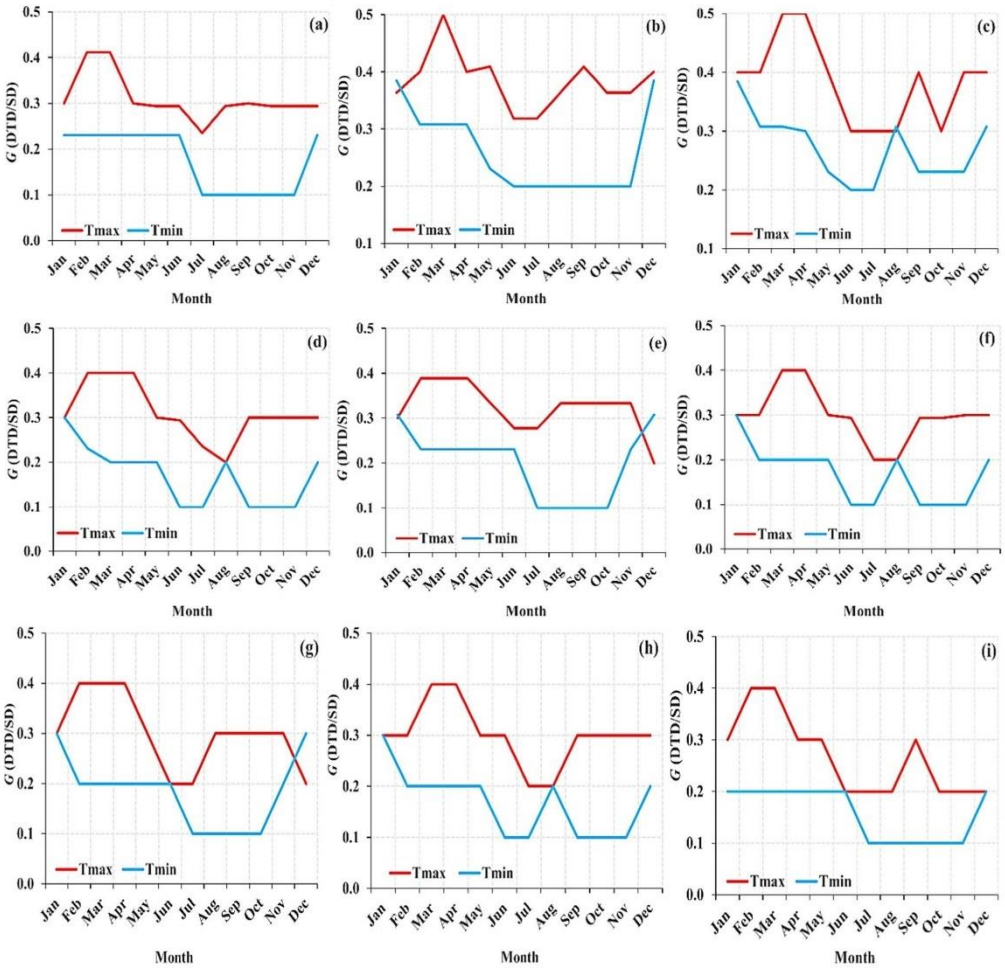


Fig. 2 Average monthly G (DTD/SD) for DTD T_{max} and DTD T_{min} of Accra (**a**), Ada Foah (**b**), Apam (**c**), Cape Coast (**d**), Denu (**e**), Elmina (**f**), Keta (**g**), Saltpond (**h**), and Tema New Town (**i**) from 1981–2021

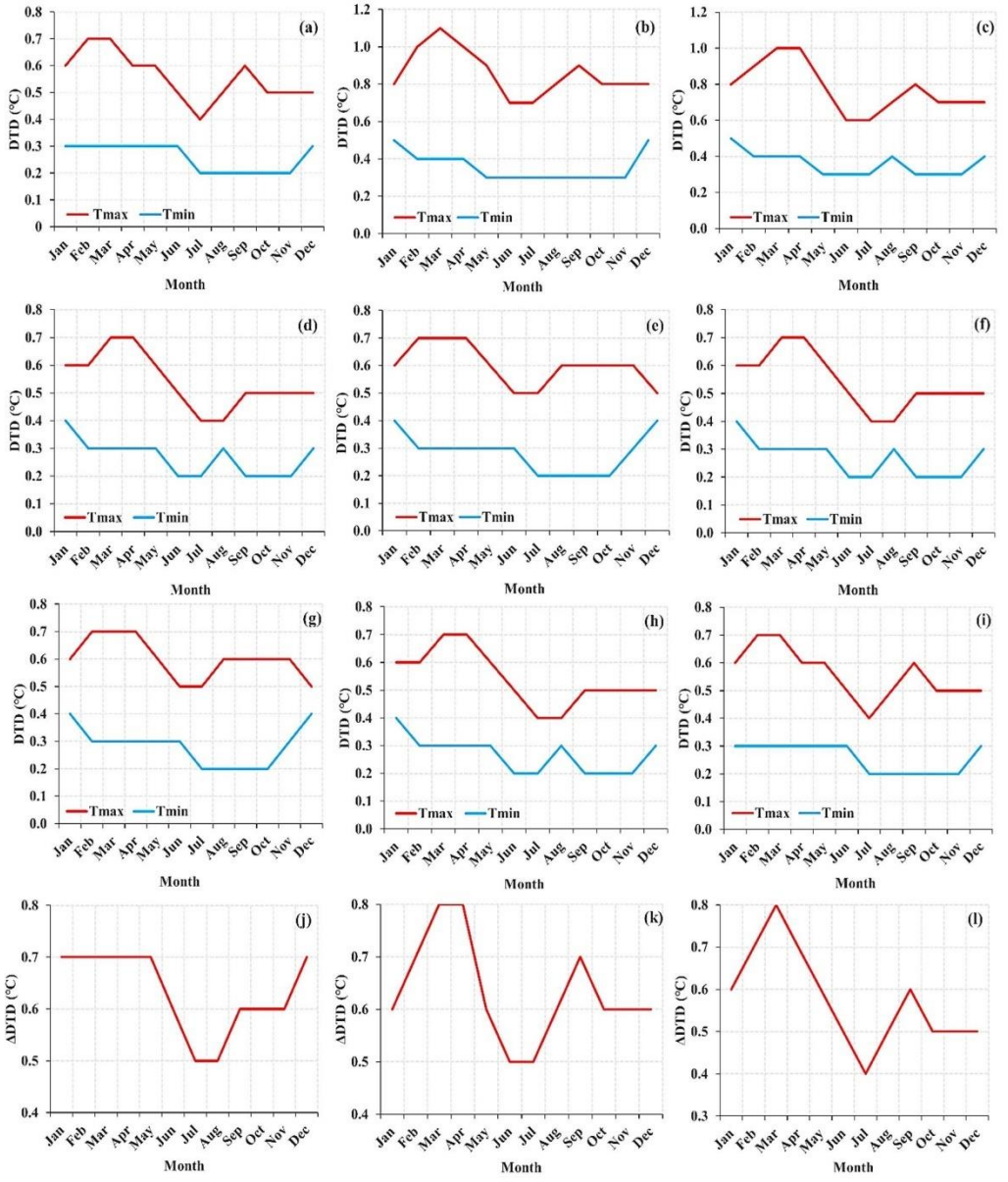


Fig. 3 Monthly averages of DTD T_{max}, DTD T_{min}, and ΔDTD for Accra **(a, j)**, Ada Foah **(b, k)**, Apam **(c, l)**, Cape Coast **(d, m)**, Denu **(e, n)**, Elmina **(f, o)**, Keta **(g, p)**, Saltpond **(h, q)**, and Tema New Town **(I, r)** from 1981–2021

of the monthly averages of ΔDTD. Generally, the monthly average DTD T_{max} is greater than the DTD T_{min} (Fig. 3a–i), for all the study locations. A clear seasonal pattern reflecting higher values in the dry season and lower values in the wet season is observed in both the monthly averages, DTD T_{max} and DTD T_{min} (Fig. 3a–i) for all the study locations. Among the study locations, the monthly average maximum DTD T_{max} (1.1 °C) occurred in Ada Foah (Fig. 3b), and a minimum monthly average DTD T_{max} (0.4 °C) was recorded in all locations except Ada Foah, Apam (Fig. 3c), Denu (Fig. 3e), and Keta (Fig. 3g). Ada Foah and Apam had the highest monthly average DTD T_{min} value of 0.5 °C,

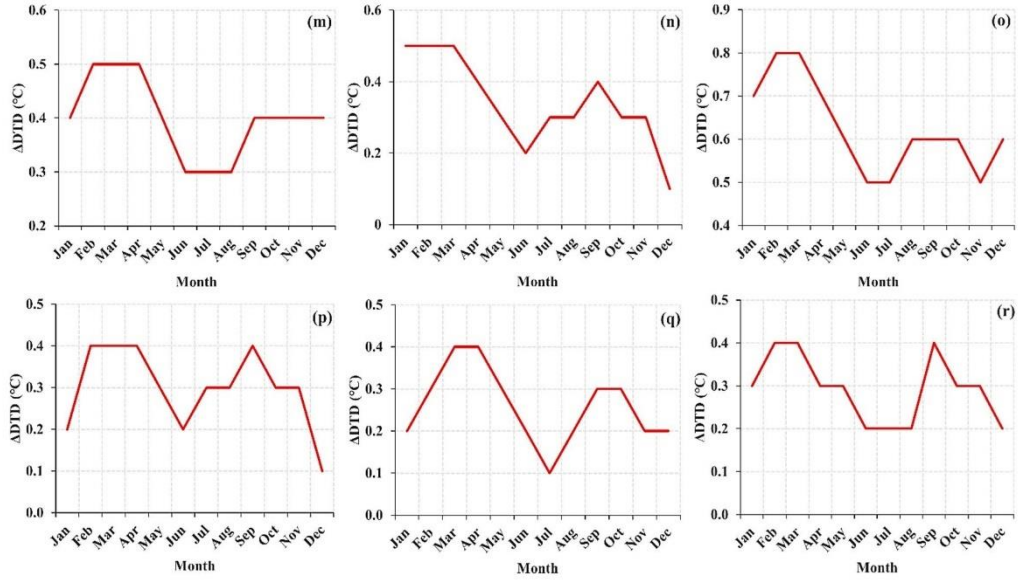


Fig. 3 (continued)

Table 4 Linear regression analysis for monthly averages of ΔDTD. Note: * shows significance at 0.05

Locations	Slope coefficient	*p*-value
Accra	−0.0097	0.14
Ada Foah	−0.0097	0.25
Tema New Town	−0.0087	0.20
Elmina	−0.0199	0.01*
Cape Coast	−0.0083	0.19
Saltpond	−0.0087	0.26
Apam	−0.0206	0.02*
Keta	−0.0090	0.27
Denu	−0.0262	0.00*

while the other locations had the lowest monthly average DTD T_{min} value of 0.2 °C.

Generally, it can be observed in Figs. 3j–r that the monthly averages ΔDTD are greater for the dry season (November–March) than the wet season (May–August) for all the study locations except for Denu (Fig. 3n) and Keta (Fig. 3p), where the ΔDTD in December (part of the dry season) for both locations was smaller than in the wet season. For Accra (Fig. 3j), monthly averages ΔDTD reach their highest in December–May and their lowest in July and August. For Ada Foah (Fig. 3k), the highest and lowest ΔDTD occur in March and April and June and July, respectively. A similar trend occurs in Apam (Fig. 3l), where the greatest monthly averages ΔDTD appeared in March and the least in July. In Cape Coast, the DTD monthly averages (Fig. 3m) are highest in February–April and lowest in July and August. For Denu (Fig. 3n), monthly averages ΔDTD are higher in the months of January–March and lower in December. Likewise, Elmina's DTD monthly averages are highest in February and March and lowest in June, July, and November (Fig. 3o). Keta (Fig. 3p) has maximum monthly averages ΔDTD in February–April and a minimum in December. The highest and lowest monthly averages ΔDTD are observed in the months of March, April, and July, correspondingly for Saltpond (Fig. 3q). For Tema New Town (Fig. 3r), the highest monthly averages ΔDTD occur in February, March, and September, and the lowest in June–August and December.

Comparing the study locations, it can be seen that the greatest monthly average ΔDTD (0.8 °C) occurred in Ada Foah in March and April, Apam in March, and Elmina in February and March, while the lowest (0.1 °C) was observed in Denu and Keta in December, and Saltpond in July. Table 4 shows that the monthly averages of ΔDTD decreased significantly in Apam, Denu, and Elmina but not in Accra, Ada Foah, Cape Coast, Saltpond, or Tema New Town, using regression and an alpha level of 0.05.

3.3 Threshold exceedances by 2 °C and 4 °C

The threshold exceedances by 2 °C in DTD T_{max} and T_{min} are shown in Figs. 4a–i and j–r, respectively, and the 4 °C is depicted in Figs. 4 s-za, while Table 5 shows the linear

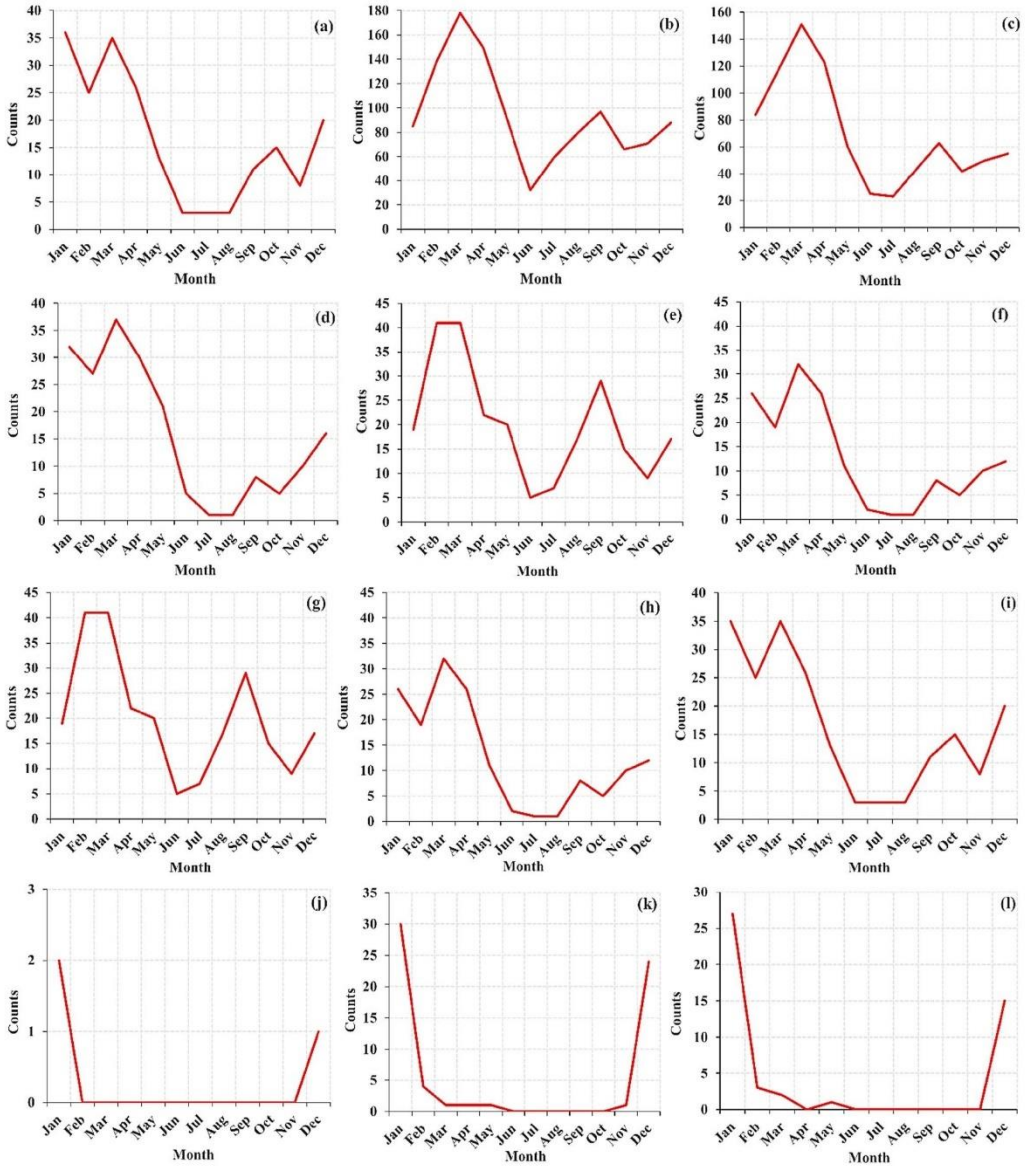


Fig. 4 2 °C threshold exceedances for DTD T_{max} and DTD T_{min}, and 4 °C thresholds for DTD T_{max} for Accra **(a, j, s)**, Ada Foah **(b, k, t)**, Apam **(c, l, u)**, Cape Coast **(d, m, v)**, Denu **(e, n, w)**, Elmina **(f, o, x)**, Keta **(g, p, y)**, Saltpond **(h, q, z)**, and Tema New Town **(I, r, za)** from 1981–2021

regression analysis. Throughout the year, Ada Foah has the highest 2 °C DTD T_{max} (Fig. 4b) and T_{min} (Fig. 4 k), except in January, when Keta has the highest DTD T_{min} (Fig. 4p). In Figs. 4a–i, all locations have their highest monthly DTD T_{max} variation occurring in March except Accra (Fig. 4a), where the highest appeared in February, and a tie in February and March for Denu (Fig. 4e) and Keta (Fig. 4 g). This is different from Figs. 4j–r, where the highest 2 °C exceedances in DTD T_{min} variation occurred in January for all the locations. A similar trend is observed in Figs. 4s–za. Here, the 4 °C threshold exceedances in DTD T_{max} variation were greatest in Ada Foah (Fig. 4t) compared to the other locations, and all the highest monthly DTD T_{max} occurred in March. The 4 °C threshold exceedances in DTD T_{min}

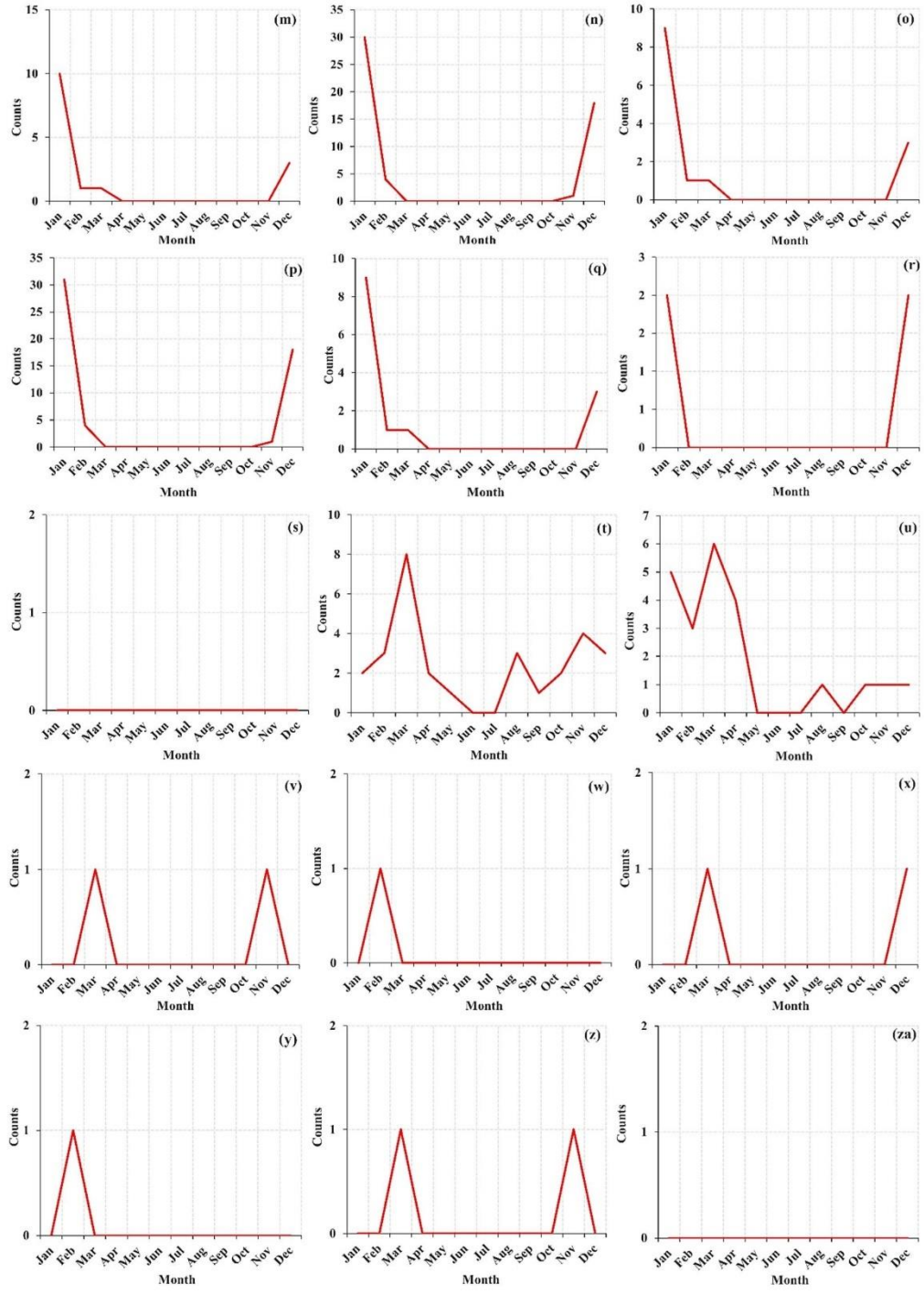


Fig. 4 (continued)

variation (not shown on the graph) appeared only in Cape Coast (count: 1 in January), with no variation (count: 0) for the other locations. From Table 5, it can be seen that the 2 °C threshold exceedances for DTD T_{max} declined significantly in most locations, such as Accra, Apam, Cape Coast, Elmina, Saltpond, and Tema New Town, but not in Ada Foah, Denu, or Keta. However, there was no sign of a significant decline in the 2 °C threshold exceedances for DTD T_{min} at any of the study sites.

3.4 Temporal trends in DTD Temperature

Figures 5a–i show the temporal trends of the annual averages of DTD T_{max} and DTD T_{min} for the study locations, while Table 6 shows the linear regression analysis. The

Table 5 Linear regression analysis for threshold exceedances by 2 °C and 4 °C in DTD T_{max} and T_{min} Note: * shows significance at 0.05

Locations	2 ℃ DTD T_{max}		2 ℃ DTD T_{min}	
	Slope coefficient	p-value	Slope coefficient	p-value
Accra	−2.007	0.04*	−0.0385	0.49
Ada Foah	−5.6748	0.10	−0.3776	0.68
Tema New Town	−1.9685	0.04*	0.3333	1.0
Elmina	−1.9056	0.02*	−0.2867	0.20
Cape Coast	−2.542	0.00*	−0.3252	0.19
Saltpond	−1.9056	0.02*	−0.2867	0.20
Apam	−7.1364	0.03*	−0.6154	0.41
Keta	−1.6224	0.10	−0.5944	0.49
Denu	−1.6224	0.10	−0.5559	0.51

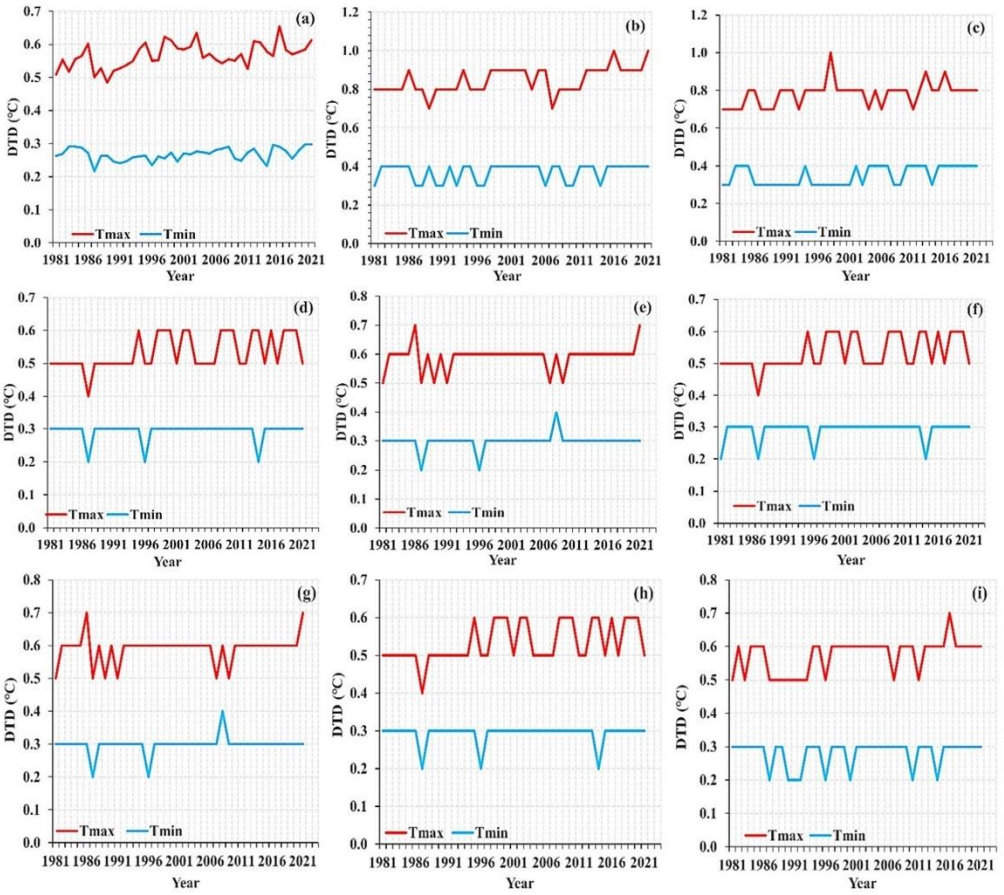


Fig. 5 Time series of DTD T_{max} and DTD T_{min} of Accra (**a**), Ada Foah (**b**), Apam (**c**), Cape Coast (**d**), Denu (**e**), Elmina (**f**), Keta (**g**), Saltpond (**h**), and Tema New Town (**i**) from 1981–2021

highest annual average DTD T_{max} (1.0 °C) was recorded in Ada Foah (Fig. 5b) in 2016 and 2021 and in Apam (Fig. 5c) in 1998, while the lowest (0.4 °C) was recorded in Cape Coast (Fig. 5d), Elmina (Fig. 5f), and Saltpond (Fig. 5h) in 1987. The annual average changeability resulting from the DTD T_{max} is highest in Ada Foah and Apam compared to the other locations. A similar trend is observed in the annual averages of DTD T_{min}. The highest (0.4 °C) annual averages of DTD T_{min} appeared in Ada Foah (Fig. 5b) and Apam (Fig. 5c) in most of the years and Keta (Fig. 5g) in 2008, whereas the lowest (0.2 °C) was recorded in all the study locations, excluding Ada Foah and Apam. From Table 6, the annual average DTD T_{max} significantly increased for Accra, Ada Foah, Apam, Cape Coast, Elmina, Saltpond, and Tema New Town, except Denu and Keta. A dissimilar trend was observed for the annual averages of DTD T_{min}. Here, the annual average of DTD T_{min} significantly increased for only Apam.

4 Discussion

The study assessed the DTD in nine areas (Accra, Ada Foah, Apam, Cape Coast, Denu, Elmina, Keta, Saltpond, and Tema New Town) located along the coast of Ghana. The study was conducted using the day-to-day variability framework developed by Gough (2008) and Tam et al. (2015). Using the framework, the study found the G value to be less than 1 throughout the year in the nine urban areas, indicating an orderly climate. The G value revealed a greater degree of changeability in T_{max} and was highest in Ada Foah and Apam. Although in a different climatic location, this finding is consistent with those of Gough (2008), who first applied the framework to the cities of Toronto and Calgary, Canada, and Tam and Gough (2012) in their study on past temperature variability in three locations in Canada. The G T_{min} showed less changeability than the T_{max}, especially in the wet season, and this could be linked to the humidity relief effect of the tropical Atlantic Ocean (Gulf of Guinea) and other large inland waterbodies in the area. High relative humidity increases the possibility of T_{min} (night temperature) condensing, which can result in the formation of dew. The process reduces nighttime temperatures and affects diurnal temperature extremes, which decreases the likelihood of temperature variation from one day to the next (Gough 2008). Cui et al. (2021) assert that the urban lakes located near the city centre can weaken the nighttime cooling effects due to increased humidity. The impact of urbanisation and changes in land use and land cover on urban surface temperatures has been observed to be significant in the metropolitan area of Atlanta, U.S.A. (Fu and Weng (2016), in Delhi, India (Mohan and Kandya 2015), in the western coastal cities of India (Desai and Dhorde 2018), and in Odisha State, India (Gogoi et al. (2019). Several studies have highlighted the impact of urbanisation and related changes in land use and land cover on urban surface temperatures in Ghana's coastal and inland metropolitan areas. For example, in Accra (Addae and Oppelt 2019; Asabere et al. 2020; Buo et al. 2021), Tema (Mariwah et al. 2017), Takoradi (Adua and Baffoe (2013): Biney and Boakye 2021; Kumi-Boateng et al. 2015; Mensah et al. 2019), Kumasi (Asori and Adu 2023; Mensah et al. 2020), and Tarkwa (Kusimi 2008). According to the findings of Bou et al. (2021), there is evidence of an increased intensity of urban heat islands in the cities of Accra and Kumasi. This phenomenon can be attributed to the expansion of built-up areas within these cities as well as the existence of bare lands and limited vegetation, which contribute to increased surface temperatures. Adua and Baffoe (2013) emphasised the increased temperatures observed in the city of Sekondi-Takoradi, attributing them to changes in land use and land cover as well as urban expansion. The presence of large water bodies like the Odaw River, Keta Lagoon, Pra River, Ankobra River, and Volta River enhances the reduction of nighttime cooling effects in Accra, Keta, and the entire coastal region of Ghana. These bodies of water contribute to the improvement of humidity levels, thereby providing relief during the night (Ackom et al. 2020; Duku et al. 2021; Kutir et al. 2022). However, the ability of these water bodies to reduce nighttime cooling effects has been reduced due to the effects of rapid urbanisation and changes in land use and land cover (Ackom et al. 2020; Awotwi et al. 2019; Duku et al. 2021; Kutir et al. 2022).The seasonal pattern in DTD T_{max}, T_{min}, and ΔDTD was higher in the dry season (November–March) than in the wet season (May–July). This may be due to the high solar radiation and greater insolation observed during the dry season in Ghana. Tanu et al. (2021), in their earlier study on the evaluation of global solar radiation, cloudiness

Table 6 Linear regression analysis for annual averages of in DTD T_{max} and T_{min}. Note: * shows significance at 0.05

Locations	DTD T_{max}		DTD T_{min}	
	Slope coefficient	*p*-value	Slope coefficient	*p*-value
Accra	0.0015	0.00*	0.0005	0.07
Ada Foah	0.0031	0.00*	0.0009	0.15
Tema New Town	0.0021	0.00*	0.0005	0.36
Elmina	0.0021	0.00*	0.0005	0.26
Cape Coast	0.0021	0.00*	0.0001	0.77
Saltpond	0.0021	0.00*	0.0001	0.77
Apam	0.0022	0.00*	0.0021	0.00*
Keta	0.0008	0.16	0.0005	0.21
Denu	0.0008	0.16	0.0005	0.21

index, and sky view factor as potential indicators of Ghana's solar energy resource, stressed the increased insolation in the dry season in Ghana. The higher dry season variation could also be associated with the influence of the seasonal wind development (the north-east trade or the harmattan), which originates from the Sahara desert and becomes superior to the south-westerly moist winds from the Atlantic, resulting in no rainfall but higher temperatures, especially during the day. From the results, the ΔDTDshowed positive values for the locations. This finding is in line with the results from Tam et al. (2015), who reported positive ΔDTD values for the urban pair stations in North America. The 2 °C and 4 °C threshold exceedances in DTD T_{max} and T_{min} were distorted, with higher threshold exceedances occurring in the dry season than in the wet season. Again, this could be attributed to the solar radiation (high insolation) during the dry season and the humidity mitigation effect of the Gulf of Guinea and other large inland water bodies such as the Odaw River, Keta Lagoon, Pra River, Ankobra River, and Volta River during the wet season (Ackom et al. 2020; Awotwi et al. 2019; Duku et al. 2021; Kutir et al. 2022). Tam and Gough (2012) detected a threshold exceedance of 5 °C and 10 °C in DTD T_{max} and T_{min} in Moosenee, Thunder Bay, and Toronto, Ontario, Canada, which is greater than the 2 °C and 4 °C identified in the present study. The greater degree of threshold exceedances observed in the Canadian territory may be attributed to the coexistence of cold and warm weather conditions as well as seasonal variations. Most mid-latitude and temperate climatic regions experience both cold and warm weather conditions and varying seasons. The variations in weather and seasonal patterns within these regions give rise to both positive and negative values in daily weather and climate computations, consequently leading to greater variability. According to Gough (2008) and Tam and Gough (2012), the quotient becomes positive when dividing two negative weather values, such as daily temperature values, using the SD as a measure of daily statistical variability. This outcome leads to an increase in day-to-day variability. Therefore, employing a relevant day-to-day statistical measure of variability, such as the methods proposed by Gough (2008) and Tam et al. (2015), indicates that regions characterised by both cold and warm temperature conditions, along with distinct seasonal patterns, are expected to exhibit a greater degree of day-to-day variability compared to regions solely characterised by warm temperatures and seasonal patterns, as exemplified by Ghana.

From 1981 to 2021, the annual averages of DTD T_{max} and T_{min} increased. However, the improvements in T_{min} were weak. Largely, higher variations in annual averages of DTD T_{max} and T_{min} were observed in the towns of Ada Foah and Apam (similar in the ΔDTD and the threshold exceedances) compared to the other areas. Although with a similar climate, it is obvious that local variation exists, and this may be due to dynamics in local topography apart from the similar large seasonal wind development. Studies conducted elsewhere (Gough 2008; Mohsin and Gough 2010; Tam and Gough 2012) have shown how important the local topography is and how it can cause dramatic changes in temperature. The evidence of DTD in the study locations, especially in Ada Foah and Apam (where the highest variability occurred), could pose several threats to the inhabitants, especially to their health and daily activities. As mentioned elsewhere in the study, DTD negatively affects human health. Evidence on this has been reported by several researchers in various parts of the world, including the U.S.A. (Noelke et al. 2016), England, and Wales (Zhang et al. 2018), among others. Extreme day-to-day variations can cause mortalities, especially for the elderly (Bi et al. 2022; Zhan et al. 2017; Zhou et al. 2020). This situation may not be different from the study locations or the Ghanaian context in general. Research studies such as those of Azongo et al. (2012), Klutse et al. (2014), Oheneba-Dornyo et al. (2022), Song and Yan (2022), and Výberči et al. 2018) have highlighted the dire impacts of temperature variability on human health in Ghana, especially malaria transmission. Paaijmans et al. (2010) reported evidence of daily temperature fluctuations and increased malaria transmission in Africa. The DTD occurring in the locations could also affect agricultural activities, which contribute immensely to the livelihood opportunities of the people in the zone. Extreme DTD can increase evapotranspiration through evaporation from soil and water surfaces and transpiration from plants, and this could affect productivity and crop yields due to insufficient water from crops (IPCC 2018).

Several research studies have been conducted to examine urbanisation and its associated changes in land use and land cover and their effects on temperature patterns in the metropolitan areas of coastal Ghana and other areas within Ghana. Notable studies conducted by Addae and Oppelt (2019), Aduah and Baffoe (2013), Ackom et al. (2020), Asabere et al. (2020), Biney and Boakye (2021), Buo et al. (2021), Duku et al. (2021), Kumi-Boateng et al. (2015), Kutir et al. (2022), Mariwah et al. (2017), and Mensah et al. (2019) have contributed to the existing body of knowledge on this subject. Additionally, other relevant research by Asori and Adu (2023), Kusimi (2008), and Mensah et al. (2020) also examined related topics in different areas of Ghana. In order to enhance our understanding of urbanisation challenges, urban heat islands, and their impact on temperature in coastal Ghana, it is essential to conduct a comparative analysis of climate stations in urban and rural areas. Elsewhere, studies such as Anderson et al. (2018), Gough and Hu (2016), Mohsin and Gough (2010), Papanastasiou and Kittas (2012), Tam et al. (2015), and Tong et al. (2022) performed a comparison of climate stations located in both urban and rural areas. These studies have highlighted urbanisation and

the related urban heat island effect across different areas, including Toronto, Canada, China, and North America. Future research will benefit from conducting a comparative analysis of the DTD across nine distinct locations, with particular emphasis on Accra, a major urban centre and capital city, in contrast to a rural area located in a different climate zone, to show the effect of urbanisation.

5 Conclusion

This study applied Gough's (2008) and Tam et al. (2015) DTD frameworks to assess day-to-day temperature variability across nine urban areas in coastal Ghana. The study's results add to the Gough (2008) and Tam et al. (2015) DTD frameworks for how temperatures change from one day to the next. The framework has helped to realise that an orderly ($G < 1$) climate exists for the study locations. The monthly averages in the G (DTD/SD) revealed higher levels of variability in the DTD T_{max} than the DTD $T_{min,}$ and both were greatest for Ada Foah and Apam, especially in the month of March. Also, the highest monthly averages ΔDTD were observed in Ada Foah, Apam, and Elmina, while the lowest occurred in Denu, Keta, and Saltpond. Notwithstanding, the monthly averages ΔDTD significantly declined in the locations of Denu, Elmina, and Apam. At a threshold exceedance of 2 °C and 4 °C in both DTD T_{max} and T_{min}, it was established that Ada Foah experienced the greatest DTD throughout the year except in January, where it was surpassed by Keta. A dissimilar case occurred in the 4 °C threshold exceedances in DTD T_{min}, where no records were observed for all locations except Cape Coast. It is worth mentioning that there was enough evidence of a decline in the 2 °C thresholds in all locations except for Ada Foah, Denu, and Keta, where the threshold in the DTD T_{max} increased. The temporal trends in the annual averages DTD T_{max} and T_{min} were superior in Ada Foah and Apam. While evidence of an increase appeared in the annual averages of DTD T_{max} for most of the locations, evidence of an increase in DTD T_{min} was shown only in Apam. The study revealed that the day-to-day temperature variability in the mid-latitude and temperature regions is greater than that in the tropical regions due to the positive and negative weather and climate values associated with the regions in the mid-latitude and temperature regions.

In all the analyses, it was observed that the variations from one day to the next were higher in the dry season (November–March) than in the wet season (May–July). This is attributed to factors such as high insolation and the seasonal wind developments, which are highest during the dry season, and the Gulf of Guinea is attributed to serving as a moisture mitigating effect during the wet season, thereby resulting in low temperature variability. It was observed that, although the locations have similar climates, local variations exist, especially in Ada Foah and Apam in comparison to other locations, and this could be due to the dynamics of local topography.

The study has established how the results could pose threats to people in the area, especially to their health and agricultural activities, considering these as critical for their livelihoods. The study has given more examples from other parts of the world where DTD has resulted in high respiratory diseases, cardiovascular diseases, emotional problems, and mortalities. In Ghana, several studies have reported the effects of temperature variability, especially on malaria cases and related morbidities and mortalities. A continuous increase in DTD could negatively affect the people in the area, especially their health.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00704-024-05004-7.

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Author Contributions JA conceptualised the idea of the study, prepared materials, analysed data, and wrote the first draft of the manuscript. All authors commented on the previous version of the manuscript. Supervision was done by AM and HM. All authors read and approved the final manuscript.

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Data availability The datasets analysed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

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2.3. Climate risks and adaptation strategies: the perspectives of farmers in coastal Ghana

Paper 7



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RESEARCH AND THEORY

Climate risks and adaptation strategies: the perspectives of farmers in coastal Ghana

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Abstract
The significance of farmers' perceptions of climate risks, particularly in developing countries with limited capacity for adaptation, is equally important as the actual impacts, considering the increased risks posed by global climate change. This study examined smallholder farmers' perceptions of climate risks and adaptation strategies in coastal Ghana using a mixed-methods approach. A multi-stage sample technique was used to survey 800 farmers, and 8 farmers were selected as key informants through interviews in the coastal Savannah agroecological zone. Existing climatological records were analysed using the Kriging interpolation technique, and farmers' adaptive capacity was predicted using binary logistic regression. The results revealed a substantial increase in farmers' climate change knowledge. The majority of the farmers perceived increased temperatures (100%) and decreased total annual rainfall (64%), along with an increase in wind speed (100%) across the zone. The farmers revealed that extreme temperatures, drought, and decreasing rainfall result in the ripening of unmatured crops, the drying of crops, a decrease in crop yield, and farm losses. The farmers recognised poverty (75%) and food insecurity (23%) as the main effects of climate risks. The farmers have employed various adaptation strategies, including cultivating different types of crops (46%) and planting improved seed varieties (18%). However, financial constraints (48%) and high costs for farm inputs or fertilisers (32%) hinder these strategies. Farmers' age, gender, education, and years of farming significantly predicted their decisions to adopt various adaptation strategies. Policy initiatives on subsidised farm inputs are required to safeguard the farmers' activities and enhance their livelihoods.

Keywords Climate change · Climate variability · Adaptation · Risk perception · Agriculture

Introduction

Climate change and variability continue to pose significant risks to all life forms (Solomon et al. 2007), making them one of the most pressing concerns of the twenty-first century (Easterling 2007). Climate change and variability have an impact on global temperatures, precipitation, and other essential factors such as wind speed (Célestin et al. 2019). According to the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report (AR5), global mean surface air temperature increased by 0.85 °C (0.65 °C to 1.06 °C) between 1880 and 2012, with a further projected increase of 0.3 °C to 4.8 °C between 2081 and 2100 in comparison to 1986–2005 (Bindoff et al. 2013). Global temperatures are projected to increase, as are precipitation and wind speed (Célestin et al. 2019). Changes in global precipitation follow a pattern in which wetter regions remain wetter and drier parts remain drier (IPCC 2007). Wind speed is projected to increase in many northern hemisphere regions, as well as in the tropics and subtropics (Akinsanola et al. 2021; Zha et al. 2021), as is the frequency of extreme events (Hounkpè et al. 2022).

Climate change and variability pose risks to all sectors of the global economy, particularly agricultural activity and food security (Ayeni and Adewumi 2023; Aydinalp and Cresser 2008; Brink et al. 2023). Several studies have highlighted climate change and variability risks to agricultural activities on the continental scale (e.g., Aryal et al. 2020; Steffen et al. 2011; Zhang et al. 2023) and on the

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global scale (Calzadilla et al. 2013; Wang et al. 2018) and their related effects on farmers' livelihoods (Tieminie et al. 2023). Despite this, the situation for farmers in developing countries, particularly those in Sub-Saharan Africa (SSA), whose agricultural activities are rain-fed and climate-sensitive and who rely solely on farming for their livelihoods, is dire (Batungwanayo et al. 2023; Hounnou et al. 2023; IPCC 2014; Naab et al. 2019). Temperatures in SSA are projected to increase, and rainfall will be erratic, potentially leading to a decrease in crop productivity, threatening food security, and affecting agricultural livelihoods (IPCC 2014).

Risk perceptions and knowledge among farmers regarding climate change and variability are thus critical for the application of appropriate adaptation strategies (Ricart et al. 2023; Yaro 2013). Ricart et al. (2023) describe risk perception as the way by which people receive information or stimuli from their surroundings and convert them into psychological awareness in order to act or react appropriately. Ado et al. (2019) argued that increased knowledge is critical in the initial stages of the adaptation process to reduce climate change and variability impacts and susceptibility because awareness levels reflect a community's level of exposure to climate-related risks. Yaro (2013) emphasised that communities whose livelihoods depend on natural resources are aware of their surroundings and are able to detect climatic inconsistencies and their consequences. As a result, Yaro (2013) stressed that local knowledge and perceptions of climate change and variability should form the basis of agricultural policies in a bottom-up manner and not just a mere acknowledgement by policymakers, as perceptions define adaptation outcomes. Risk perceptions and knowledge of farmers with varying characteristics are thus critical for designing practical adaptation plans (Yaro 2013). The implementation of proactive measures across geographic locations are required to adapt to the consequences of climate change and variability (Christensen et al. 2007). As a result, proper and precise risk perception is crucial for planned adaptation actions, as poor risk perception may result in maladaptation (Barnett and O'Neill 2010; Johnson et al. 2023), increasing farmers' susceptibility to climate change and variability, whereas proper risk perception may positively affect the adaptation process (Ricart et al. 2023; Yaro 2013).

Numerous research studies have been conducted on climate risk perception in various countries, including Ado et al. (2019), Batungwanayo et al. (2023), Chaachouay and Zidane (2024), Fahim and Sikder (2022), Hossain et al. (2022), Hubertus et al. (2023), Kabir et al. (2022), Shah et al. (2023), Smith (2018), Smith and Mayer (2018), Tasnim et al. (2023), and Wheeler et al. (2021). These studies recognise the significant role of climate risk perception in adaptation. Several studies in Ghana have also explored climate risk perception and adaptation strategies, with studies conducted by Antwi-Agyei et al. (2017), Asravor (2018), Fosu-Mensah et al. (2012), Lawson et al. (2020), Naab et al. (2019), Ntim-Amo et al. (2022), Sadiq et al. (2019), Tambo and Wünscher (2017), Yamba et al. (2019), Yaro (2013), and Yiridomoh et al. (2021). Notwithstanding insights gleaned from these studies, they focus solely on smallholder farmers' activities in the mid-to-northern half of Ghana. However, no research has examined smallholder farmers' perceptions of climate risks and strategies for adaptation in coastal Ghana, particularly those located in the coastal Savannah agroecological zone. Therefore, conducting research of this nature is necessary to bridge this information gap and improve understanding of farmers' perceptions of climate risks and their decision-making process for adaptation in Ghana.

The aim of this study is to examine smallholder farmers' perceptions of climate risks and adaptation strategies in the coastal Savannah agroecological zone of Ghana, a zone where there is currently a lack of research on this topic. Specifically, the study seeks to examine: (i) the perceived knowledge and causes of climate change and variability among smallholder farmers; (ii) the perceived climate risks that smallholder farmers face in their farming activities; (iii) the spatial distribution of annual variations and trends in climatological records in the zone and whether they support farmers' perceptions; (iv) the adaptation strategies employed by smallholder farmers to mitigate climate risks; and (v) predicting the odds of smallholder farmers choosing specific adaptation strategies using the binary logistic regression test.

This study not only contributes to the current literature on farmers' perceptions of climate risk but also has the potential to provide insights for the formulation of efficient adaptation strategies that aim to safeguard the livelihoods of smallholder farmers in the zone. Furthermore, this emphasises the potential and additional benefits of enhancing the climatological literacy of farmers, as well as the significance of informal knowledge in the field of science.

Literature review

The continuous warming of the global climate, which is primarily caused by negative anthropogenic activities (IPCC 2022; Karl and Trenberth 2003), is expected to endure for an extended period of several centuries (Karl and Trenberth 2003). Based on the findings of Karl and Trenberth (2003), the main cause of global climate change can be attributed to the alteration of atmospheric composition resulting from human activities. According to the IPCC's AR6, it is evident that the negative impacts of anthropogenic climate change and related extreme events on people and the environment are far greater than the inherent variability observed in natural climate patterns (IPCC 2022). According to Célestin et al. (2019), there is a projected increase in global temperatures and precipitation. The projected change in climate

poses significant risks to several sectors of the global economy, with particular emphasis on the agricultural sector (Hitz and Smith 2004). Furthermore, the potential impacts extend to the interrelated food systems, as emphasised by the IPCC's AR6 (IPCC 2022). The potential consequences of global warming on food security due to climate change have been highlighted in previous studies (Calzadilla et al. 2013; Wheeler and von Braun 2013). This could result in adverse effects such as hunger, malnutrition, and nutrient deficiencies, particularly in the vulnerable regions of the Global South that have limited or no adaptation measures (IPCC 2022). The situation is worse for Africa (Tirado et al. 2015) and the Sub-Saharan African (SSA) region in particular (Adesete et al. 2023; Liu et al. 2008). For example, Sylla et al. (2016) assert that the climate in West Africa has been warming as a result of its response to harmful anthropogenic greenhouse gas forcing. According to the IPCC's AR5, the West African region experienced a warming of 0.3 °C to 1.0 °C during the current decade (Bindoff et al. 2013). Sylla et al. (2016) reported that there is a projected rise in temperature, while precipitation in the region exhibits increased variability. The current circumstances have the potential to result in a higher frequency of extreme events, such as droughts and floods, which are characteristic of the climatic conditions in the region (Ekwezuo and Ezeh 2020). The findings of Gebrechorkos et al. (2019) showed that the East African region has warmed and rainfall has become more variable. According to Niang et al. (2014), rainfall in East Africa has greater inter-annual variability, which is characterised by devastating extreme events such as drought and floods (Haile et al. 2020). The climate change situation in Southern and Central Africa is no different from that in East Africa (Niang et al. 2014). Temperatures have increased and rainfall has become variable in Southern Africa (IPCC 2019; Kapuka et al. 2022). In most areas of Southern Africa, the IPCC (2019) projects increased extreme temperatures and wildfire incidence in drier summers. Southern Africa's subtropical locations anticipate a decrease in rainfall (Archer et al. 2017; Kapuka et al. 2022). Research studies such as those of Aloysius et al. (2016) and Mba et al. (2018) have highlighted the warming and variable rainfall in the Central African region.

Sani and Chalchisa (2016) reiterate that climate change poses severe impacts on agriculture in SSA, which has a substantial number of smallholder farmers. Agricultural production in most of the countries in SSA is climate-sensitive, which makes them vulnerable (Brügger 2020; Omotoso et al. 2023). The impacts of climate change on agriculture in SSA pose a significant challenge for the sustainable development of the region and the entire African continent (Juana et al. 2013). Notwithstanding the increased impacts of climate change on agricultural production in the SSA, research studies such as those by Juana et al. (2013) and Mertz et al. (2009) have established that most farmers in the SSA have improved knowledge about climate change risks and have adopted various adaptation strategies. The significance of adaptation in addressing the challenges posed by global climate change is widely recognised. However, it is important to acknowledge the socio-political dynamics and power struggles associated with the practice of adaptation (Eriksen et al. 2015). As a result, research studies such as those of Barnett and O'Neill (2010) and Johnson et al. (2023) have highlighted the need for careful planning to prevent maladaptation. Therefore, it is imperative to increase people's knowledge and perceptions of climate-related risks in order to develop effective strategies for adaptation (Ricart et al. 2023; Yaro 2013). Ricart et al. (2023) provided a review of climate change awareness, perceived impacts, and adaptation based on the experiences and behaviours of farmers. Within this context, the authors describe risk perception as the way people receive information or stimuli from their surroundings and subsequently convert them into psychological awareness, enabling them to take appropriate actions or reactions. Griffin et al. (2008) further explained risk perception as the integration of an individual's assessments regarding the likelihood of a hazard occurring, coupled with their perception of the potential severity of the ensuing outcomes. The variations in climate risk assessment within a community can be attributed to disparities in information, varying levels of uncertainty, distinct political structures, and divergent interests among individuals and groups (Glaus et al. 2020; Slovic 1987). The concept of risk perception has been recognised by several researchers as a fundamental catalyst for adaptive behaviour (Barbara et al. 2023; Ricart et al. 2023; Yaro 2013). However, Wiegel et al. (2021) contend that its incorporation into environmental research has been infrequent.

Several studies on the climate risk perceptions, knowledge, and adaptation strategies of smallholder farmers have been conducted in the SSA region. For instance, Chichongue et al. (2015) reported that farmers in Lichinga and Sussundenga districts, Mozambique, perceive increased temperatures and variable rainfall to have adversely affected maize cultivation in the area. As a result, the farmers have diversified their crops and cultivated drought-resistant crops as a way of adapting to or coping with climate change (Chichongue et al. 2015). According to Sutcliffe et al. (2016), farmers in rural Ngabu Town and Kasungu-Lilongwe Plain, Malawi, prefer to cultivate maize in the short season and believe that it is the best adaptation strategy to drought events. Regardless, the researchers found that the meteorological data for the locations showed contrary evidence for the short season and advised that the adaptation effort by the farmers may not be appropriate (Sutcliffe et al. 2016). Additionally, Ochieng et al. (2017) pointed out that a substantial number of farmers in rural Kenya believe in climate

change incidence, especially in the increasing and changing parameters of temperature and rainfall. The researchers assert that the farmers adapt by cultivating different crop varieties under the guidance of extension services (Ochieng et al. 2017). According to the researchers, age and access to extension services are the main factors that shape the farmers' perceptions of climate risks (Ochieng et al. 2017). In the Zou Department of Benin, the findings of Fadina and Barjolle (2018) showed that farmers have an increased perception of climate change, increasing temperatures and winds, and decreasing rainfall. According to the findings, farmers adapt by adopting strategies such as fertiliser and pesticide application, improving seed varieties, crop diversification, and livestock rearing, among others (Fadina and Barjolle 2018). The findings further demonstrated that the educational level and years of farming significantly influenced the farmers' adaptation decisions (Fadina and Barjolle 2018). Tesfahun and Chawla (2020) reported that most farmers in Ethiopia's Eferatena-Gidem district believed that temperature and rainfall had increased and decreased in the last two decades, respectively. The researchers further indicated that the farmers in the area have employed a range of adaptation strategies, including changing the planting dates of their crops, engaging in off-farm livelihood activities, and planting improved seed varieties, among others (Tesfahun and Chawla 2020). The findings of Amadou et al. (2022) showed that most farmers in the Béguéné village in central Mali believe that temperature and rainfall have increased and decreased, respectively. The researchers further stated that the farmers cultivate drought-resistant crops and water-saving measures as their adaptation strategy (Amadou et al. 2022). The findings of Amani et al. (2022) have once again revealed farmers' perceptions and adaptation strategies in the Bafuliru and Lega areas of the Itombwe Mountains in the eastern Democratic Republic of the Congo. According to the researchers, the farmers in the Bafuliru area reported more climate risks and have adopted numerous adaptation measures than in the Lega area (Amani et al. 2022). The researchers highlighted the diverse sociocultural contexts that exist in the area and suggested a better adaptation strategy (Amani et al. 2022). In Senegal, Zagre et al. (2024) found that farmers in the Meouane, Daga Birame, and Thiel regions have improved knowledge of climate risk indicators such as increasing temperatures and variable rainfall patterns. The researchers further indicated that various factors, including government subsidies, credit access, extension services, and farming experience, among others, influence farmers' adaptation choices (Zagre et al. 2024). The findings of Alhassan and Haruna (2024) also established that aside from possessing increased knowledge about climate risks, rural farmers' household income and land size shape their adaptation decisions to climate risks in Nigeria and Ethiopia. Local social networks and agricultural extension services heavily influence farmers' adaptation choices, according to the researchers (Alhassan and Haruna 2024).

Ghana is not exempt from the escalating effects of climate change and variability, and it has comparable vulnerabilities to other countries in the SSA region. The Ministry of Environment, Science, Technology, and Innovation (MESTI) in Ghana reported a temperature rise of about 1.0 °C from 1960 to 2006 and has projected a further increase ranging from 1.7 °C to 2.0 °C (MESTI 2013). The climate in Ghana has undergone significant changes and has become more variable (Asare-Nuamah and Botchway 2019). Therefore, this has posed considerable difficulties for agricultural practises and the livelihoods of smallholder farmers (Cudjoe et al. 2021). Considering the changing and variable nature of Ghana's climate and its related impacts on agriculture, it is imperative to acknowledge the significance of farmers' risk perceptions and knowledge, particularly among smallholder farmers, in order to effectively implement suitable adaptation strategies.

A number of studies have been undertaken to examine the risk perceptions, knowledge, and adaptation strategies of smallholder farmers in Ghana in relation to climate change and variability. For instance, Ntim-Amo et al. (2022) reported that farm households in the northern region of Ghana have a perception of severe floods, perceive a greater likelihood of flooding, experience a sense of worry, and face potential risks to their farm inputs and yields. According to Ntim-Amo et al. (2022), it was found that farmers in northern Ghana have a low rate of adoption of flood risk adaptation strategies. However, the researchers suggest that these farmers are inclined to adopt a greater number of strategies in order to effectively adapt to and mitigate flood risks. Using the climate variability perception index, Yiridomoh et al. (2021) found that women smallholder farmers in the Wa West district are vulnerable to drought, floods, and bush fires. The researchers further indicated that the smallholder farmers have engaged in multiple off-farm adaptation strategies such as petty business, poultry and livestock keeping, and agro-processing as a response to climate variability (Yiridomoh et al. 2021). In the Lawra and Nandom districts in the Upper West region, Lawson et al. (2020) highlighted that women smallholder farmers perceive rainfall to be increasing erratic and increased average temperatures. The adoption of adaptation strategies in these districts is influenced by socio-economic factors such as age, marital status, and residential status. Within farmer households, power dynamics and decision-making processes further shape these factors (Lawson et al. 2020). Similarly, Yamba et al. (2019) provided information indicating that smallholder farmers in the Bosomtwe district in the Ashanti region have reported a noticeable rise in temperature and erratic rainfall patterns. These observations corroborated the meteorological data collected in the area. According to Yamba et al. (2019), a majority of farmers hold the belief that deforestation plays

a substantial role in both climate change and variability. Additionally, using multinominal logit regression, Sadiq et al. (2019) reported that in the Yilo Krobo municipality and the Ayensuano district in the Eastern region of Ghana, smallholder farmers adoption of appropriate agricultural practises is influenced by their perceptions of rainfall, credit access, and farming experience, whereas their adoption of soil-related strategies is influenced by gender and rainfall perception. The researchers went on to state that smallholder farmers farming experience and rainfall perception influenced their adoption of improved variety strategies (Sadiq et al. 2019). The findings of Asravor (2018) revealed that the effects of the variations in crop yield, prices of fertiliser, and crop prices on household income were perceived as the greatest sources of risk by smallholder farmers in northern Ghana. According to Asravor (2018), the most effective risk management strategies of the farmers in northern Ghana include stabilising household income through the cultivation of different crops, storing feed and seed reserves, and spreading sales. Furthermore, the study conducted by Antwi-Agyei et al. (2017) revealed variations in the perception of climatic and non-climatic stressors among smallholder farmers in northern Ghana. Nevertheless, the researchers identified several predominant stressors that were consistently reported across different levels. These stressors encompassed a lack of money, the high cost of farm inputs, erratic rainfall, damage to crops by cattle, limited access to markets, and a lack of farming equipment. Moreover, Yaro (2013) highlights that small-scale farmers in Gomao-Akotsi and commercial farmers in Nsawam, Ghana, possess a comprehensive understanding of climate change patterns and their impact on agricultural productivity and other aspects of their livelihoods. According to Yaro (2013), the results indicate that commercial farmers exhibited a broader understanding of the scientific aspects of climate change, whereas small-scale farmers provided a localised explanation of observed climate changes. Also, Fosu-Mensah et al. (2012) reported that most smallholder farmers perceive increasing and decreasing temperatures and rainfall, respectively, in the Sekyedumase district in the Ashanti region. Using logit regression analysis, the researchers went ahead to indicate that access to extension services, credit, soil fertility, and land tenure are the essential factors influencing farmers' perception and adaptation in the district (Fosu-Mensah et al. 2012).

In Ghana, like other SSA countries (Akinyi et al. 2021; Gbegbelegbe et al. 2018), smallholder farmers employ various strategies to effectively adapt to the negative impacts of climate change and variability. The strategies encompass a range of activities such as livestock husbandry, the application of fertilisers, engaging in small-scale business ventures, cultivating drought-resistant crop varieties, utilising improved seed varieties, practising crop rotation, using irrigation systems, adopting mulching techniques, and engaging in non-farm activities, among other approaches (Asravor 2018; Sadiq et al. 2019; Yamba et al. 2019; Yaro 2013; Yiridomoh et al. 2021). Despite the implementation of various adaptation strategies by smallholder farmers in the country, they face several constraints, including financial limitations, pest and disease infestations, low market demands, high input costs, and inadequate extension services (Sadiq et al. 2019; Yiridomoh et al. 2021).

As previously noted, the aforementioned studies primarily focused on examining the climate risk perception and adaptation strategies of smallholder farmers' activities in the mid-to-northern half of Ghana. However, they overlooked the equally significant coastal Savannah agroecological zone. This zone warrants an investigation in order to gain a comprehensive understanding of climate-related challenges and adaptive measures among smallholder farmers. Conducting research on the climate risk perception and adaptation strategies of smallholder farmers in the coastal Savannah agroecological zone, an area where no research exists, is of utmost importance. This study holds significant importance for the region of Ghana as well as the broader global society, given the spatial, temporal, and socio-political dimensions of the phenomenon of global climate change. This study contributes to the growing body of literature about climate change risk perception and adaptation strategies, examining these issues across several spatial, temporal, socio-economic, and socio-political levels.

Methodology

Study area

The coastal Savannah agroecological zone is located within the central and eastern portions of Ghana's coast and encompasses three distinct administrative regions, namely the Central, Greater Accra, and Volta regions (Fig. 1). The climate of the zone and Ghana as a whole is characterised by a tropical environment that experiences distinct periods of dryness and rainfall (Addi et al. 2021). The intertropical discontinuity and the West African monsoon both play a significant role in shaping this climatic pattern in the zone (Addi et al. 2021).

Based on climatology, the zone is classified as a dry equatorial climate zone and is recognised as the driest in Ghana (Addi et al. 2021). The zone has a maximum and minimum mean annual temperature of 27.9 °C and 26.6 °C, respectively (Ankrah et al. 2023a; Baidu et al. 2017). Despite exhibiting a bimodal rainfall pattern, the zone is characterised by the lowest precipitation levels in the country (Baidu et al. 2017; Ghana Statistical Service [GSS] 2013).

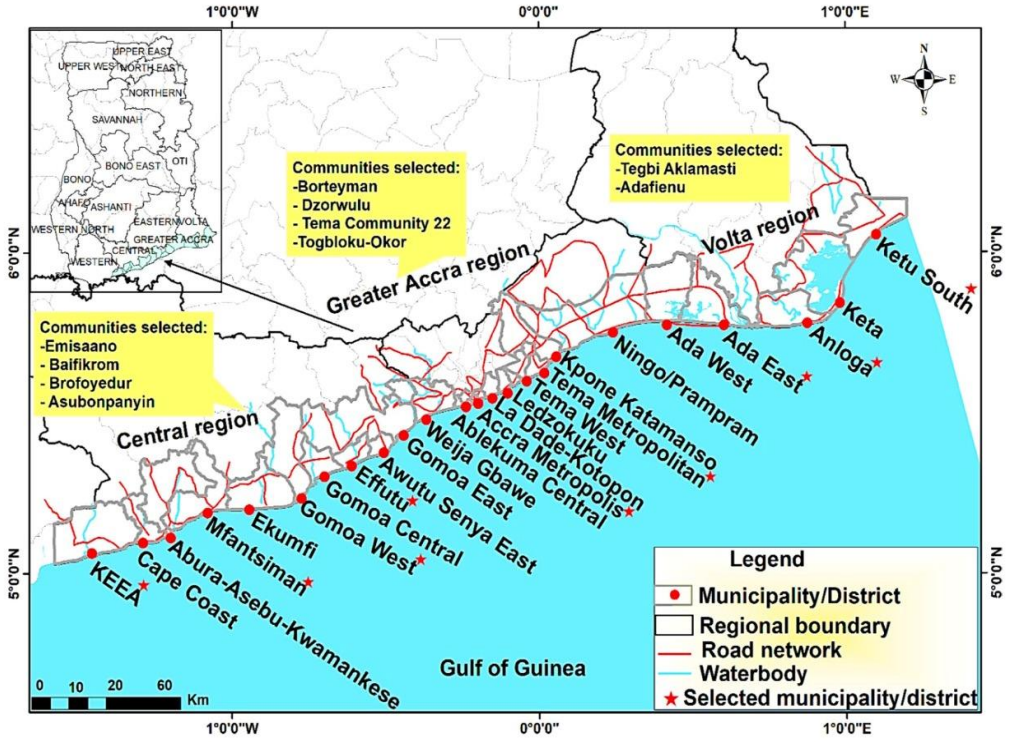


Fig. 1 Map showing the coastal Savannah agroecological zone and the selected municipalities and districts

According to Ankrah et al. (2023a), the range of average annual rainfall varies from a minimum of 978.4 mm to a maximum of 1339.9 mm. The major season of rainfall in the zone spans from April to July, while the minor season starts from September to early November. Subsequently, the dry season commences from late November to March (Dickson and Benneh 2001). The elevation of the zone varies from a minimum of – 3 m to a maximum of 641.2 m (Ankrah et al. 2023a). The terrain of the area is comprised of isolated hills, undulating plains, and lowland cliffs characterised by sandy beaches and marshes (GSS 2013).

The predominant vegetation in the zone consists primarily of grassland, with a few trees in the central portion and the presence of shrubs, thickets, and mangroves in the eastern section (GSS 2013). The coastal nature of the zone significantly contributes to Ghana's gross domestic product (GDP) (GSS 2013). Agriculture is widely recognised as a significant economic activity within the zone, owing to its favourable conditions for cultivating various crops, including maize, cassava, cocoyam, plantains, and vegetables, among others (Addi et al. 2021; GSS 2013; Yaro 2013).

Several factors led to the decision to study the coastal Savannah agroecological zone. Despite having two distinct rainfall seasons, the coastal Savannah agroecological zone receives the least amount of rainfall when compared to the other five agroecological zones in the country (Addi et al. 2021). The area's coastal position increases its susceptibility to impacts caused by land and ocean interactions (Addi et al. 2021). The findings of Addi et al. (2021) and the Ghana Statistical Service (GSS) (2013) confirm that agriculture plays a significant role in the economic activities within the coastal Savannah agroecological zone.

Description of data sources and collection procedure

The study used a combination of data sources: qualitative and quantitative data (mixed-methods approach) (Creswell 2014; Tashakkori and Creswell 2007) to gain insight into smallholder farmers' perceptions of climate risks and adaptation strategies in the coastal Savannah agroecological zone of Ghana. The study used data from both primary and secondary sources. Primary data were acquired through a semi-structured questionnaire survey and interviews. The Ghana Meteorological Agency (GMet) provided the secondary data, which included climatological records of maximum

and minimum temperature, rainfall, and wind speed from 1981 to 2021. The use of this period was necessitated by the presence of more gaps in the years preceding 1981. In other words, this study did not include the years before 1981 because they had a percentage of missing values greater than 5%. The data was collected from eleven synoptic stations of the GMet for various locations, such as Elmina, Cape Coast, Saltpond, Apam, Winneba, Accra, Tema, Ada Foah, Anloga, Keta, and Denu. In each dataset, the percentage of missing values was less than 2%. In accordance with the recommendation put forth by Monteiro et al. (2018), the National Aeronautics and Space Administration/Prediction of Worldwide Energy Resources (NASA/POWER) (https://power.larc.nasa.gov/) satellite data were employed for the purpose of addressing these data deficiencies.

The semi-structured questionnaire survey consisted of four different sections: socio-demographic characteristics, perceived knowledge and causes of climate change and variability, perceived climate risks to farming activities, and adaptation strategies. The survey instrument comprised a combination of closed-ended and open-ended questions. Typically, the completion of a questionnaire requires approximately 20 to 30 min of a respondent's time. Six field assistants were provided with training on the questionnaire, the use of the KoboToolbox software (https://www.kobotoolbox.org/), and ethical considerations pertaining to data collection. The selection of field assistants was characterised by diversity, as individuals proficient in distinct languages such as Fante, Ga-Dangme, and Ewe were chosen to work in the eight selected communities. The survey was conducted among respondents using mobile devices through the KoboToolbox platform from February to April 2023.

In order to qualify as a key informant for the interview, several criteria must be met. First of all, the individual must be a native of the farming community under study. Additionally, they must have lived in this community for at least 40 years. Lastly, their livelihood must be exclusively dependent on farming. The farmers who were considered key informants were also smallholder farmers. After receiving recommendations from at least five respondents who completed the questionnaire in each community, the researcher proceeded to engage with these farmers, who served as key informants. Following the administration of the questionnaire survey, the field assistants proceeded to informally engage the respondents in identifying a specific farmer within the community whom they perceive as their 'leader' and who possesses a longer history in farming (including themselves if they believe they are the one). Leader here means the person has been farming for at least forty years and is a native of their community. The researcher compiled these farmers' names for each community, identified the most frequently mentioned by the respondents, and scheduled an interview with them. The respondents for the questionnaire administration were distinguished from those for the interview based on two factors: the number of years lived and being a native of the community. The interview primarily addressed inquiries pertaining to the strategies employed for adaptation and the barriers hindering the adoption of such strategies.

Nielsen and D'haen (2014) emphasised the significance of the participants' perceptions provided to the researchers during the data collection process. Nielsen and D'haen (2014) further underlined the importance of researchers' awareness, as these perspectives can either hinder or aid the process of collecting data. Hay (2010) emphasised the importance of thoughtful reflection, when researchers recognise their social positions and carefully assess their positionality, social interactions, and their possible effect on data collection and interpretation of findings. Throughout the interview process in the present study, the researcher recognised the concept of positionality and its possible effect on data collection. Consequently, the researcher endeavoured to reduce any possible prejudices. Because the selection of the eight study communities did not include the community the researcher belongs to in the coastal Savannah zone, the researcher adopted an outsider (Holmes 2020; Richa and Geiger 2007). The participants identified the researcher as an insider based on the researcher's proficiency in speaking native languages (Holmes 2020; Richa and Geiger 2007). As a result, the researcher gained trust, which led the participants to be more truthful and elaborate in sharing their experiences regarding their adaptation strategies and the barriers that limit their adoption of such strategies. The participant perceived the researcher as harmless, which encouraged the researcher to ask more detailed questions and even extend invitations to visit their farms. Some participants felt that the researcher's high level of education made him appear very informed about the interview topics. As a result, they would occasionally seek confirmation from the researcher based on their own answers. The researcher perceived this as a concern and resolved it by instilling confidence in the participants. The researcher achieved this by acknowledging the participants' knowledge as long-standing farmers with decades of experience. The researcher emphasised their role in gathering valuable insights to inform more effective policies. The researcher's insider position did not have a negative effect on the qualitative findings. Instead, it facilitated the generation of more detailed and in-depth shared knowledge and experiences from the participants, specifically addressing their farming adaptation strategies and the barriers that limit their adaptation decisions. In the process of transcribing the interview, the researcher, although regarded as an insider, maintained objectivity, cultural neutrality, and impartiality towards the prejudices of the participants (Holmes 2020; Kusow 2003).

Prior to commencing the interview, the participant was provided with a consent form that outlined their rights as a participant, such as the voluntary nature of the interview and their prerogative to withdraw from the study or request the removal or deletion of their previously recorded responses. Anonymity and confidentiality were ensured for the participant through the omission of personal identifying information, such as their name. The abbreviations D1, D2, D3, D4, D5, D6, D7, and D8 were used to represent the participant names, which were then followed by their respective communities. For example, the abbreviations D1: Emisano, D2: Baifikrom, D3: Brofoyedur, D4: Osobonpanyin, D5: Borteyman, D6: Togbloku Okor, D7: Tegbi Aklamatsi, and D8: Adafienu represent the participants in the communities of Emisano, Baifikrom, Brofoyedur, and Osobonpanyin, Borteyman, Togbloku Okor, Tegbi Aklamatsi, and Adafienu, respectively. The commencement of the interview was contingent upon the participant's explicit agreement and subsequent execution of the consent form. The interview took place in a setting where the participant was actively involved, specifically within the confines of their own home, which gave them a sense of freedom and privacy. The interview was carried out using the languages that were familiar to the leaders, such as Fante, Ga-Dangme, Ewe, and Twi. The interviews were recorded solely upon the agreement of both the interviewer and the participant. Furthermore, detailed notes were taken, leading to a total of 200 h spent, during which each of the eight key informants was interviewed for a duration of 25 min. The responses of the participants were transcribed verbatim, capturing their exact words. The quotations provided in this study reflect the individual viewpoints of the participants, which were collected through interviews conducted from February to April of 2023.

The study focused on two main research objectives: identifying smallholder farmers' adaptation strategies and understanding the barriers that limit their adoption of these strategies. These objectives guided the analysis of interviews conducted with eight key informants. Subsequently, the study utilised an engaging and inductive qualitative approach to analyse the data and directly generate themes (Arku et al. 2012; Strauss and Corbin 1990). The interviews were transcribed from the local languages of the key informants into English. This was done thoroughly by carefully reading the interview notes and continuously playing back the recorded audio to guarantee the accuracy and reliability of the findings (Arku et al. 2012; Krefting 1991). The interview transcripts were categorised into themes according to the participants' strategies for adaptation, barriers that limit their adoption of these strategies, and additional factors that encourage or hinder adaptation. The interview transcripts were coded and analysed using the trial version 24.0 of ATLAS.ti software, available at https://atlasti.com/free-trial-version. This analysis enabled the identification of the variations, similarities, and associations in the adaptation strategies and barriers faced by the farmers (key informants). The graphical representation of a network of themes was accompanied by direct quotations, serving to offer the necessary context for the farmers' viewpoints.

Sampling procedure

A multi-stage sampling technique was used to collect primary data from the respondents. Saunders et al. (2012) assert that the use of the multi-stage sampling technique is advantageous in addressing the issue of face-to-face interaction with a sample that is geographically spread out. The coastal Savannah agroecological zone was purposefully selected in the first stage due to its lower rainfall amounts compared to the other five agroecological zones as well as its higher frequency of drought and wetness events, which negatively affect agricultural activities (Addi et al. 2021; Ankrah et al. 2023a). In the second stage, the simple random sampling technique was employed to select eight districts or municipalities (Table 1) across the zone. Additionally, one community was randomly selected from each of the municipalities or districts, resulting in a total of eight communities (Table 1). Due to the urbanised nature of the Greater Accra region, the present study deemed it necessary to treat the Ashaiman, Kpone-Katamanso, and Ayawaso West municipalities as a single community. This decision was made in response to the challenges encountered in accurately identifying farmers within these areas.

The third stage involved a random selection of 100 smallholder farmers each from the eight communities, for a total of 800 farmers. The random selection of 100 smallholder farmers from each of the eight communities ensured a fair representation of the farmers, as community-specific data

Table 1 Communities and districts/municipalities selected for the study

Community	District/Municipality	Region
Asubonpanyin	Effutu	Central
Brofoyedur	Gomoa West	Central
Emisaano	Komenda/Edina/Eguago/Abirem	Central
Baifikrom	Mfantsiman	Central
Tema Community 22	Ashaiman[a]	Greater Accra
Borteyman	Kpone-Katamanso[a]	Greater Accra
Dzorwulu	Ayawaso West[a]	Greater Accra
Togbloku-Okor	Ada East	Greater Accra
Adafienu	Ketu South	Volta
Tegbi Aklamasti	Anloga district	Volta

[a]Treated as a single community

regarding the number of farmers at the municipal or district level of the respective communities were unavailable. In the last stage, a purposeful decision was made to interview eight smallholder farmers who were recognised as key informants. One participant was selected from each of the communities in question.

Data analysis and statistical measures

The data obtained from the questionnaire survey was exported in Excel format and subsequently imported into the Statistical Package for the Social Sciences (SPSS) software (version 26.0) for the purpose of analysis. As a result, an appropriate statistical analysis was conducted. The independent variables in this study encompassed the socio-demographic characteristics of the smallholder farmers, including age, gender, level of education, and years of farming. These variables were chosen based on their theoretical positive influence on climate risk perception and adaptation strategies (Fosu-Mensah et al. 2012). For instance, researchers have suggested that the gender of farmers can impact their perceptions of climate risks and the strategies they use to adapt to them (Fosu-Mensah et al. 2012; Phiri et al. 2004). Research has shown that there is a positive association between the level of education and the adoption of modern technology among farming households (Deressa et al. 2009; Fosu-Mensah et al. 2012). Fosu-Mensah et al. (2012) and Nhemachena and Hassan (2007) argued that more farming experience enhances farmers' odds of adopting adaptive strategies. According to the researchers, farmers gain expertise and knowledge about the climate and make informed decisions about the most suitable crops and planting methods (Fosu-Mensah et al. 2012; Nhemachena and Hassan 2007). The study focused on the aforementioned variables, but it is worth noting that other factors, such as farm size, income, credit access, access to extension services, household size, social networks (members of associations), information, and social status, have also been identified as influencing farmers' perceptions and adaptation strategies (Ado et al. 2020; Bagambilana and Rugumamu 2023; Dasmani et al. 2020; Jairo and Korir 2019). The binary logistic regression analysis was employed to assess the effect of the independent variables on the adoption of adaptation strategies by farmers. The choice to use binary logistic regression in this study was influenced by its extensive use in previous research on farmers' perceptions of climate risks and adaptation strategies. Notable studies that have employed this method include Abid et al. (2015), Ado et al. (2020), Bagambilana and Rugumamu (2023), Batungwanayo et al. (2023), Fosu-Mensah et al. (2012), Sertse et al. (2021), Shah et al. (2023), and Tesfahun and Chawla (2020). This study assessed farmers' adoption of particular adaptation strategies based on five variables: cultivating different types of crops, fertiliser application, planting improved varieties of seed, rearing livestock, and the use of irrigation. Each of these five dependent variables was measured on a dichotomous scale and represented as 1 (if a farmer adopted a particular adaptation strategy) and 0 (if a farmer did not adopt a particular adaptation strategy). Previous studies, including those of Ado et al. (2020), Bagambilana and Rugumamu (2023), Batungwanayo et al. (2023), Dasmani et al. (2020), Shah et al. (2023), and Yaro (2013), informed the choice of these variables. The statistical procedures mentioned above were chosen because the variables involved are categorical and dichotomous. The aim was to assess the predictive capacity of these variables in determining the odds of farmers' adoption of particular adaptation strategies. The ordinary Kriging interpolation technique was employed to understand the spatial distribution of annual variations in the climate variables. The linear regression test was again used to represent the trends in the climate variables across the zone, as used earlier by Jaiswal et al. (2015).

Ethical considerations

The study started after adhering to the research ethics protocol and obtaining approval from the ethics commission of the Faculty of Arts and Humanities at the University of Porto. The research, including the instruments used for data collection, went through an ethical review procedure to ensure compliance with ethical standards and to eliminate any potential risks or disadvantages for the participants. The approval was granted through the adoption of Resolution No. 31/CEFLUP/.

Results

Socio-demographic characteristics of respondents

Table 2 shows the socio-demographic characteristics of the 800 respondents who participated in the study. The majority of respondents (48%) were within the age range of 41 to 50 years, while the lowest number (58, or 7%) were above the age of 50. The survey indicated a higher participation rate among males (78%) in comparison to females (22%). A substantial number (790, or 99%) of the respondents were in a marital relationship, with just a few (10, or 1%) identified as widows. The majority of the respondents (49%) had only received a primary education, while 31% had no formal education, according to their educational level, with the lowest number (4%) having completed senior secondary or high school. The majority of the respondents, specifically 43%, reported having a household size of 4, followed by 27% who reported having a household size greater than 5. Conversely, the lowest proportions of respondents, each accounting for

Table 2 Socio-demographic characteristics of respondents

Variable	Category	Frequency	Percentage (%)
Age	20 – 30	0	0
	30 – 40	361	45
	41 – 50	381	48
	> 50	58	7
Gender	Female	179	22
	Male	621	78
Marital status	Married	790	99
	Widow(er)	10	1
Educational level	Junior Secondary/high School	129	16
	Senior secondary/high school	33	4
	No formal education	245	31
	Primary	393	49
Household size	3	121	15
	4	343	43
	5	121	15
	> 5	215	27
Native of a community	Yes	800	100
	No	0	0
Years of farming	< 20	380	47
	20 – 30	344	43
	> 30	76	10

Source: (Field survey, 2023)

15%, reported having household sizes of 3 and 5. All of the respondents (100%) indicated that they were native to their respective communities. A substantial majority of the respondents (47%) reported having engaged in farming for a time frame of less than 20 years, followed by 43% between 20 and 30 years, and the least (10%) for more than 30 years.

Online Resource 1 displays the socio-demographic characteristics of each community, highlighting the variations between them. The majority of respondents (77%) in the Dzorwulu-Borteyman-Tema Community 22 community were between the ages of 31 and 40. The Togloku-Okor community came in second with 74% in the same age groups, while Tegbi Aklamatsi had the lowest percentage (0%) among those over 50. None (0%) of respondents in the communities were between the ages of 20 and 30 (Online Resource 1). Their gender distribution ranged from 93% for males in the Togloku-Okor community to 7% for females (Online Resource 1). All (100%) of the respondents in the communities of Emisano, Brofoyedur, Dzorwulu-Borteyman-Tema Community 22, and Togloku-Okor were married. Only a few of them were widows, mostly in Baifikrom (1%), Osobonpanyin (3%), Tegbi Aklamatsi (2%), and Adafienu (4%). Their level of education ranged from a high of 59% in the Togloku-Okor community for primary education to 0% in the Emisano and Baifikrom communities for senior secondary or high school. None (0%) of the respondents in the study communities had completed tertiary education at the time of the survey (Online Resource 1). Respondents in the Tegbi Aklamatsi community had the largest (53%) household size of four, while the Emisano community had the smallest (3%) household size of three (Online Resource 1). All of the respondents (100%) were native to their community. The majority (64%) of respondents in Dzorwulu-Borteyman-Tema Community 22 had less than 20 years of farming experience, while the lowest (7%) were in the communities of Dzorwulu-Borteyman-Tema Community 22 and Togloku-Okor with more than 30 years of farming experience.

Perceived knowledge and causes of climate change and variability

Table 3 shows the respondents perceived knowledge and causes of climate change and variability. According to Table 3, all of the respondents (800, or 100%) indicated their awareness of climate change and variability. The majority of respondents (662, or 83%) mentioned that television serves as the primary medium through which they obtain information regarding climate change and variability. A substantial portion of respondents (316, or 40%) attributed climate change and variability primarily to negative human actions. Subsequently, a proportion of 284 or 35% was observed for both negative human actions and natural events, while the lowest percentage of 24 or 3% was attributed to God's

Table 3 Perceived knowledge and causes of climate change

Variable	Category	Frequency	Percentage (%)
Awareness about climate change	1. Yes	800	100
	2. No	0	0
Sources of information about climate change	1. Radio	138	17
	2. Television	662	83
Causes of climate change	1. Both negative human actions and natural events	284	35
	2. Natural events	176	22
	3. Negative human actions	316	40
	4. Punishment from God	24	3
Factors contributing to climate change	1. A natural event	189	24
	2. Bush burning	0	0
	3. Deforestation	611	76
	4. Urbanization	0	0
	5. Vehicular fumes/carbon monoxide	0	0
Temperature over the last two decades	1. Increased	800	100
	2. Decreased	0	0
	3. No change	0	0
	4. Don't know	0	0
Dry season temperature over the last two decades	1. Increased	800	100
	2. Decreased	0	0
	3. No change	0	0
	4. Don't know	0	0
Rainy season temperature over the last two decades	1. Increased	762	95
	2. Decreased	0	0
	3. No change	38	5
	4. Don't know	0	0
Length of the hot periods over the last two decades	1. Increased	800	100
	2. Decreased	0	0
	3. No change	0	0
	4. Don't know	0	0
Length of the cold periods over the last two decades	1. Increased	0	0
	2. Decreased	757	95
	3. No change	19	2
	4. Don't know	24	3
Rainfall changes over the last two decades	1. Increased	285	36
	2. Decreased	515	64
	3. No change	0	0
	4. Don't know	0	0
Wet season rainfall over the last two decades	1. Increased	473	59
	2. Decreased	326	41
	3. No change	1	0
	4. Don't know	0	0
Dry season rainfall over the last two decades	1. Increased	8	1
	2. Decreased	761	95
	3. No change	31	4
	4. Don't know	0	0
Intensity of rainfall events over the last two decades	1. Increased	632	79
	2. Decreased	168	21
	3. No change	0	0
	4. Don't know	0	0

Table 3 (continued)

Variable	Category	Frequency	Percentage (%)
Wind over the last two decades	1. Increased	800	100
	2. Decreased	0	0
	3. No change	0	0
	4. Don't know	0	0
Intensity of dry season wind over the last two decades	1. Increased	800	100
	2. Decreased	0	0
	3. No change	0	0
	4. Don't know	0	0
Intensity of wet season wind over the last two decades	1. Increased	694	89
	2. Decreased	106	13
	3. No change	0	0
	4. Don't know	0	0
Gendered dimension of accessing information in farmers' awareness and understanding of climate change			
Sources of information about climate change			
-Television	1. Males (females)	540 (122)	87 (68)
-Radio	2. Males (females)	81 (57)	13 (32)
Causes of climate change			
-Both negative human actions and natural events	1. Males (females)	233 (51)	37 (28)
-Natural events	2. Males (females)	104 (72)	17 (40)
-Negative human actions	3. Males (females)	277 (39)	45 (22)
Punishment from God	4. Males (females)	7 (17)	1 (10)
Factors contributing to climate change			
-A natural event	1. Males (females)	107 (82)	17 (46)
-Deforestation	2. Males (females)	514 (97)	83 (4)

Source: (Field survey, 2023)

punishment. The respondents identified deforestation (611, or 76%) and natural events (189, or 24%) as the primary factors responsible for climate change and variability. The respondents in the study were unable to identify the significant impact of urbanisation and vehicular emissions.

In terms of gender dimensions, both males and females appeared to use television more than radio when accessing information about climate change awareness and understanding. However, more males (540, or 87%) used television than females (122, or 68%). The causes of climate change vary according to gender. A substantial number (277, or 45%) of males assigned the reasons for climate change to negative human actions, whereas 72, or 40%, of females attributed it to natural events. Both male and female respondents attributed deforestation to causing climate change and variability. Nonetheless, response rates varied from 514 (83%) for men to 97 (54%) for women (Table 3).

All of the respondents (800, or 100%) indicated that temperatures and particularly dry season temperatures in their respective communities observed an increase over the past two decades. A significant percentage (762, or 95%) of respondents reported that there has been an increase in temperatures during the rainy season over the past two decades. However, a small minority (38, or 5%) perceived no change in temperatures during this period. In addition, all of the respondents (800, or 100%) stated that the length of hot periods in their respective communities has shown an increase over the course of the past two decades. Furthermore, a significant majority (757, or 95%) of the respondents reported a decrease in the length of cold periods during the same time frame. The majority of the respondents (515, or 64%) reported a decrease in total rainfall over the past two decades, whereas 285 or 36% observed the opposite trend. Notwithstanding, most of them (473, or 59%) reported an increase in the wet season rainfall over the last two decades, and the opposite of 761 or 95% was true for the dry season rainfall. A large proportion of the respondents (632, or 79%) reported an increase in the intensity of rainfall events in their respective communities over the past two decades, with only 168 or 21% indicating a decrease. All of the respondents (800, or 100%) claimed that overall wind speed, particularly the intensity of the wind during the dry season, has exhibited an increase over the past two decades. The vast majority (694, or 87%) of respondents similarly reported

the same pattern for the wet season wind in their respective communities.

Online Resource 2 presents the differences in perceived knowledge and causes of climate change, as well as the variability of the individual study communities. All respondents (100%) from the individual communities were aware of climate change and variability (Online Resource 2). The highest number of respondents (94%) in Dzorwulu-Borteyman-Tema community 22 identified television as their source of climate change information, while the lowest number (6%) identified radio as their source of information. None of the respondents mentioned newspapers as a source of climate change information (Online Resource 2). The respondents' attribution of the causes of climate change varied from a high of 63% for negative human actions in the community of Dzorwulu-Borteyman-Tema community 22 to a low of 0% for punishment from God in Dzorwulu-Borteyman-Tema community 22, Togbloku Okor, Tegbi Aklamatsi, and Adafienu (Online Resource 2). The Togbloku Okor community received the most (98%) responses on the factors contributing to climate change and variability when compared to the other communities (Online Resource 2). There were no variations in respondents' perceptions of temperature change, dry season temperature, rainy season temperature, and the length of hot periods over the last two decades, as all respondents (100%) reported an increase in the aforementioned variables (Online Resource 2). The majority (100%) of respondents in Baifikrom, Brofoyedur, Dzorwulu-Borteyman-Tema community 22, Togbloku Okor, and Adafienu reported that the length of cold periods had decreased over the last two decades, while the lowest (8%) in the community of Osobonpanyin reported no change. None of the respondents (0%) reported an increase in the aforementioned issue (Online Resource 2). Over the last two decades, the response rate to rainfall change ranged from 100% in Osobonpanyin, indicating a decrease, to 18% in Brofoyedur, indicating an increase. The responses to the wet season rainfall ranged from a high of 78% in Togbloku Okor, who indicated an increase, to a low of 1% in Tegbi Aklamatsi, who observed no change (Online Resource 2). The majority (100%) of respondents in Baifikrom, Brofoyedur, Dzorwulu-Borteyman-Tema community 22, Togbloku Okor, and Adafienu mentioned that dry season rainfall had decreased over the last two decades, while the lowest (8%) in Osobonpanyin reported both an increase and no change (Online Resource 2). Respondents in the Emisano community recorded the highest (97%) response rate to increased intensity of rainfall events over the last two decades, while the lowest (3%) emerged in that same community as a decrease. Over the last two decades, there has been no variation in responses to wind change or the intensity of dry season wind, with all (100%) respondents indicating an increase. On the other hand, responses to wet season wind changes varied from a high of 95% in Emisano and Togbloku Okor communities to a low of 5% in the same communities (Online Resource 2).

Perception of climate risks for farming activities

The respondents perceived climate risks for farming activities (Table 4). All of the respondents (100%) reported that their farming activities are susceptible to risks caused by climate change and variability. The respondents expressed diverse viewpoints regarding the climate-related risks that affect their farming activities. All of the respondents (100%) unanimously identified extreme temperatures as the primary climate risk that impacts their farming activities. This was followed by 99% for both drought and pest and disease risk on crops, with the lowest being 4% for erosion or soil fertility. The majority of the respondents (43%) identified the ripening of unmature crops as the primary effect of temperature changes, while 36% mentioned the drying of crops or seedlings. According to the majority of respondents (46%), a decrease in yield or harvest was the main impact of changes in rainfall on farming activities. Conversely, poor crop growth was deemed the least significant effect, with only 12% of respondents considering it as such. All of the respondents (100%) acknowledged that wind speed has significant implications for farming activities, particularly in terms of crop destruction and losses. The respondents also identified low productivity (53%) and losses (34%) as the primary effects of extreme events on farming activities. A significant proportion of the respondents (75%) identified poverty as the main effect of climate risks on their farming activities, while 23% stated food insecurity as the additional impact.

Online Resource 3 depicts the variations in respondents' perceptions of climate risks for farming activities in the various study communities. All respondents (100%) in their respective communities stated that climate change poses a risk to their farming activities (Online Resource 3). Extreme temperature was unanimously identified as the most impactful climate risk across all communities, with respondents in the individual study communities having varying perceptions of other climate risks affecting their farming activities (Online Resource 3). Respondents from the study communities had varying perspectives on the major effects of temperature on farming activities. However, the Brofoyedur community had the largest (63%) response rate to the ripening of unmatured crops, while the Osobonpanyin community had the lowest (8%) response rate, believing that temperature changes were less relevant than rainfall (Online Resource 3). Responses to the major effects of rainfall changes varied substantially throughout the study communities. Regardless, the majority (60%) of responses were about seedlings that failed to germinate in Dzorwulu-Borteyman-Tema Community 22, while the least (8%) were about poor crop growth

Table 4 Perception of climate risks for farming activities

Variable	Category	Frequency	Percentage (%)
Climate change poses risk to farming activities	1. Yes	800	100
	2. No	0	0
Climate risks that affect farming activities[a]	1. Drought	791	99
	2. Flood	83	10
	3. Pest and diseases on crops	792	99
	4. Heavy storms	519	65
	5. Livestock diseases	359	45
	6. Erosion/soil fertility	32	4
	7. Heat waves	219	27
	8. Delayed onset of rainfall	187	23
	9. Early cessation of rainfall	443	55
	10. Extreme temperature	800	100
Major effects of temperature on farming activities	1. Poor yields	157	20
	2. Ripening of unmatured crops	343	43
	3. Drying of crops/seedlings	292	36
	4. Not important as rainfall	8	1
Major effects of rainfall on farming activities	1. Lower yields/harvest	369	46
	2. Poor crop growth	92	12
	3. Seedlings unable to germinate	339	42
Major effects of wind on farming activities	1. Crop destruction and losses	800	100
Major effects of extreme events on farming activities	1. Crop destruction	105	13
	2. Losses	273	34
	3. Low productivity	422	53
Overall impact of climate variability and change	1. Food insecurity	184	23
	2. Low income	8	1
	3. Poverty	600	75
	4. Pest and diseases, rots and damages	8	1

[a]The participants had the option to select all the variable categories that were applicable to their case. As a result, each variable category had an expected frequency between 0 and 800, as well as up to 100%. Source: (Field survey, 2023)

in the Emisano community (Online Resource 3). There was no difference in responses to the major effect of wind on farming activities, as all respondents (100%) in the study community reported crop destruction and losses (Online Resource 3). The major effects of extreme events on farming activities varied greatly. The majority (68%) of the Tegbi Aklamatsi community reported low production, while only 10% of the Emisano community reported crop destruction. Climate change has a wide-ranging impact, with 91% indicating poverty in the Emisano community and 8% indicating low income, pests, diseases, rots, and damages in the Osobonpanyin community (Online Resource 3).

Spatial distribution of annual variations and trends in climate variables

Figures 2a–d illustrate the spatial variations of average annual rainfall, maximum and minimum temperatures, and wind speed, while Figs. 2e–g present the trends observed in the aforementioned climatic variables, excluding wind speed, across the zone. Figure 2a shows variability in rainfall across the zone. Notably, rainfall increased from the Central region to the Volta region, with an average annual amount ranging from a high of 1339.9 mm to a low of 978.4 mm between 1981 and 2021 (see Fig. 1 to understand the regional divisions). Thus, the communities located in the Central region experience a greater amount of annual rainfall in comparison to those in the Greater Accra and Volta regions. Figure 2b shows a contrasting pattern in the mean annual maximum temperatures. Here, mean annual maximum temperatures decrease from the Central region to the Volta region, with a range of 29.4 °C to 31.8 °C (Fig. 2b). The zone exhibits variations in mean annual minimum temperatures, ranging from 22.6 °C to 24.1 °C (Fig. 2c). Mean annual minimum temperatures appeared to be higher in some areas of the Greater Accra and Volta regions in comparison to those in the Central (Fig. 2c) (see Fig. 1 to understand the regional divisions). In general, wind speed

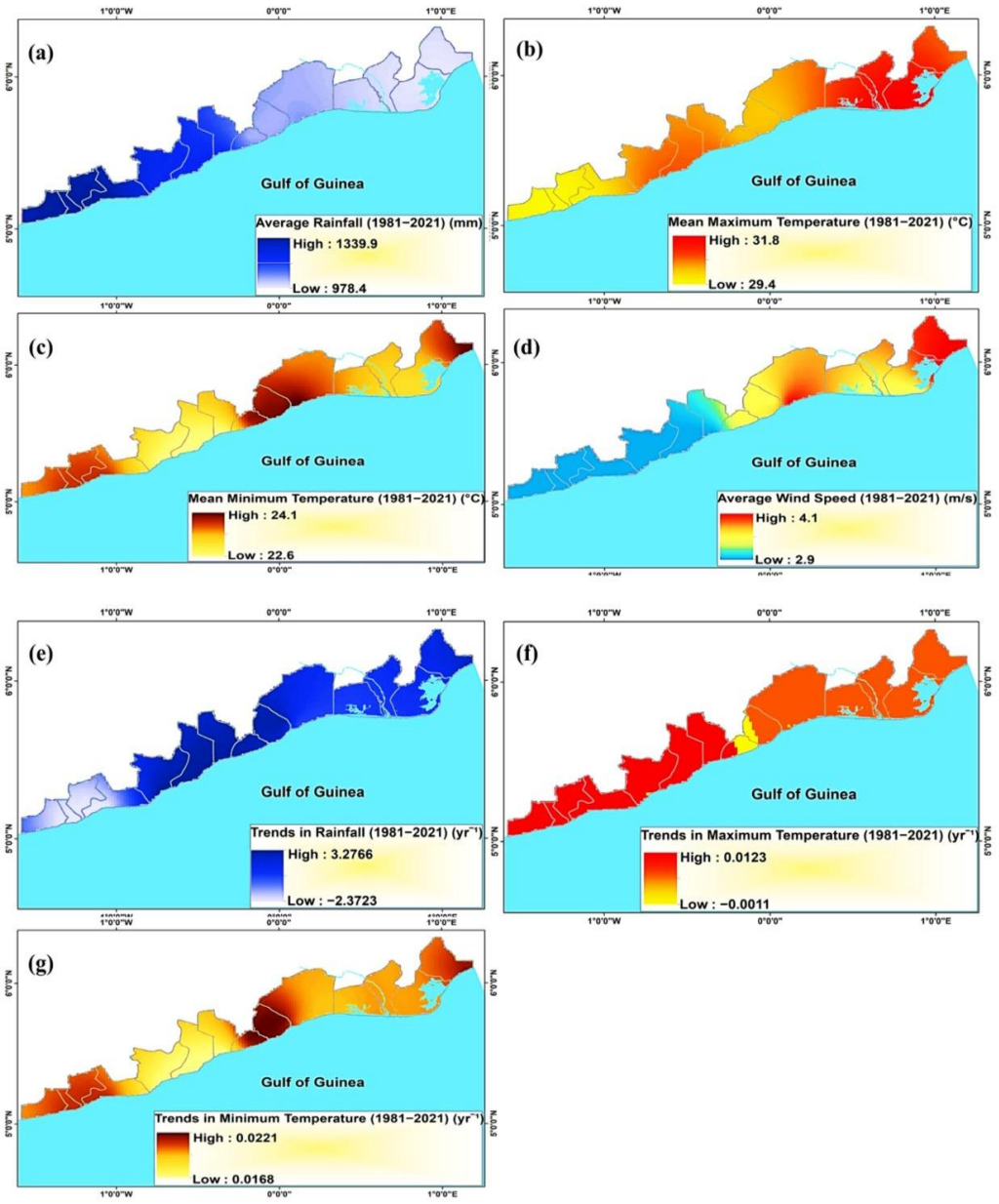


Fig. 2 Spatial variations of average annual rainfall (**a**), maximum (**b**), and minimum (**c**) temperatures, wind speed (**d**), and trends in average annual rainfall (**e**), maximum (**f**), and minimum (**g**) temperatures from 1981 to 2021

increases from the Volta region to the Central region, with an annual average range of 2.9 m/s to 4.1 m/s (Fig. 2d). The Greater Accra and Volta regions showed positive but weak rainfall trends, while the Central region exhibited a combination of positive and negative trends (Fig. 2e). The Central and Volta regions exhibited positive but weak trends in the mean annual maximum temperature, whereas the Greater Accra region displayed both positive and negative trends (Fig. 2f). The annual minimum temperature mean showed positive but weak trends across the zone (Fig. 2g).

Adaptation strategies to mitigate climate risks

Table 5 shows the adaptation or coping strategies utilised by the respondents in order to effectively manage the risks associated with climate change and variability in their farming activities. According to Table 5, 46% of the respondents employ the strategy of cultivating different crops on a single piece of land to adapt to or cope with the risks associated with climate change and variability. Subsequently, 18% of the respondents opted to employ the strategy of utilising improved seed varieties for planting, while only 1% resorted to using their family members as a means of labour in order to minimise costs. The main obstacles impeding the respondents' adoption of adaptation or coping strategies were financial constraints, accounting for 48% of the identified barriers, and the high prices of farm inputs or fertilisers, which constituted 32% of the barriers. The respondents identified the high prices of livestock feed as the least notable constraint, with only 2%.

Online Resource 4 depicts the variations in respondents' adaptation strategies as well as the barriers that limit their adaptation strategies in the study communities. Respondents in the various study communities use a variety of adaptation strategies, as presented in Online Resource 4. The Baifikrom community received the most (57%) responses for cultivating different types of crops, while the Osobonpanyin community received the fewest (4%) responses for using family labour (Online Resource 4). The major barriers to respondents' adoption of adaptive techniques differ substantially across study communities. A substantial number (65%) mentioned financial constraints in the Brofoyedur community, while just 4% reported poor extension services in the Baifikrom community (Online Resource 4).

Themes and constructs based on qualitative data

Participants' adaptation strategies

Figure 3 shows the graphical representation of the themes and constructs an analysis of the participants' adaptation strategies based on interview data derived from the eight farmers who were considered key informants of the study. Online Resource 5 displays a report on the farmers' adaptation strategies, the barriers that limit their strategies, and other factors that aid or hinder adaptation. According to Fig. 3, various themes were identified in the participants' adaptation strategies. These themes ranged from a high network of crop diversification to a low network of monocropping and support from microfinance groups. The networks (in blue dotted lines) show similarities in the adaptation strategies employed by the participants in the various communities. It appeared that participants in the communities of Emisano Togbloku Okor, Adafienu, and Osobonpanyin diversified their crops. The participants are of the view that it is always better to cultivate different types of crops, as they believe that when one crop dies or does not grow well, maybe the other can support it. For example, one participant shared their experience using crop diversification as an adaptation measure and noted: "I grow different types of vegetables like green pepper, cucumber, onion, cabbage, and maize. The maize is on different land." Another participant stated that he cultivates lettuce and cauliflower, which take a few months to harvest, and then cultivates cabbage, cumcumber, okro, or green pepper. A participant who cultivates similar crops three times a year also expressed that:

> It takes three months for the green pepper to mature. I cultivate green peppers three times a year, as well

Table 5 Adaptation strategies and barriers to mitigate climate risks

Variable	Category	Frequency	Percentage (%)
Adaptation strategies	1. Cultivate different types of crops	371	46
	2. Fertilizer application	120	15
	3. Use of family labour	4	0
	4. Plant improved variety of seeds	142	18
	5. Plant drought resistant crops	8	1
	6. Rearing of livestock	47	6
	7. Use irrigation	108	14
Major barriers that limit the adoption of the adaptation strategies	1. Financial constraints	386	48
	2. High prices of farm inputs/fertilizers	255	32
	3. Inadequate government support	62	8
	4. Poor extension services	79	10
	5. High prices of livestock feed	18	2

Source: (Field survey, 2023)

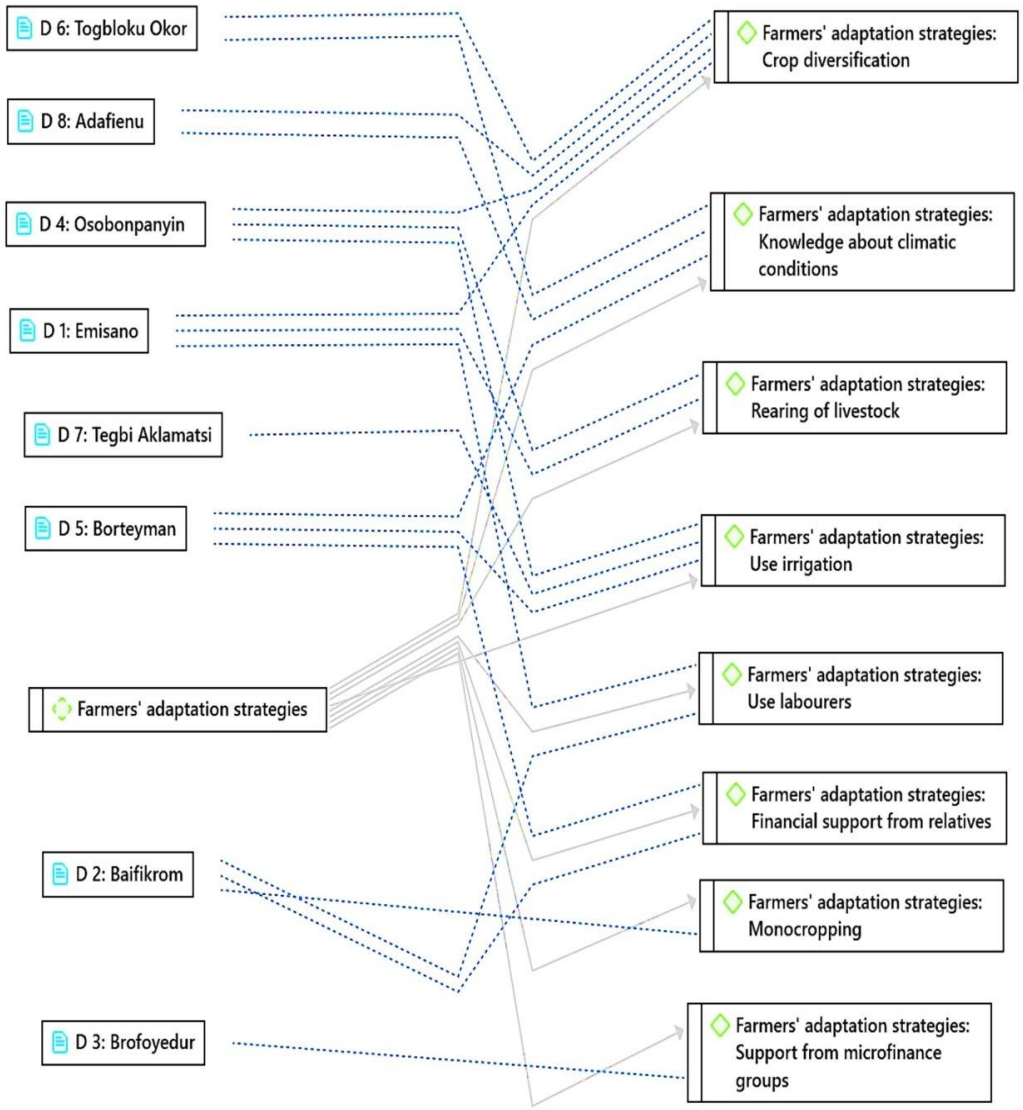


Fig. 3 A network of themes and constructs related to farmers' adaptation strategies in the study communities

as cucumbers. Cucumber farming is very fast. It takes a month and two weeks to mature, and you can sell it to get your money. If I want to take a break from the green pepper farming, I plant cucumber, which is easier to work on than this green pepper (D4: Osobonpanyin).

Some participants, particularly those residing in Borteyman, Togbloku Okor, and Adafienu, have years of experience in farming and possess knowledge regarding the climatic conditions specific to their areas. To strategically plant their crops, they rely on their knowledge of climatic conditions and seasonal variations. Within this particular adaptation strategy, a participant conveyed: "Every season has its own crop to grow. If you grow a particular crop at the wrong time, it will die, and you will not get back the money you put in." A participant again stated that he plants his crops close to the months of May, June, and July (the major season), where rainfall is reliable. Another participant whose understanding of the climatic conditions

helps him to save money by avoiding the need for frequent irrigation, reported that

> It is not common for the rain to come this month (March). Probably next month (April) or May. During these months, we have more rainfall and less irrigation. That also saves us some money. Even if it rains, we still irrigate the land because the land here dries up quickly as the temperatures continue to rise every day (D5: Borteyman).

The participants in the communities of Emisano and Osobonpanyin rear livestock such as goats as an adaptation strategy along with crop diversification, which fetches them money. The participants, particularly those in the communities of Osobonpanyin, Borteyman, and Tegbi Aklamatsi, appeared to use irrigation as a major adaptation strategy. A participant mentioned that he farms all year because he has an irrigation network on his farm. Again, a participant shared that he irrigates his crops with water from a nearby dam, but it is costly. Another participant who has no river or dam near his farm stated that he irrigates his crops with pipe-borne water, which he believes is bad for his crops because of the high ion content. The participants in Emisano and Baifikrom employ farm labourers because they cannot undertake their farm activities alone, especially during harvest. Some of the participants, especially those in the communities of Baifikrom and Borteyman, also receive financial support from their friends and relatives. They consider this important because it helps them adapt. Regarding this matter, a participant indicated that he borrows money from his brother, a public sector employee, who has easier access to loans from banks than him. Aside from this support network, some of the participants also receive assistance from microfinance groups. One participant stated that he and his wife have joined a "susu" (savings and loans) group that provides them with loans. The participant further noted that he can borrow once, and the amount is not huge, and he can borrow again after paying the previous loan.

Barriers that limit participants' adaptation strategies

Figure 4 depicts the graphical representation of the themes and constructs an analysis of barriers that limit participants' adaptation strategies based on interview data derived from the eight farmers who were considered key informants to the study. Figure 4 indicates that the participants encounter several barriers to their adaptation decisions. These barriers include lack of government support, financial constraints, high prices of farm inputs, lack of agricultural extension services, farm losses, the size of farmland, inadequate support from financial institutions (banks), bureaucracy in securing bank loans, the need for irrigation systems, the need for the right adaptation measures, the need for high-quality research institutions, and poor soil nutrients. The network of barriers ranges from a high lack of government support to a low level of farm losses and farmland size.

Figure 4 also reveals a connection between some of the barriers identified. For example, the lack of agricultural extension services and the need for high-quality research institutions are part of the lack of government support. Again, the need for the right adaptation measures and poor soil nutrients are part of farm losses. Inadequate support from financial institutions (banks) and bureaucracy in securing bank loans is also part of financial constraints.

Most of the participants lamented the lack of government support. According to these participants, a lack of government support encompasses several other supports, such as improved agricultural extension services and high-quality research institutions. One participant lamented about the lack of institutional support. A participant again stated that the farmers in his municipality do not receive training from anyone, and that no extension officer has ever been to his farm. Additionally, one farmer lamented about the inadequate, high-quality research institutions that give signals to the farmers on what the season will be like each year. Another farmer shared a similar worry, stating that

> For me, institutional failure is a major problem, despite the incidence of climate change. There should be the right instructions to help us, the farmers, with our adaptation strategies. Why is it that in Burkina Faso, there are tomatoes all year? Perhaps their research institutions are working to help farmers find the right species to grow, unlike here in Ghana (D7: Tegbi Aklamatsi).

The participants again revealed financial constraints as a major barrier to their adaptation decisions. The participants assert that inadequate support from financial institutions (banks) and bureaucracies in securing bank loans further complicates this adaptation barrier. A participant expressed that he cannot do the farming business without having money. A participant again stated that crops such as maize require regular weeding, and it is not easy for him to get money to pay labour costs or buy farm inputs. A participant who has the desire to cultivate more crops noted: "I wish I had more land to plant more, but I cannot afford the price." The participants were also worried about the inadequate support they received from financial institutions and the bureaucracy for securing bank loans. One participant stated that a bank asked him for collateral before they would give him a loan, which he could not afford. Another participant who was able to secure a loan from the bank indicated that the process is tedious; however, he said that if farmers take their time and present the right documents about their farm, they

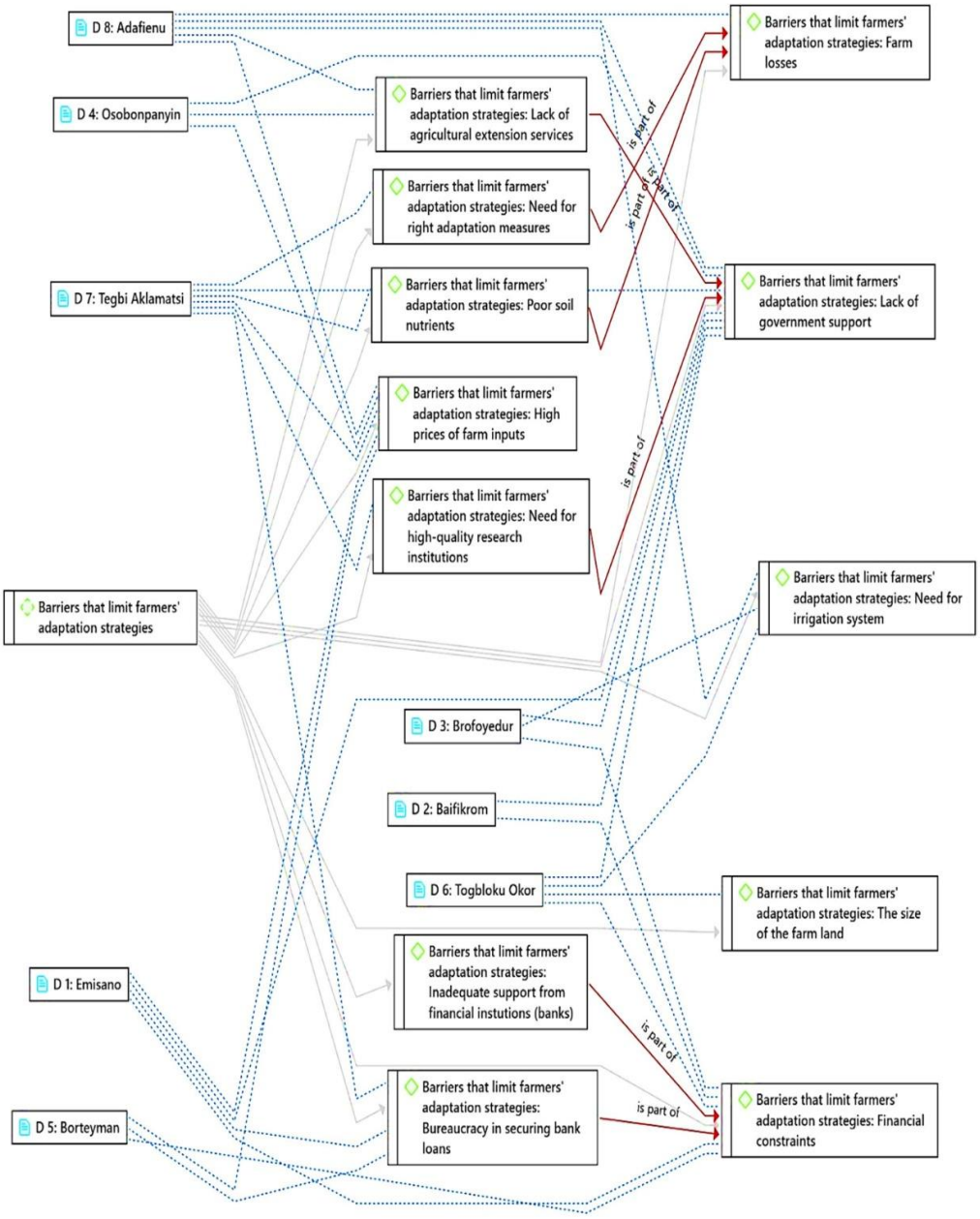


Fig. 4 A network of themes and constructs related to farmers' barriers that limit their adaptation strategies in the study communities

will get the loan they want from the banks. The participants considered the high prices of farm inputs a major concern, as they rely heavily on these inputs for their activities to boost production. On this issue, the participants lamented the high prices of fertilisers and manure, and they urged the government to do something about it to ensure food security in the country. Still on this issue, a participant noted: "The fertilisers are very expensive. The cost of manure, which should be more affordable, has also risen. When we

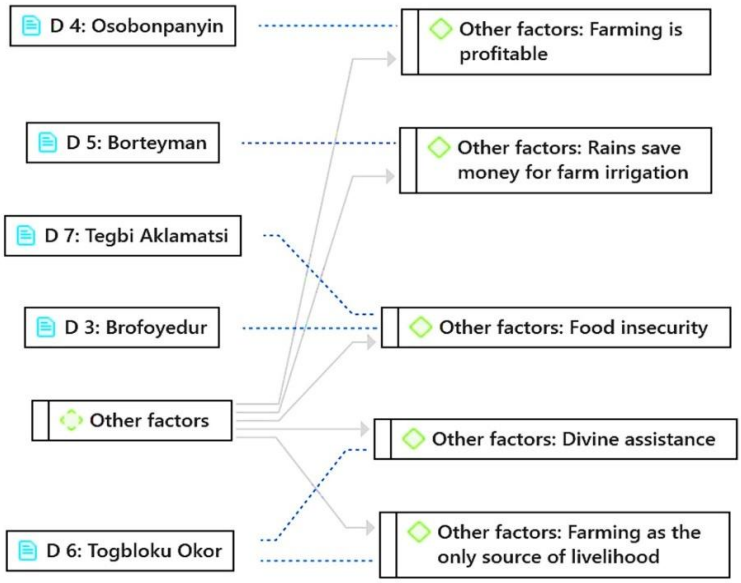


Fig. 5 A network of themes and constructs related to other factors that aid or hinder farmers' adaptation strategies in the study communities

buy fertiliser, instead of spreading it on the farm, we take handfuls and place them on the crop, which is not the best practice."

Some of the participants also expressed concerns about the need for irrigation systems, which they considered a barrier to their adaptation. These participants recognised the value of the use of irrigation even though they did not have access to one. One participant reported that it is better for him to irrigate his crop, but he cannot afford it as there is no river nearby his farm. Regarding the issue of land size, a participant expressed regret over his limited farmland, stating that it is not sufficient for his needs and that he must cultivate various crops on it. The participants complained about farm losses, which they attributed to poor soil nutrients. Regarding this matter, a participant expressed concern and advocated for the implementation of appropriate adaptation measures by stating that

> The pipe-borne water contains ions that harm soil and crops. Even if you use fertiliser, it still does not provide support because the soil here is deficient in nutrients…. Although climate change is a major problem, having the right adaptation measures, like fertiliser applications, will help, but we do not have them (D7: Tegbi Aklamatsi).

Other factors that aid or hinder participants' adaptation strategies

Figure 5 displays the graphical representation of the themes and constructs an analysis of other factors that aid or hinder participants' adaptation strategies based on interview data derived from the eight farmers who were considered key informants to the study. According to Fig. 5, the participants identified several other factors that aid or hinder their adaptation strategies. One of the participants underscored that farming is a profitable venture that everybody, especially youth, should consider undertaking. Another participant pointed out that rainfall reduces the cost of irrigation. Some participants argued that there will be food insecurity in the country due to the low irrigation system utilisation and the wrong adaptation choices. Another participant depends solely on farming for a livelihood and strongly believes in divine (God) assistance in his activities. A participant expressed concern about farming as a profitable venture and noted: "There is money in farming, but people have not realised it." A participant raised concerns about food insecurity, stating

> …If the government wants to see food in the market every day, then they should take agriculture seriously. Something like maize, if we have irrigation systems, we can grow crops like maize all year round. To me, there should not be a shortage of maize in the country. The same applies to some vegetable crops, like tomatoes (D3: Brofoyedur).

Table 6 Binary logistic regression showing the relationship between independent variables and adaptation strategies of farmers

Variables	B	S.E	Wald	df	Sig	Exp(B)	95% C.I. for EXP (B)	
							Lower	**Upper**
Adaptation strategy: Cultivate different types of crops								
Age	−0.059	0.124	0.225	1	0.635	0.943	0.739	1.203
Gender	0.530	0.187	8.050	1	0.005[a]	1.698	1.178	2.448
Education	0.157	0.091	3.001	1	0.083	1.170	0.980	1.398
Years of farming	0.078	0.081	0.933	1	0.334	1.081	0.923	1.266
Constant	−1.480	0.542	7.464	1	0.006[a]	0.228		
Nagelkerke (*pseudo* R^2)	0.025							
Adaptation strategy: Fertilizer application								
Age	−0.395	0.163	5.865	1	0.015[a]	0.674	0.489	0.927
Gender	0.158	0.292	0.295	1	0.587	1.172	0.661	2.075
Education	0.747	0.152	24.278	1	0.000[a]	2.110	1.568	2.840
Years of farming	0.038	0.114	0.114	1	0.736	1.039	0.831	1.300
Constant	−3.105	0.823	14.232	1	0.000[a]	0.045		
Nagelkerke (*pseudo* R^2)	0.094							
Adaptation strategy: Plant improved variety of seeds								
Age	0.751	0.221	11.542	1	0.001[a]	2.119	1.374	3.268
Gender	−0.669	0.231	8.373	1	0.004[a]	0.512	0.326	0.806
Education	−0.805	0.130	38.445	1	0.000[a]	0.447	0.347	0.577
Years of farming	−0.342	0.115	8.869	1	0.003[a]	0.710	0.567	0.890
Constant	0.188	0.776	0.058	1	0.809	1.206		
Nagelkerke (*pseudo* R^2)	0.167							
Adaptation strategy: Rearing of livestock								
Age	1.045	0.343	9.307	1	0.002[a]	2.844	1.453	5.565
Gender	−0.288	0.388	0.551	1	0.458	0.750	0.350	1.604
Education	1.015	0.281	13.027	1	0.000[a]	2.760	1.590	4.790
Years of farming	0.032	0.178	0.031	1	0.859	1.032	0.728	1.464
Constant	−7.636	1.411	29.308	1	0.000[a]	0.000		
Nagelkerke (*pseudo* R^2)	0.088							
Adaptation strategy: Use irrigation								
Age	0.285	0.204	1.959	1	0.162	1.330	0.892	1.984
Gender	0.070	0.258	0.075	1	0.785	1.073	0.647	1.780
Education	−0.580	0.134	18.690	1	0.000[a]	0.560	0.431	0.728
Years of farming	0.079	0.121	0.431	1	0.511	1.083	0.854	1.372
Constant	−1.521	0.787	3.736	1	0.053	0.218		
Nagelkerke (*pseudo* R^2)	0.051							

[a]Significant at 0.05. Source: (Field survey, 2023)

Odds of choosing a specific adaptation strategy using binary logistic regression

The binary logistic regression analysis shows that gender is a significant predictor ($p=0.005$) of whether or not respondents would cultivate different kinds of crops as a way to adapt (Table 6). The Nagelkerke (*pseudo* R^2) is 0.025, showing that gender accounts for only 2.5% of the variations in respondents' adoption of different types of crops as an adaptation strategy. Based on their gender, the odds of respondents choosing to cultivate different types of crops as an adaptation strategy increase by 1.698. The use of fertiliser as an adaptation strategy was significantly predicted by age ($p=0.015$) and education ($p=0.001$). The *pseudo* R^2 is 0.094, indicating that age and education account for just 9.4% of the variation in respondents' use of fertiliser as an adaptation strategy. Based on their age and education, the odds of respondents choosing to use fertiliser as an adaptation strategy increase by 0.674 and 2.110, respectively. Similarly, age ($p=0.002$) and education ($p=0.001$) predicted respondents' adoption of livestock rearing as an adaptation strategy. The *pseudo* R^2 is 0.088, implying that age and education account for only 8.8% of the

variations in respondents' adoption of raising livestock as an adaptation strategy. Based on their age and education, the odds of respondents choosing to raise livestock as an adaptation strategy increase by 2.844 and 2.760, respectively.

Age ($p=0.001$), gender ($p=0.004$), education ($p=0.001$), and years of farming ($p=0.003$) all predicted respondents' choice to plant improved varieties of seeds as an adaptation strategy. The *pseudo* R^2 is 0.691, indicating that age and education account for 69.1% of the variations in respondents' preferences for planting improved seed varieties as an adaptation strategy. The odds of choosing to plant improved varieties of seeds as an adaptation strategy increase with age by 2.119, gender by 0.512, education by 0.447, and years of farming by 0.710. Education was the only factor that significantly predicted irrigation as an adaptation strategy ($p<0.001$). The *pseudo* R^2 is 0.051, indicating that education explains only 5.1% of the variations in respondents' use of irrigation as an adaptation strategy. Based on their education, the odds of using irrigation as an adaptation strategy increase by 0.560. Although the model is a significant predictor of the dependent variable (the various adaptation strategies), given the small variations in the model provided by the *pseudo* R^2, other significant predictors may exist.

Discussion

This study examined smallholder farmers' perceptions of climate risks and adaptation strategies in the coastal Savannah agroecological zone of Ghana. The agricultural sector of many land economies faces substantial risks from climate change and variability, thereby threatening global food security and the livelihoods of people (Brink et al. 2023; Wang et al. 2018). Farmers, particularly those in developing countries, face critical difficulties due to their climate-sensitive agricultural practises and limited capacity for adaptation (IPCC 2014; Yaro 2013). The significance of farmers' perceptions regarding the risks associated with climate change and variability is equally as crucial as the resultant impacts. Consequently, it is imperative to conduct research utilising a bottom-up approach in order to comprehend the societal perspectives on climate change and variability, as well as the adaptive and coping strategies employed by people. specifically, those engaged in small-scale farming.

The results revealed that there has been a notable increase in smallholder farmers' awareness and understanding of climate change and variability. This positive change can be attributed to the enhanced dissemination of information through broadcast media platforms such as television and radio. This finding is consistent with the previous research conducted by Obossou et al. (2023) in the northern region of Benin and Manandhar et al. (2011) in the Rupandehi district of Nepal. The farmers attributed climate change and variability primarily to negative human actions, aligning with the prevailing scientific consensus (IPCC 2014). The gendered dimension of information availability in farmers' awareness and understanding of climate change indicated that both men and women farmers used television more than radio. However, a large number (87%) of men used television more than women (68%). Although both men and women identified deforestation as a major contributor to climate change and variability, the proportions ranged from 83% for men to 54% for women. While the findings are consistent with previous studies by Memon et al. (2023) in Pakistan and Partey et al. (2020) in Northern Ghana, they contradict those of Issa et al. (2015), who reported that personal experiences were the primary source of climate change awareness and understanding among farmers in Nigeria's north-central and north-west agroecological zones. The present study provides a unique contribution to the existing literature by offering a comprehensive and detailed analysis of the farmers' climate risk perception and adaptation strategies in the coastal Savannah agroecological zone. Although the findings align with previous studies conducted in different contexts, this study shows its originality in examining the farmers' perspectives, understandings, and experiences on climate risk and strategies for adaptation in the coastal Savannah agroecological zone, where no study of such nature existed. The study's findings are consistent with and support the existing scientific consensus in the broader literature regarding the increasing adverse effects of climate risks on agricultural activities. This underscores the need for enhanced adaptation strategies across different countries and scales. Farmers have identified deforestation as the primary factor that contributes to climate change and variability. The findings of this study align with the previous research conducted by Codjoe et al. (2014) in Ghana and in the eastern portion of the Amazon, Brazil, by Gatti et al. (2021). The viewpoints of farmers regarding rising temperatures in the region, as well as changes in hot and cold periods, agree with the findings of Batungwanayo et al. (2023) in northeastern Burundi and the IPCC AR5 (Bindoff et al. 2013; IPCC 2014). The perspectives regarding the increase in hot periods and decrease in cold periods within the zone agree with the previous study conducted by Ankrah et al. (2023b). The farmers perceived a decrease in the total annual rainfall in the zone, along with an increase in the intensity of rainfall events.

The analysis of climatic variables revealed greater variability in rainfall patterns across the zone. Previous studies, such as those conducted by Fosu-Mensah et al. (2012), Lawson et al. (2020), and Yamba et al. (2019), have reported the perceptions of farmers regarding the perceived decrease and erratic rainfall in other parts of Ghana, in the Kirundo and Muyinga in northeastern Burundi by Batungwanayo et al. (2023), and in the northern Ethiopian highlands by Hubertus et al. (2023). According to the IPCC's AR5, the SSA region

is expected to experience more erratic rainfall, which could have adverse impacts on crop productivity, pose a threat to food security, and impact the livelihoods of farmers (IPCC 2014). Previous studies by Ntim-Amo et al. (2022) and Yiridomoh et al. (2021) found an increased perception of extreme rainfall events among farmers in Ghana's Sudan and Guinea Savannah agroecological zones. The farmers perceived a decrease in rainfall over the past two decades; however, a study conducted by Ankrah et al. (2023b) indicates that there is a projected increase in rainfall. According to the farmers, there has been an observed increase in the overall wind speed, particularly during the dry season, over the past two decades. The findings of the spatial distribution analysis of wind speed provided support for their assertions, indicating an overall increase in wind speed and a greater degree of variability in the zone.

Again, the farmers perceive extreme temperatures, drought, pests and diseases as the major climate risks that have an impact on their agricultural practices. The major effects associated with temperature risks include the ripening of unmature crops and the drying of crops or seedlings. The farmers have identified a decrease in crop yield as the main impact of changes in rainfall on their agricultural practices. These findings are consistent with the earlier studies conducted by Yaro (2013) in Ghana, by Shah et al. (2023) in Pakistan, and by Tasnim et al. (2023) in northwest Bangladesh. According to the study by Rowhani et al. (2011), variations in temperature and precipitation, both within and between seasons, have a significant impact on cereal crop yields in Tanzania. The main effects of wind speed and extreme events, as determined by the farmers, include crop destruction, losses, and low productivity. This is consistent with the previous studies conducted by Ntim-Amo et al. (2022), Yiridomoh et al. (2021) in other parts of Ghana, in the U.S.A. by Yaddanapudi and Mishra (2022), and in China by Zhang et al. (2017). The farmers believe that the increased risks posed by climate change and variability in their agricultural methods have led to poverty, thereby impacting their means of livelihood and contributing to food insecurity in the country. These assertions made by the farmers support previous studies conducted by Aydinalp and Cresser (2008), Aryal et al. (2020), Brink et al. (2023), Hallegatte and Rozenberg (2017), Hounnou et al. (2023), Zhang et al. (2023), and the IPCC AR5 (IPCC 2014).

The results also showed that the smallholder farmers employed various adaptation or coping strategies, especially the practice of cultivating different crops on a single plot of land and the use of improved seed varieties for planting purposes. The findings are consistent with previous studies conducted in other parts of Ghana, such as those of Asravor (2018), Fosu-Mensah et al. (2012), Sadiq et al. (2019), Yamba et al. (2019), Yaro (2013), and Yiridomoh et al. (2021), and elsewhere, including those of Shah et al. (2023), Tasnim et al. (2023), Batungwanayo et al. (2023), Fahim and Sikder (2022), and Metcalfe et al. (2020). The farmers have identified a number of obstacles that impede their farming activities, with financial constraints and high costs of farm inputs or fertilisers being the main obstacles. This finding agrees with previous studies conducted by Yaro (2013), Batungwanayo et al. (2023), and Shah et al. (2023). The results of the binary logistic regression analysis revealed that the socio-demographic characteristics, namely age, gender, education, and years of farming experience, were found to be significant predictors of the farmers' decision to adopt or employ various adaptation or coping strategies. These strategies included cultivating different types of crops, using fertilisers, engaging in livestock rearing, adopting improved seed varieties, and employing irrigation techniques. This finding is consistent with previous studies conducted by Shah et al. (2023).

This study's limitations include the lack of a sample frame to determine the minimum required sample size for the study communities. This was due to a lack of official records indicating the total number of smallholder farmers in the various municipalities or districts. This could affect how representative the study results are for various study communities and the entire zone. However, the unbiased nature of the sample process, in which 100 farmers were selected from each of the eight communities, ensures fairness and allows for generalisation of the study findings. Lawson et al. (2020) encountered a similar challenge in determining the minimum required sample size for their study on the intersectional perceptions and adaptation strategies of women smallholder farmers in Ghana's Upper West region, as there were no official records available. Also, all eight participants selected for the interview were male, indicating a disparity in gender representation. However, at least five respondents, including the females who participated in the questionnaire survey in each community, identified these key informants. Further research that examines the influence of factors such as farm size, income, credit access, extension services, household size, social networks, information, and social status on the perceptions and adaptation strategies of farmers, particularly women farmers, and the power dynamics they face in accessing resources would be beneficial and contribute to informed policy decisions for the farmers in the zone.

Conclusion

This study examined smallholder farmers' perceptions of climate risks and adaptation strategies in the coastal Savannah agroecological zone of Ghana. The main findings indicate a noticeable increase in understanding and awareness of climate change and variability among farmers. The farmers

attributed climate change and variability to negative human actions. The farmers perceived increasing temperatures, hot periods, and decreasing cold periods, as well as a decrease in the total annual rainfall accompanied by a rise in the intensity of rainfall events across the zone. The findings are consistent with the existing body of scientific literature. The farmers' agricultural practises are adversely impacted by climate risks, such as extreme temperatures, drought, and the proliferation of pests and diseases. The effects that result from these risks include the ripening of unmature crops, the drying of crops or seedlings, a decrease in crop yield, crop destruction, losses, and low productivity. The assertion made by the farmers suggests that the increase in climate risks has resulted in both poverty and food insecurity in the country.

Regardless of the increased risks, the findings indicate that smallholder farmers have implemented various adaptation strategies, such as cultivating different crops on a single plot of land, using improved seed varieties for planting, using fertilisers, and rearing livestock, among others. Despite the adoption of various adaptation strategies by farmers, they encounter numerous obstacles that hinder their farming activities. The obstacles include a range of challenges, such as increased financial constraints, high costs of farm inputs, inadequate government support, and poor extension services, among others.

The findings above have major consequences for the agricultural practises of smallholder farmers in the zone, specifically in relation to the changes in climatic variables. It is anticipated that the majority of risks arising from changes in temperature, rainfall, and related extreme events will persist within the zone. However, the development of an early warning system, increased awareness through mass media, and improved academic engagement in addressing existing and potential risks may prove beneficial for farmers. The improved understanding of the risks resulting from changes in temperature, rainfall, droughts, and floods among farmers will serve as a basis for their informed choices regarding adaptations or coping strategies. The limited implementation of these initiatives for farmers results in a greater tendency for maladaptation, potentially leading to increased risk and resulting negative effects on their livelihoods. Based on the findings of the study, it is evident that the smallholder farmers have already implemented at least one adaptation or coping strategy. However, they are faced with various constraints that limit their ability to adapt or cope, thus necessitating policy interventions and support. It is advised that financial institutions, including both public and private entities, undertake a reduction in interest rates applicable to loans and enhance the flexibility of loan acquisition procedures, with a specific focus on catering to the needs of farmers, particularly smallholder farmers. Ghana's patriarchal society necessitates the implementation of targeted policies by the government and financial institutions, specifically designed to support women farmers. These policies should address the domination faced by women, as well as their limited access to resources such as land and capital and the unequal power dynamics they encounter. It is recommended that the government, through the ministry of food and agriculture, consider implementing subsidies for farm inputs, with a particular focus on fertilisers, in order to enhance affordability and availability for farmers. Taking a step in this particular direction would consequently contribute to the enhancement of the economic status, the safeguarding of agricultural practises, and the improvement of the livelihoods of the farmers.

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Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Johnson Ankrah]. The first draft of the manuscript was written by [Johnson Ankrah] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The data used in this study is available upon request.

Declarations

Ethics approval The ethics commission of the Faculty of Arts and Humanities at the University of Porto provided approval for the conduct of the study with resolution No. 31/CEFLUP/.

Informed consent The research ethics commission of the Faculty of Arts and Humanities at the University of Porto reviewed and provided approval for the data collection instruments used in the study. Prior to the start of the interview, the participant was provided with a consent form that outlined their rights as a participant, such as the voluntary nature of the interview and their prerogative to withdraw from the study or request the removal or deletion of their previously recorded responses.

Competing interest The authors declare no competing of interest.

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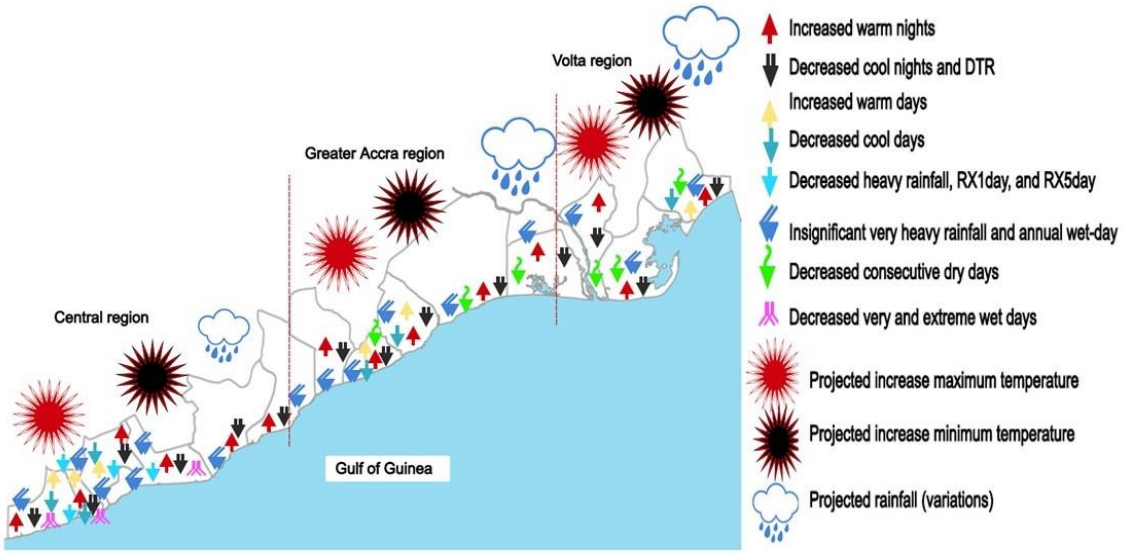
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CHAPTER 3: Projection of possible future climate change scenarios for the coastal savannah agroecological zone of Ghana

3.1. Extreme Temperature and Rainfall Events and Future Climate Change Projections in the Coastal Savannah Agroecological Zone of Ghana

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Extreme Temperature and Rainfall Events and Future Climate Change Projections in the Coastal Savannah Agroecological Zone of Ghana

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Abstract: The global climate has changed, and there are concerns about the effects on both humans and the environment, necessitating more research for improved adaptation. In this study, we analyzed extreme temperature and rainfall events and projected future climate change scenarios for the coastal Savannah agroecological zone (CSAZ) of Ghana. We utilized the ETCCDI, the RClimDex software (version 1.0), the Mann–Kendall test, Sen's slope estimator, and standardized anomalies to analyze homogeneity, trends, magnitude, and seasonal variations in temperature (T_{max} and T_{min}) and rainfall datasets for the zone. The SDSM was also used to downscale future climate change scenarios based on the CanESM2 (RCP 2.6, 4.5, and 8.5 scenarios) and HadCM3 (A2 and B2 scenarios) models for the zone. Model performance was evaluated using statistical methods such as R^2, RMSE, and PBIAS. Results revealed more changepoints in T_{min} than in T_{max} and rainfall. Results again showed that the CSAZ has warmed over the last four decades. The SU25, TXn, and TN90p have increased significantly in the zone, and the opposite is the case for the TN10p and DTR. Spatially varied trends were observed for the TXx, TNx, TNn, TX10p, TX90p, and the CSDI across the zone. The decrease in RX1day, RX5day, SDII, R10, R95p, and R99p was significant in most parts of the central region compared to the Greater Accra and Volta regions, while the CDD significantly decreased in the latter two regions than in the former. The trends in CWD and PRCPTOT were insignificant throughout the zone. The overall performance of both models during calibration and validation was good and ranged from 58–99%, 0.01–1.02 °C, and 0.42–11.79 °C for R^2, RMSE, and PBIAS, respectively. T_{max} is expected to be the highest (1.6 °C) and lowest (−1.6 °C) across the three regions, as well as the highest (1.5 °C) and lowest (−1.6 °C) for the entire zone, according to both models. T_{min} is projected to be the highest (1.4 °C) and lowest (−2.1 °C) across the three regions, as well as the highest (1.4 °C) and lowest (−2.3 °C) for the entire zone. The greatest (1.6 °C) change in mean annual T_{max} is expected to occur in the 2080s under RCP8.5, while that of the T_{min} (3.2 °C) is expected to occur in the 2050s under the same scenario. Monthly rainfall is expected to change between −98.4 and 247.7% across the three regions and −29.0 and 148.0% for the entire zone under all scenarios. The lowest (0.8%) and highest (79%) changes in mean annual rainfall are expected to occur in the 2030s and 2080s. The findings of this study could be helpful for the development of appropriate adaptation plans to safeguard the livelihoods of people in the zone.

Keywords: climate change; temperature and rainfall extreme indices; climate projection; statistical downscaling; SDSM; coastal Ghana

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1. Introduction

The global climate has changed, and there are concerns about its impacts. Global land surface temperatures increased by 0.85 °C between 1880 and 2012 [1]. The last three

decades have been warmer than every other decade since 1850 [1,2]. While temperature increases have been observed in nearly every region of the world, rainfall trends and the magnitude of change vary by region and season [1,3–5]. The IPCC [1] reported an increase in rainfall of 0.5–1% per decade in the middle and high latitude regions of the Northern Hemisphere and 0.2–0.3% in the tropical regions during the twentieth century. In their study, Maidment et al. [4] noted an increase and a decrease in annual rainfall in the Sahel, Southern Africa, and Eastern Africa, respectively. Although the majority of climate change research has focused on the changes in the average climate [6], significant attention has been given in recent decades to the variability in climate [7]. Extreme climate or weather events have negative effects on society, the economy, and the environment [8–12]. Numerous studies conducted over the past century have revealed significant changes in climate variables [13–15]. Alexander et al. [3] and Frich et al. [13] have recorded changes in the frequency and severity of extreme events on a global scale. Similar research has been conducted in North America [16,17], Europe [18], Asia [14,19], South America [20,21], Oceania [22,23], and Africa [24,25].

According to the IPCC's fifth assessment report (AR5) [1], since 1950, the number of cold days and nights and hot days and nights has decreased and increased, respectively, in most land regions. In addition, the IPCC [1] reports with high confidence that the frequency of extreme events such as heat waves has increased in larger portions of Europe, Asia, and Australia, but with moderate confidence for other regions such as West Africa. Over Africa and the West African region, confidence is moderate because of the limited number of weather stations and their unequal distribution [26,27]. In addition, there is a dearth of high-quality long-term data and limited availability of data [8,28,29]. As a result, data on daily weather and climate extreme events are scarce in developing regions of the world [24,30].

Few studies have focused on extreme weather or climate events [29]. According to De Longueville et al. [31], the outcomes of extreme events in the West African subregion are contradictory and inconsistent. For example, New et al. [24] noted an increase in extreme rainfall in Nigeria. Hountondji et al. [32] reported stability in Benin's rainfall indices from 1960 to 2000. On the contrary, Obada et al. [33] reported a general increase in all wet indices in Benin over 1991–2010. Mouhamed et al. [34] found a significant decrease in the number of cold nights, as well as frequent warm days and warm spells, and concluded that the West African Sahel warmed from 1960 to 2010. Similarly, Barry et al. [26] emphasized the frequency of warm days and nights and the rarity of cold days and nights in West Africa's climate. Ghana, which is also a part of West African territory, is not an exception to the lack of long-term climate data and has limited research on extreme weather or climate events. Increases in yearly temperature indices were observed by Larbi et al. [35] for the Vea catchment in Ghana. Again, Atiah et al. [36] found a significant decrease in wet extreme indices over Volta Lake and an increase in wet extreme indices over northern Ghana. In addition, Braimah et al. [37] found no significant trends in the number of very wet and extremely wet days in southern Ghana. Variability in temperature and rainfall, as well as an increase in the frequency of extreme weather or climate events, have devastating effects on society, especially in West Africa [38,39] and Ghana, where most of the population relies on rain-fed agriculture [40,41].

As a result of the demand for additional investigation into the consequences of extreme weather and climate events, the Expert Team on Climate Change Detection and Indices (ETCCDI) has established a set of extreme rainfall and temperature indices [42]. Using these indices, we may examine climate and weather extremes consistently [42]. There are currently twenty-seven indices in use because of the modification of the ETCCDI due to the difficulties in defining certain indicators, such as heat waves [42]. Anthropogenic activities have been identified as the cause of the current 1 °C (0.8–1.2 °C) global warming compared to pre-industrial levels [43]. This value is projected to increase by 0.5 °C between 2030 and 2052 [43]. Consequently, climate-related threats to humans and natural systems are widespread [1,44–50].

Various climate research centers have developed general circulation models (GCMs) that aid in forecasting, modeling, and predicting weather and climate change to get an accurate picture of the future climate change. GCMs are recognized as appropriate tools for assessing climate change and variability [49]. However, the horizontal resolution of GCMs, which ranges from 250 to 600 km, is insufficient for most local impact studies [44,45]. In addition, the application of GCMs requires significant computational resources, making it unrealistic for most developing nations [45]. Despite these limitations, numerous dynamical and statistical downscaling techniques and tools have been developed. Wilby and Wigley [51] thoroughly reviewed the most frequently utilized downscaling techniques and discussed their limitations and future application challenges. Statistical downscaling is more flexible, cheaper, and easier to compute compared to dynamical downscaling [51,52].

In recent decades, there has been an increase in the use of statistical downscaling tools in conjunction with GCM outputs such as the second generation Canadian Earth System Model (CanESM2), the first, second, and third versions of the Canadian Coupled Global Climate Models (CGCM1, 2, and 3), the Hadley Centre Coupled Model versions 2 and 3 (HadCM2 and 3), and the Institut Pierre Simon Laplace model (IPSL-CM5A-MR). As one of its objectives, statistical downscaling evaluates the superiority of statistical over dynamic models and compares many statistical models [44,45]. Widely used statistical downscaling tools include the Statistical Downscaling Model (SDSM) and the Long Ashton Research Station Weather Generator (LARS-WG). The SDSM uses a method based on regression [53], whereas the LARS-WG relies on a stochastic weather generator [54]. The statistical downscaling method has been utilized in different regions of the world [55–61]. Numerous research studies (e.g., [44,45,62–66]) have reported improved model performance using the statistical downscaling technique. Khan et al. [67,68] also measured the uncertainty of the same method when they downscaled the daily precipitation and the maximum and minimum temperatures in Quebec, Canada.

As the application of statistical downscaling tools continues to increase, Ghana's contribution remains limited, particularly in coastal zones. Few research studies, such as [44,69–71], have utilized the SDSM in Ghana. It should be noted that these studies are confined to the river catchments and basin areas (Vea Catchment, White and Black Volta Basins) of the country, to the exclusion of other equally important regions, such as the coastal zones. The analysis of extreme weather or climate events and the projection of future climate change for the coastal zones of Ghana are necessary considering the immense socio-ecological contributions.

This present study has two purposes. The first part analyzed a suite of ETCCDI and their trends over space and time in the coastal Savannah agroecological zone of Ghana. Here, the study specifically analyzed changepoints and homogenization, the long-term changes in extreme temperature and rainfall indices and trends, and the decadal variations and anomalies of temperature and rainfall. The second part employed the SDSM tool to downscale future climate change scenarios based on two GCMs (CanESM2 and HadCM3). Here, the monthly changes in future maximum and minimum temperatures and rainfall were projected for the 2030s, 2050s, and 2080s, as well as the projected annual change. While the present study contributes to the limited literature on climate change in Africa and Ghana in particular, the results also stand to benefit the agriculture sector of Ghana and the smallholder farmers in coastal Ghana, to be precise. The present study therefore encourages climate action in Ghana.

2. Materials and Methods

Here, we describe the methods and statistical measures used to analyze the extreme temperature and rainfall indices (Section 2.2) and future climate change projections (Section 2.3) in the zone.

2.1. Study Area

The coastal Savannah agroecological zone is one of the six agroecological zones located on the central and eastern coasts of Ghana (Figure 1). The zone is part of the central, Greater Accra, and Volta administrative regions of Ghana (Figure 1). The elevation of the zone ranges from the lowest point of −3.8 m from the coast to the highest point of 641.2 m inland (Figure 1). The zone has two rainfall seasons: the major, from April to July (with maximum rainfall in June), and the minor, from September to early November (with maximum rainfall in October) [72,73]. The dry season begins in late November and continues until March. Although the zone has a double maxima rainfall regime, it receives the least amount of rainfall out of the six agroecological zones in Ghana [73]. The average monthly temperature ranges from a minimum of 24.7 °C in August to a maximum of 32.7 °C in March [74]. Most of the zone's vegetation is grassland, with few trees in the central portion and shrubs, thickets, and mangroves in the eastern portion [73]. Given its coastal nature, the zone makes a substantial contribution to Ghana's gross domestic product [73]. Agriculture, fishing, tourism, trade, transportation, and services are the principal economic activities in the zone [72]. Among the major towns are Accra (the capital city), Cape Coast, Elmina, Moree, Saltpond, Apam, Winneba, Bortianor, Tema, Prampram, Ada Foah, Anloga, Keta, and Denu (Figure 1). Table 1 shows the coordinates and population of the major towns, which also served as the data stations for the study.

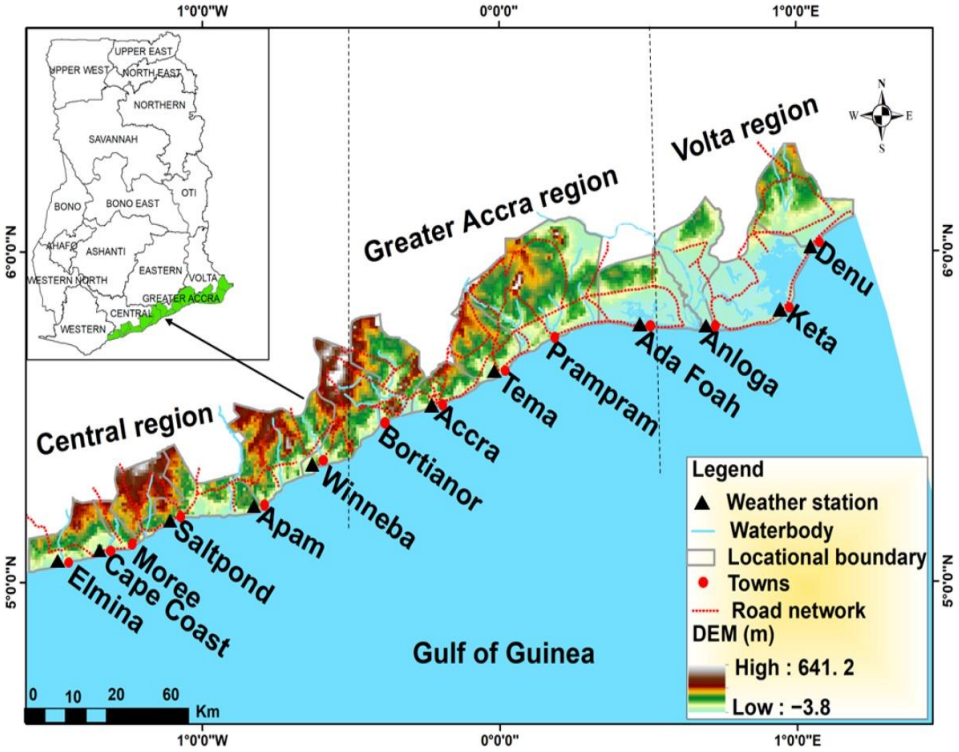


Figure 1. Map showing the study locations and the coastal Savannah agroecological zone of Ghana.

Table 1. Study locations, coordinates, and population. **Source:** Ghana Statistical Service (GSS) [73].

S/N	Location	Latitude	Longitude	Population
1	Accra	5° 60′ N	0° 18′ W	1,665,086
2	Ada Foah	5° 46′ N	0° 37′ E	71,671
3	Anloga	5° 47′ N	0° 53′ E	22,722
4	Apam	5° 17′ N	0° 44′ W	135,189
5	Bortianor	5° 30′ N	0° 20′ W	32,485
6	Cape Coast	5° 06′ N	1° 15′ W	169,894
7	Denu	6° 03′ N	1° 11′ E	160,756
8	Elmina	5° 05′ N	1° 20′ W	144,705
9	Keta	5° 45′ N	0° 30′ E	147,618
10	Moree	5° 07′ N	1° 12′ W	117,185
11	Prampram	5° 43′ N	0° 07′ E	14,897
12	Saltpond	5° 20′ N	1° 05′ W	144,332
13	Tema	5° 44′ N	0° 01′ E	402,637
14	Winneba	5° 21′ N	0° 37′ W	68,597

2.2. Data Sources and Methods of Analysis

2.2.1. Observed Data

Observed daily maximum (T_{max}) and minimum (T_{min}) temperature and rainfall data that spanned from 1981 to 2021 was obtained from the Ghana Meteorological Agency (GMet) and the National Aeronautics and Space Administration/Prediction of Worldwide Energy Resources (NASA/POWER). Data for 11 stations, including Accra, Ada Foah, Anloga, Apam, Cape Coast, Denu, Elmina, Keta, Saltpond, Tema, and Winneba, were provided by the GMet, while those of Moree, Bortianor, and Prampram were acquired from the NASA/POWER satellite data. The R-Instat software (version 0.70) was employed to check for missing gaps in the station data obtained from the GMet. Under this analysis, the number of missing gaps in each dataset was less than 2%. In developing nations, climate data quality is a major obstacle [44], and as reiterated by Wilby et al. [75], the regions most susceptible to climate variability also have the largest data gaps.

With less than 2% missing data in each dataset, the complete case analysis could have been an acceptable method [76]. However, we used multiple imputation by chained equations (MICE) to fill in the gaps. MICE was chosen because it has the capacity to fill in missing values in the original dataset by creating multiple missing values [77,78]. In this method, a prediction model is developed for the target attribute, and missing values are imputed based on the observed values for a particular station. Thus, missing values become indicative of the observed data. Recent research conducted by Abdullah et al. [79] demonstrates the suitability of the MICE approach. See Azur et al. [80] for more information about the MICE method, including the imputation procedure and relevant software.

2.2.2. Homogeneity Test and Homogenization

We utilized the RClimDex software (version 1.0) (http://etccdi.pacificclimate.org/software.shtml accessed on 15 September 2022) to examine each station's daily T_{max}, T_{min}, and rainfall datasets for any anomalous values. Here, we first determined whether a situation existed in which the daily T_{max} was equal to or less than the T_{min} and rainfall was less than zero. Again, we highlighted outliers within four standard deviations in each of the datasets [81]. Additional evaluations were performed on the detected outliers to keep those that matched the value for a certain week or month. Without a suitable replacement for the highlighted values, we marked them as missing.

The RHtestsV4 package (http://etccdi.pacificclimate.org/software.shtml accessed on 15 September 2022) was further employed to check for homogeneity in the T_{max} and T_{min} datasets. So, the RHtestsV4 package made it possible to turn the daily T_{max} and T_{min} data into monthly datasets. During this phase, there were also a number of other steps, such as finding a reference dataset for the monthly T_{max} and T_{min} for homogenization, using the RHtests_dlyPrcp package (http://etccdi.pacificclimate.org/software.shtml accessed on

15 September 2022) for rainfall, and using the Quantile Matching (QM) adjustment method for the final homogenization.

According to Wang and Feng [82], a reference dataset is utilized to increase the precision of homogeneity analysis. Using the Penalized Maximal F (PMF) test, the homogeneity of the monthly T_{max} and T_{min} datasets from each of the 14 stations was evaluated [83,84]. This method is strongly advised for homogeneity analysis of reference datasets [82,85]. Through this analysis, it was determined that the Ada Foah station was homogeneous for both the T_{max} and T_{min} datasets; therefore, it was used as the reference series.

The Penalized Maximal t (PMT) test was then used to determine whether the monthly T_{max} and T_{min} datasets were homogeneous [83,84]. The base-minus-reference series was analyzed using this test to determine the significance and location of the changepoint and to develop a regression model to estimate the magnitude of the change [82]. Several research studies, such as works of [79,86,87], have demonstrated the superiority of the PMT test for inhomogeneity and changepoint analysis over other traditional approaches. Wang and Feng [82,85] have advised against using daily T_{max} and T_{min} datasets for PMT tests due to the noisy nature of daily time series and their computationally intensive nature, which may cause erroneous changepoint detection. Therefore, the monthly T_{max} and T_{min} datasets were utilized for the change point analysis. In addition, because the 14 stations lacked metadata that could have assisted us in analyzing the detected changepoints, we kept only Type-1 changepoints, which were significant even without metadata.

Due to the non-Gaussian and variable nature of rainfall [79], identifying an appropriate reference series is always a challenge [82,85]. For changepoint detection in rainfall datasets, the RHtests dlyPrcp package (http://etccdi.pacificclimate.org/software.shtml accessed on 15 September 2022) was used rather than the PMT test. According to Wang et al. [88], the RHtests dlyPrcp package converts a Box-Cox power transformation procedure into a common trend two-phase regression-model-based test that can detect changepoints in non-Gaussian datasets. Only the Type-1 changepoints were kept in this analysis.

Subsequently, the T_{max}, T_{min}, and rainfall datasets were homogenized with the use of the QM adjustment method. In this case, the QM adjustments for the various non-homogeneous datasets made use of the identified Type-1 changepoints. To make sure the QM adjustment process did not create any duplicated values, the homogenized datasets were again examined for unrealistic values. The outcome was a homogenized dataset in which the patterns of daily T_{max}, T_{min}, and rainfall data were consistent both prior to and after the changepoint analysis [88]. Wang et al. [88] went into greater detail about the QM adjustment process.

2.2.3. Calculation of Extreme Climate Indices

In this study, we utilized 23 out of the 27 ETCCDI variables (http://etccdi.pacificclimate.org/software.shtml accessed on 15 September 2022) to analyze extreme climatic events in the coastal Savannah agroecological zone of Ghana. Table 2 shows the list of the indices that were employed in this study. From Table 2, the 23 selected indices can be broadly grouped into absolute, percentile, and threshold categories [3,13]. The indices were calculated using 1981–2010 as the baseline period.

2.2.4. Trend Analysis

The Mann–Kendall (MK) test [89,90] was used to analyze trends in extreme climate indices, while Sen's slope estimator was used to assess magnitudes of change [91]. The MK is a nonparametric test that compares the presence of a trend in a time series to the null hypothesis of no trend [92]. See da Silva et al.'s [92] work for more information on the MK test and Sen's slope estimator. In this analysis, the Kendall tau statistic and its corresponding p-value were used to show the extent of the change, whether it was increasing or decreasing, and its significance. The MK test and Sen's slope estimator were given confidence levels of 5% and 95% in this study, respectively. The MK test and Sen's slope estimator were applied to the 14 individual stations first, then to the three regions

(central, Greater Accra, and Volta), and finally to the entire zone (the average indices of all the 14 stations).

Table 2. Description and definition of climate indices.

Type	Indices	Description	Definition	Units
Temperature indices	TR20	Tropical nights	The annual count of days when daily minimum temperature is greater than 20 °C	Days
	CSDI	Cold spell duration index	A sequence of 6 or more days where daily minimum temperature is below the 10th percentile	Days
	WSDI	Warm spell duration index	A sequence of 6 or more days where daily maximum temperature is exceeds the 90th percentile	Days
	SU25	Summer days	The annual count of days where daily maximum temperature exceeds 25 °C	Days
	TNx	Max T_{min}	Computes monthly or annual maximum of daily minimum temperature	°C
	TNn	Min T_{min}	Computes monthly or annual minimum of daily minimum temperature	°C
	TN10p	Cool nights	Computes monthly or annual proportion of minimum temperature below 10th percentile	Days
	TN90p	Warm nights	Computes monthly or annual proportion of minimum temperature above 90th percentile	Days
	TXx	Max T_{max}	Computes monthly or annual maximum of daily maximum temperature	°C
	TXn	Min T_{max}	Computes monthly or annual minimum of daily maximum temperature	°C
	TX10p	Cool days	Computes monthly or annual proportion of maximum temperature below 10th percentile	Days
	TX90p	Warm days	Computes monthly or annual proportion of maximum temperature above 90th percentile	Days
	DTR	Diurnal temperature range	Computes the mean daily diurnal temperature range. The frequency of observation can either be monthly or annual	°C
Precipitation indices	R10	Number of heavy precipitation days	Computes the annual count of days where daily precipitation is more than 10 mm per day	Days
	R20	Number of very heavy precipitation days	Computes the annual count of days where daily precipitation is more than 20 mm per day	Days
	SDII	Simple precipitation index	Computes the annual sum of precipitation in wet days (days with precipitation over 1 mm) during the year divided by the number of wet days in the years	mm
	CDD	Consecutive dry days	Maximum number of days when precipitation is less than 1 mm	Days
	CWD	Consecutive wet days	Maximum number of days when precipitation is more than 1 mm	Days
	RX1day	Max 1-day precipitation amount	Computes monthly maximum 1-day precipitation	mm
	RX5day	Max 5-day precipitation amount	Computes monthly maximum consecutive 5-day precipitation	mm
	R95p	Very wet days	Computes the annual sum of precipitation in days where daily precipitation exceeds the 95th percentile	mm
	R99p	Extremely wet days	Computes the annual sum of precipitation in days where daily precipitation exceeds the 99th percentile	mm
	PRCPTOT	Annual total wet-day precipitation	Computes the annual sum of precipitation in wet days (days where precipitation is at least 1 mm)	mm

We looked at the seasonal variability of climate indices again over the last four decades (1981–1990, 1991–2000, 2001–2010, and 2011–2020). The year 2021 was excluded because including it would have added one more year to the last decade, given that the data period was 41 years long. Following the work of Abdullah et al. [79], we first examined the decadal variations of T_{max}, T_{min}, and rainfall for the three regions using a graphical representation. Following that, we used Welch's two-sample t test (assuming unequal variance) to see if the mean changes between decades were statistically significant [79,93]. Furthermore, we examined the seasonal (wet, minor, and dry season) values for T_{max}, T_{min}, and rainfall in each decade for the three regions. Finally, we used the standardized anomaly

to examine changes in climatic variables over the last several decades. Based on the study by Larbi et al. [35], we used the standardized anomaly computation shown below.

$$SA = \frac{(x - \mu)}{\sigma} \quad (1)$$

where x represents the seasonal value of the climatic variable, μ shows the long-term average, and σ indicates the standard deviation.

2.3. General Circulation Models (GCMs) Data

In addition to the observed daily data described in Section 2.2.1, we used 26 daily atmospheric reanalysis variables obtained from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) for the periods 1961–2005 for the CanESM2 (https://climate-scenarios.canada.ca/?page=pred-canesm2 accessed on 17 September 2022) and 1961–2001 for the HadCM3 (https://climate-scenarios.canada.ca/?page=pred-hadcm3 accessed on 17 September 2022). Predictors are large-scale variables that are stored in GCM archives. The CanESM2 and HadCM3 NCEPs have spatial resolutions of 2.5° and 2.5°, respectively, with uniform longitude and latitude. The CanESM2 predictors for the central area are available in a GCM box (BOX_001X_34Y) and for Greater Accra and Volta (BOX_001X_35Y), while the HadCM3 predictors are available in a single GCM box (BOX_01X_30Y) for downscaling.

The CanESM2 and HadCM3 NCEPs are used for model calibration, while the predictors are used for validation and future projections. CanESM2 large-downscale predictor variables are available under the RCP2.6, RCP4.5, and RCP8.5 scenarios for future climate projections from 2006–2100, while HadCM3 large-downscale predictor variables are available under the A2 and B2 scenarios for future climate projections from 1961–2099. The study makes use of model data from Coupled Model Intercomparison Project phases 3 (CMIP3) and 5 (CMIP5). The principal interest is in assessing historical behavior and forecasting future coupled atmospheric-ocean general circulation models (AOGCMs). To generate future T_{max}, T_{min}, and rainfall, the statistical downscaling model (SDSM) was used. In analyzing the effects of climate change on climatic variables, the reference periods for the CanESM2 and HadCM3 are 1981–2010 and 1981–2006, respectively, while 2011–2100 and 2007–2099 are considered the future for the CanESM2 and HadCM3, in that order. Because their daily predictor variables are freely available to be inputted into the SDSM [56], the CanESM2 and HadCM3 GCMs were used in this study. Table 3 has a list of all 26 of the CanESM2 and HadCM3 daily predictor variables from NCEP.

2.3.1. Statistical Downscaling Model (SDSM)

Wilby et al. [94] created the SDSM by combining stochastic weather generators with multiple linear regression to construct local weather variables based on the statistical relationship between large-scale predictors and local climate variables. Regression-based downscaling is an established and often employed methodology [95]. The SDSM can downscale GCM outputs by establishing a statistical link between GCM variables (predictors) and local weather variables (predictands) using multiple linear regression models and stochastic bias-correction approaches [96]. To generate the daily local T_{max}, T_{min}, and rainfall using the SDSM, we used the CanESM2 acquired from the Canadian Center for Climate Modeling and Analysis as CMIP5 and the HadCM3 from the United Kingdom Hadley Centre as CMIP3, in addition to the NCEP data. Synthetic weather data were made using the CanESM2 RCP2.6, RCP4.5, and RCP8.5 scenarios from 2011–2100 and the HadCM3 A2 and B2 scenarios from 2007–2099.

The SDSM downscaling procedure includes the following steps: screening of predictor variables; model calibration; weather generation and generation of synthetic daily weather data; future ensemble data generation using predictor variables from the GCM; and summary statistics and results comparison for both observed and downscaled data [95,97]. Screening for significant predictors is an important step in statistical downscaling for model

calibration in the SDSM [94]. Statistical methods are used to choose predictors, and at least two predictors are enough during the screening process [98].

Table 3. CanESM2 and HadCM3 predictor variables used for downscaling.

	CanESM2		HadCM3	
No.	**Variable**	**Description**	**Variable**	**Description**
1	mslp	Mean sea level pressure	mslp	Mean sea level pressure
2	p1_f	Surface airflow strength	p_f	Surface airflow strength
3	p1_u	Surface zonal velocity	p_u	Surface zonal velocity
4	p1_v	Surface meridional velocity	p_v	Surface meridional velocity
5	p1_z	Surface velocity	p_z	Surface velocity
6	p1th	Surface wind direction	p_th	Surface wind direction
7	p1zh	Surface divergence	p_zh	Surface divergence
8	p5_f	500 hPa airflow strength	p5_f	500 hPa airflow strength
9	p5_u	500 hPa zonal velocity	p5_u	500 hPa velocity
10	p5_v	500 hPa meridional velocity	p5_v	500 hPa meridional velocity
11	p5_z	500 hPa vorticity	p5_z	500 hPa vorticity
12	p500	500 hPa geopotential height	p500	500 hPa geopotential height
13	p5th	500 hPa wind direction	p5th	Mean sea level pressure
14	p5zh	500 hPa divergence	p5_zh	500 hPa divergence
15	p8_f	850 hPa airflow strength	p8_f	850 hPa airflow strength
16	p8_u	850 hPa zonal velocity	p8_u	850 hPa zonal velocity
17	p8_v	850 hPa meridional velocity	p8_v	850 hPa meridional velocity
18	p8_z	850 hPa vorticity	p8_z	850 hPa vorticity
19	p850	850 hPa geopotential height	p850	850 hPa geopotential height
20	p8th	850 hPa wind direction	p8th	850 hPa wind speed
21	p8zh	850 hPa divergence	p8zh	850 hPa divergence
22	prcp	Precipitation	r500	Relative humidity at 500 hPa
23	s500	Specific humidity at 500 hPa height	r850	Relative humidity at 850 hPa
24	s850	Specific humidity at 850 hPa height	rhum	Near surface relative humidity
25	shum	Surface specific humidity	Shum	850 hPa geopotential height
26	temp	Mean temperature at 2m	temp	Mean temperature

To downscale the data from the given predictand and selected predictor variables, the calibration model was used in multiple regression equations. The model was designed to downscale T_{max}, T_{min}, and rainfall on a daily and monthly basis. The modeled data were adjusted to reflect the observed data using bias correction. The weather generator makes excellent use of independent data to validate the calibrated model. This procedure generates synthetic daily weather datasets for the specified period as well as a parameter file generated during the calibration stage using regression model weights. As a result, the SDSM provides a summary statistic that can be used to compare observed and modeled data. All 26 large-scale predictors from the NCEP were screened in this study, and the two that were found to be significant were used for model calibration.

The use of fewer predictors reduces computation time and improves the efficiency of the downscaling process [99]. The period for calibrating and validating the model between predictor and predictand data in the SDSM was divided into two parts: 1981–2010 and 1981–2006 for calibration, and 2011–2021 and 2007–2021 for validation of the CanESM2 and HadCM3 GCMs, respectively. The model was then used to generate future three-segment predictions for the 2030s (2011–2040), 2050s (2041–2070), and 2080s (2071–2100) for each GCM. A simplified representation of the SDSM is depicted in Figure 2. The mean of the generated scenarios was compared to the observed period, and the anomaly was revealed by the absolute difference in temperature and the percentage difference in rainfall from the monthly mean of the observed period to the future period. Positive and negative anomalies indicate an increase or decrease in the predictand in future periods. Using the calculations

in Birara et al. [56], the following was carried out to figure out how T_{max}, T_{min}, and rainfall will change in the future:

$$\Delta P = \frac{(Mm{\cdot}P \; - \; Obs{\cdot}P) \times 100}{Obs{\cdot}P} \tag{2}$$

$$\Delta T = \; Mm{\cdot}T \; - Obs{\cdot}T \tag{3}$$

where $Mm{\cdot}P$ and $Mm{\cdot}T$ show modeled rainfall and T_{max} or T_{min}, respectively, and $Obs{\cdot}P$ and $Obs{\cdot}T$ represent the observed rainfall and T_{max} or T_{min}, in that order.



Figure 2. A simplified representation of the SDSM. Adapted from Wilby et al. [75].

2.3.2. Model Performance Assessment

A simulation of mean monthly T_{max}, T_{min}, and rainfall was checked during the calibration and validation of the downscale model using the coefficient of determination (R^2), root mean square error (RMSE), and percent bias (PBIAS) expressed as:

To compare the explained variance of modeled data with the total variance of observed data, the coefficient of determination (R^2) is required.

$$R^2 = \frac{\sum_{i=1}^{n}(y_i - \overline{x})^2}{\sum_{i=1}^{n}(x_i - \overline{x})^2} \quad (4)$$

The RMSE expresses the difference between the modeled and observed values as follows:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n}} \quad (5)$$

$$\text{PBIAS} = 100 \times \left[\frac{\sum_{i=1}^{n}(x_i - y_i)}{\sum_{i=1}^{n}(x_i)}\right] \quad (6)$$

where x_i and y_i are the observed and modeled data, respectively.

The R^2 has a value between 0 and 1. A value close to 1 indicates that the model fits the data perfectly. The better the model's performance, the lower the RMSE. Using the PBIAS, it was determined whether the model underestimated or overestimated the observed data. The closer the PBIAS is to zero, the more precise the model.

3. Results

3.1. Results from Extreme Temperature and Rainfall Indices

3.1.1. Changepoints and Homogenization of Temperature and Rainfall

Table 4 shows the changepoints in daily T_{max} and T_{min} and rainfall. Here, all the statistically significant changepoints are detected for the climatic variables. For T_{max} and T_{min}, the detected monthly changepoints were used to adjust the daily data. The monthly changepoints are converted to daily changepoints by transforming the preceding day of the identified month to a daily changepoint (see Section 2.2.2). From Table 4, changepoints for Apam, Bortianor, and Winneba were detected in October 2003. However, these were changed to 31 September 2003, to produce segments for homogenization during the QM adjustment. A similar situation occurred for T_{min}. For instance, in both Accra and Tema, the first changepoint appeared in January 1982, followed by December 1986 and February 1988. However, to produce segments, the detected changepoints were converted to 31 December 1981, 31 November 1986, and 31 January 1988, respectively.

Table 4 also shows no changepoints for rainfall across all the 14 locations and a few for T_{max} (Apam, Bortianor, and Winneba). However, more changepoints were observed for T_{min} at most locations, except Anloga, Denu, and Keta. These changepoints can be attributed to the abrupt daily temperature fluctuations at these locations.

3.1.2. Extreme Temperature Indices

Table 5 and Figure 3a–m show the long-term changes in extreme temperature indices and the spatial distribution of the trends in temperature for the coastal Savannah agroecological zone of Ghana. According to Table 5, the annual count of days where the daily temperature exceeded 25 °C (SU25) increased significantly for all locations, all regions, and for the entire zone during the analysis period. Figure 3a shows that while the trends SU25 increased for all locations, the magnitude of change is higher for the locations in the central region than for the remaining two regions (see Figure 1 to understand the regional divisions). Similar significant increases were observed for the monthly or annual minimum of the daily maximum temperature (TXn) and the proportion of warm nights (TN90p) across all locations, regions, and the entire zone. From Figure 3g,k, the magnitudes of

changes in TXn and TN90p are higher in the Greater Accra region and some areas of the Volta region than in the central region. The proportion of cool nights (TN10p) and the diurnal temperature range (DTR) significantly decreased for all locations, regions, and the entire zone. Although the TN10p decreased significantly, the magnitude of the change was greater in the central region and some portions of the Volta region than in the Greater Accra region (Figure 3i), and the opposite occurred for the DTR (Figure 3m). Also, the cold spell duration indices (CDSI) significantly increased for the locations of Accra, Ada Foah, Anloga, Apam, Bortianor, Prampram, Saltpond, Tema, and Winneba, while a significant decrease ensued in Cape Coast, Denu, Elmina, and Moree (Figure 3d). Under the same analysis, all three regions and the entire zone decreased significantly.

Table 4. Changepoints in temperature (maximum and minimum) and rainfall datasets.

Location	T_{max}	Changepoints [a]	T_{min}	Changepoints [a]	Rainfall	Changepoints [b]
Accra	0	–	3	31 December 1981, 31 November 1986, 31 January 1988	0	–
Ada Foah	Reference station					
Anloga	0	–	0	–	0	–
Apam	1	31 September 2003	1	31 November 1986	0	–
Bortianor	1	31 September 2003	1	31 November 1986	0	–
Cape Coast	0	–	2	31 November 1981, 31 November 1986	0	–
Denu	0	–	0	–	0	–
Elmina	0	–	2	31 November 1981, 31 November 1986	0	–
Keta	0	–	0	–	0	–
Moree	0	–	2	31 November 1981, 31 November 1986	0	–
Prampram	0	–	3	31 December 1981, 31 November 1986, 31 January 1998	0	–
Saltpond	0	–	2	31 November 1981, 31 November 1986	0	–
Tema	0	–	3	31 December 1981, 31 November 1986, 31 January 1988	0	–
Winneba	1	31 September 2003	1	31 November 1986	0	–

[a] Detected from monthly data; [b] Detected from daily data.

Table 5. Trends in extreme temperature indices for the coastal Savannah agroecological zone of Ghana.

Locations	SU25	TR20	WSDI	CSDI	TXx	TNx	TXn	TNn	TN10p	TX10p	TN90p	TX90p	DTR
Accra	**0.231**	0.000	0.000	**0.000**	**0.014**	0.008	**0.033**	0.016	**−0.400**	**−0.220**	**0.383**	**0.217**	**−0.015**
Ada Foah	**0.000**	0.000	0.000	**0.000**	0.003	0.010	**0.026**	**0.026**	**−0.299**	−0.113	**0.376**	0.104	**−0.017**
Anloga	**0.000**	0.000	0.000	**0.000**	0.003	0.010	**0.026**	**0.026**	**−0.299**	−0.116	**0.376**	0.104	**−0.017**
Apam	**0.059**	0.000	0.000	**0.000**	−0.004	0.007	**0.030**	0.008	**−0.272**	−0.041	**0.378**	0.020	**−0.022**
Bortianor	**0.059**	0.000	0.000	**0.000**	−0.004	0.007	**0.030**	0.008	**−0.272**	−0.041	**0.378**	0.020	**−0.022**
Cape Coast	**0.571**	0.000	0.000	**−0.029**	0.004	**0.015**	**0.024**	0.013	**−0.409**	**−0.239**	**0.358**	**0.174**	**−0.012**
Denu	**0.167**	0.000	0.000	**−0.375**	**0.014**	**0.014**	**0.035**	0.022	**−0.432**	**−0.223**	**0.387**	**0.260**	**−0.012**
Elmina	**0.571**	0.000	0.000	**−0.029**	0.004	**0.015**	**0.024**	0.013	**−0.409**	**−0.239**	**0.358**	**0.174**	**−0.012**
Keta	**0.000**	0.000	0.000	**0.000**	0.003	0.010	**0.026**	**0.026**	**−0.299**	−0.113	**0.376**	0.104	**−0.017**
Moree	**0.571**	0.000	0.000	**−0.029**	−0.008	**0.015**	**0.024**	0.013	**−0.409**	**−0.239**	**0.358**	**0.174**	**−0.012**
Prampram	**0.053**	0.056	0.000	**0.000**	0.008	**0.013**	**0.032**	0.022	**−0.284**	−0.037	**0.399**	0.058	**−0.023**
Saltpond	**0.000**	0.000	0.000	**0.000**	0.003	0.010	**0.026**	**0.026**	**−0.299**	−0.113	**0.376**	0.104	**−0.017**
Tema	**0.231**	0.000	0.000	**0.000**	**0.014**	0.008	**0.033**	0.016	**−0.400**	**−0.220**	**0.383**	**0.217**	**−0.015**
Winneba	**0.059**	0.000	0.000	**0.000**	−0.004	0.007	**0.030**	0.008	**−0.272**	−0.041	**0.378**	0.020	**−0.022**
Central region	**0.290**	0.000	0.000	**−0.167**	0.003	**0.011**	**0.030**	0.014	**−0.335**	**−0.146**	**0.383**	0.117	**−0.016**
Greater Accra region	**0.000**	0.016	0.000	**−0.197**	0.006	0.009	**0.033**	0.019	**−0.332**	−0.140	**0.393**	**0.116**	**−0.019**
Volta region	**0.073**	0.000	0.000	**−0.233**	0.007	**0.012**	**0.029**	0.024	**−0.354**	**−0.142**	**0.393**	0.156	**−0.016**
Entire zone (all locations)	**0.176**	0.006	0.000	**−0.195**	0.005	**0.011**	**0.032**	**0.018**	**−0.346**	**−0.169**	**0.388**	0.127	**−0.018**

Note: The values in the table are from the Sen's slope estimator, which shows the magnitude of change per year. The values in bold are significant at 5% and 95% confidence levels, as observed from the MK test and Sen's slope estimator, respectively. The values not in bold are insignificant at the same confidence level.

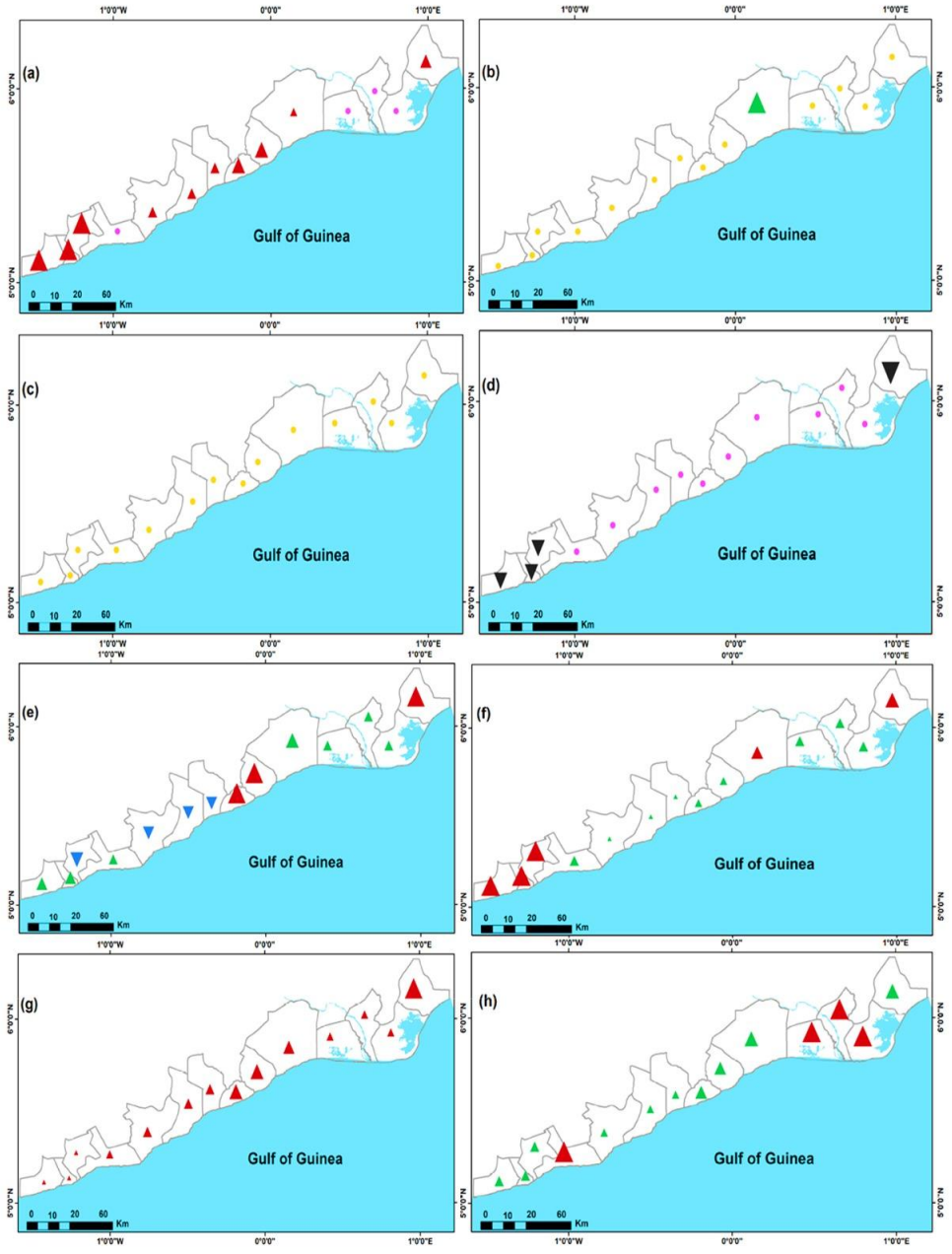


Figure 3. *Cont.*

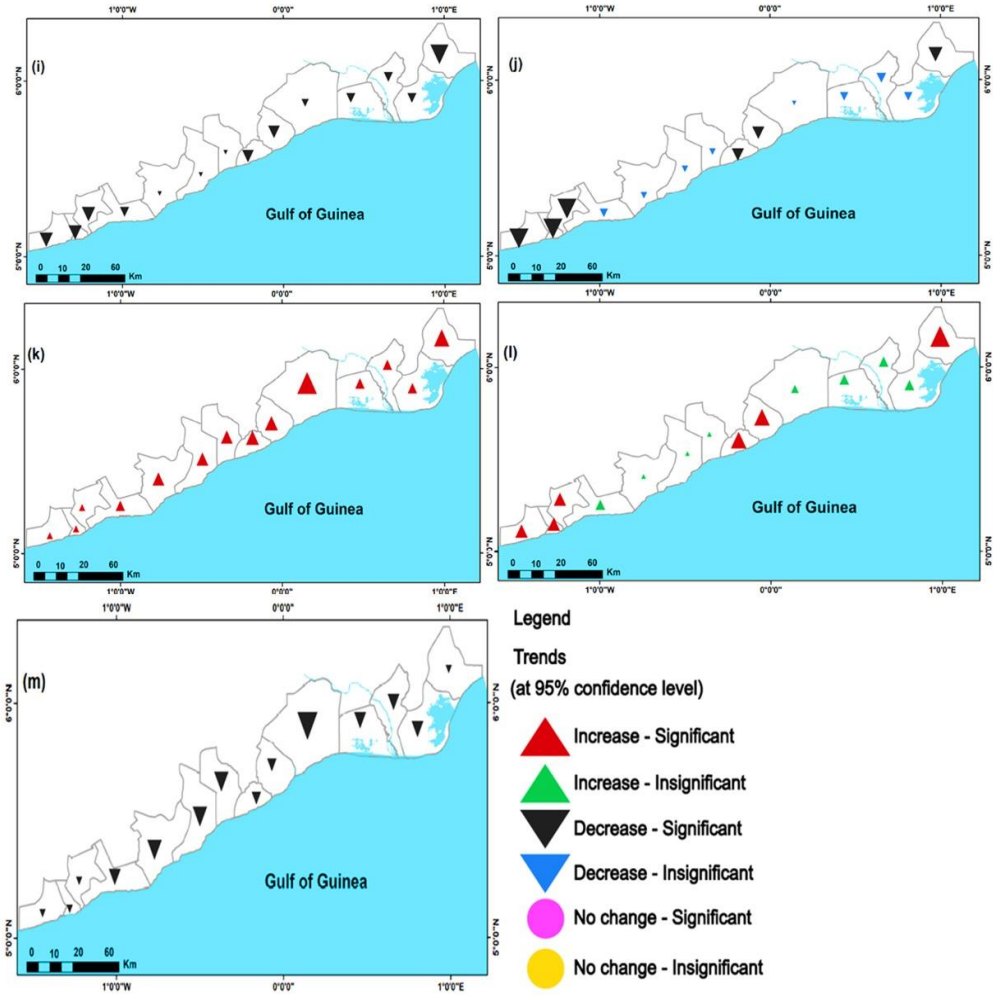


Figure 3. Spatial distribution of trends in extreme temperature indices from 1981 to 2021 in the coastal Savannah agroecological zone of Ghana. (**a**) SU25, (**b**) TR20, (**c**) WSDI, (**d**) CSDI, (**e**) TXx, (**f**) TNx, (**g**) TXn, (**h**) TNn, (**i**) TN10p, (**j**) TX10p, (**k**) TN90p, (l) TX90p, (**m**) DTR. The symbol size varies by trend slope.

The monthly or annual maximum of daily maximum temperature (TXx) (Figure 3e) significantly increased only for Accra, Denu, and Tema, whereas the monthly or annual maximum of daily minimum temperature (TNx) (Figure 3f) increased for Cape Coast, Denu, Elmina, Moree, Prampram, the central region, Volta region, and the entire zone. The monthly or annual minimum daily temperature (TNn) significantly increased in Ada Foah, Anloga, Keta, Saltpond, and the entire zone. Figure 3h reveals that the magnitude of change in TNn is higher in the Volta region and some areas of the central region than in the Greater Accra region. Moreover, the proportion of cool days (TX10p) significantly decreased for Accra, Cape Coast, Denu, Elmina, Moree, and Tema, and for the central and Volta regions and the entire zone, whereas the number of warm days (TX90p) significantly increased for Accra, Cape Coast, Denu, Elmina, Moree, and Tema, and the Greater Accra region. From Figure 3j, the decrease in TX10p is higher in the central region compared to

that in the other two regions, while the magnitude of change in TX90p (Figure 3l) is higher in some portions of the Volta and Greater Accra regions.

3.1.3. Extreme Rainfall Indices

Table 6 and Figure 4a–j show the long-term changes in extreme rainfall indices and the spatial distribution of the trends in rainfall for the coastal Savannah agroecological zone of Ghana. From Table 6, the maximum 1-day precipitation amount (RX1day) significantly decreased in Cape Coast, Elmina, Moree, and Saltpond. A similar and significant decrease, including in the central region, is observed in the maximum 5-day precipitation amount (RX5day). The simple precipitation index (SDII) significantly decreased in Cape Coast, Elmina, Moree, and Saltpond. The number of days of heavy precipitation (R10) also decreased significantly in Cape Coast, Elmina, Moree, and Saltpond. From Figure 4a–d, the magnitudes of changes in RX1day, RX5day, SDII, and R10 are greater in some areas of the central region than in the other two. The number of consecutive dry days (CDD) decreased significantly in Accra, Ada Foah, Anloga, Denu, Keta, Prampram, the Greater Accra and Volta regions, and the entire zone. That is, the Greater Accra and the Volta regions recorded more dry days than the central region (Figure 4f). The annual sum of very wet days (R95p) significantly decreased in Cape Coast, Elmina, Moree, Saltpond, and the central region. As shown in Figure 4h, the R95p in the central region is significantly lower than in the other two regions. A similar trend is observed in the annual sum of extremely wet days (R99p) (Figure 4i). From Table 6, both increasing and decreasing trends are observed for the consecutive wet days (CWD) and the annual total of wet-day precipitation (PRCPTOT). However, the trends were insignificant. This is also evident in Figure 4g,j.

Table 6. Trends in extreme rainfall indices for the coastal Savannah agroecological zone of Ghana.

Locations	RX1day	RX5day	SDII	R10	R20	CDD	CWD	R95p	R99p	PRCPTOT
Accra	−0.105	−0.228	−0.011	−0.060	−0.029	**−0.364**	0.258	−1.086	−0.552	2.994
Ada Foah	0.000	−0.375	−0.016	−0.128	−0.030	**−0.500**	0.070	−2.099	−0.619	0.396
Anloga	0.000	−0.375	−0.016	−0.128	−0.030	**−0.500**	0.070	−2.099	−0.619	0.396
Apam	−0.058	−0.111	−0.002	0.000	−0.031	−0.123	−0.082	−1.649	−0.343	2.892
Bortianor	−0.058	−0.111	−0.002	0.000	−0.031	−0.123	−0.082	−1.649	−0.343	2.892
Cape Coast	**−0.333**	**−0.895**	**−0.018**	**−0.279**	−0.078	0.067	0.101	**−4.500**	**−1.892**	−3.694
Denu	0.016	−0.244	−0.010	−0.087	0.000	**−0.500**	0.282	−1.600	0.000	1.852
Elmina	**−0.333**	**−0.895**	**−0.018**	**−0.279**	−0.078	0.067	0.101	**−4.500**	**−1.892**	−3.694
Keta	0.000	−0.375	−0.016	−0.128	−0.030	**−0.500**	0.070	−2.099	−0.619	0.396
Moree	**−0.333**	**−0.895**	**−0.018**	**−0.279**	−0.078	0.067	0.101	**−4.500**	**−1.892**	−3.694
Prampram	−0.086	−0.250	−0.014	−0.164	0.000	**−0.378**	0.308	−2.000	−0.679	0.542
Saltpond	**−0.333**	**−0.895**	**−0.018**	**−0.279**	−0.078	0.067	0.101	**−4.500**	**−1.892**	−3.694
Tema	−0.098	−0.209	−0.004	0.000	−0.039	−0.143	0.449	−1.091	−1.225	2.496
Winneba	−0.058	−0.111	−0.002	0.000	−0.031	−0.123	−0.082	−1.649	−0.343	2.892
Central region	−0.248	**−0.724**	−0.013	−0.222	−0.082	0.000	−0.044	**−3.967**	−1.521	−2.049
Greater Accra region	−0.096	−0.199	−0.010	−0.083	−0.043	**−0.294**	0.218	−1.319	−1.000	1.654
Volta region	0.022	−0.272	−0.014	−0.102	−0.032	**−0.500**	0.195	−1.850	−1.850	1.161
Entire zone (all locations)	−0.127	−0.496	−0.026	−0.163	−0.077	**−0.214**	0.104	−2.759	−1.439	−0.758

Note: The values in the table are from the Sen's slope estimator, which shows the magnitude of change per year. The values in bold are significant at 5% and 95% confidence levels, as observed from the MK test and Sen's slope estimator, respectively. The values not in bold are insignificant at the same confidence level.

3.1.4. Decadal Variations in Temperature and Rainfall

Figure 5a–c depict the average daily maximum (T_{max}) and minimum (T_{min}) temperatures and rainfall in the coastal Savannah agroecological zone of Ghana over the last four decades. The results of Welch's two-sample t test comparing the mean changes between decades for T_{max}, T_{max}, and rainfall in the central, Greater Accra, and Volta regions are presented in Table 7. Figures 6a–f and 7a–c depict the standardized anomalies of T_{max} and T_{min} and rainfall, relative to the 1981–2020 mean. Based on Figure 5a, the decadal variability of T_{max} is greatest in the Volta region, followed by the Greater Accra region, and the central region has the lowest variability. T_{max} increased substantially in the first (1981–1990), second (1991–2000), and fourth (2011–2020) decades but decreased in the

third (2001–2010). The T_{min} increased considerably across all regions and in each decade. Notwithstanding, the Volta region experienced a larger increase compared to the other two regions (Figure 5b). From Table 7, the Welch's t test showed that T_{max} decreased significantly only between the first and second decades in all three regions, while T_{min} decreased significantly between the third and fourth decades in the central and Greater Accra regions.

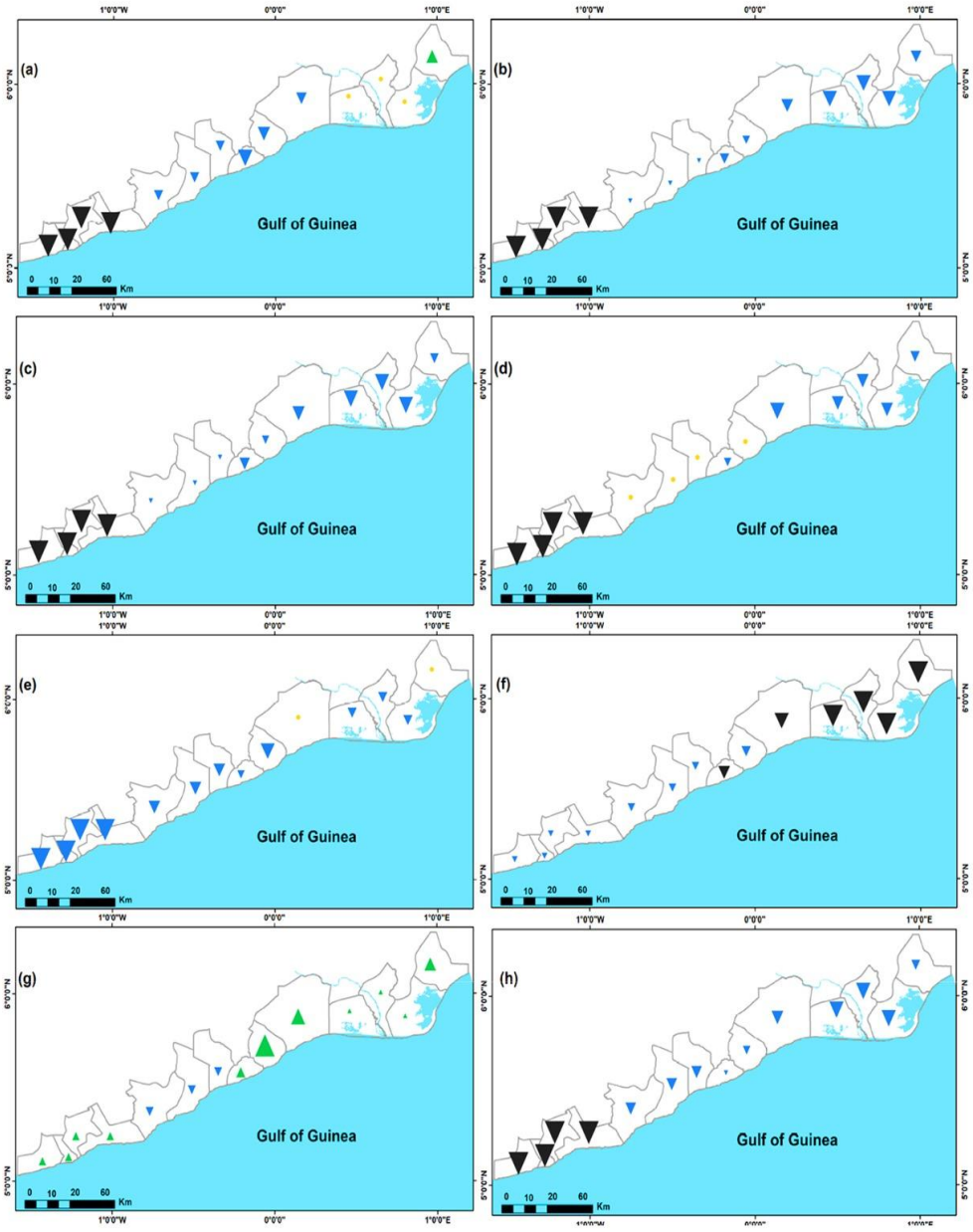


Figure 4. *Cont.*

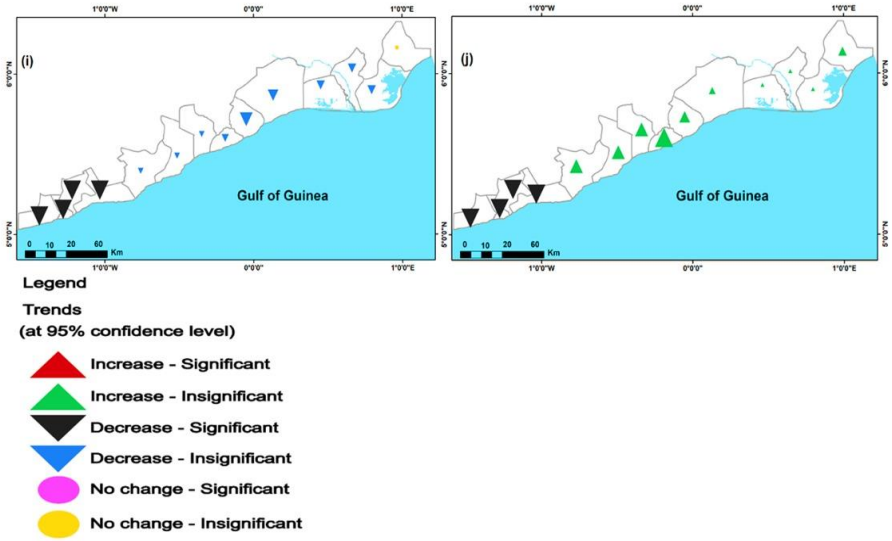


Figure 4. Spatial distribution of trends in extreme rainfall indices from 1981 to 2021 in the coastal Savannah agroecological zone of Ghana. (**a**) RX1day, (**b**) RX5day, (**c**) SDII, (**d**) R10, (**e**) R20, (**f**) CDD, (**g**) CWD, (**h**) R95p, (**i**) R99p, (**j**) PRCPTOT. The symbol size varies by trend slope.

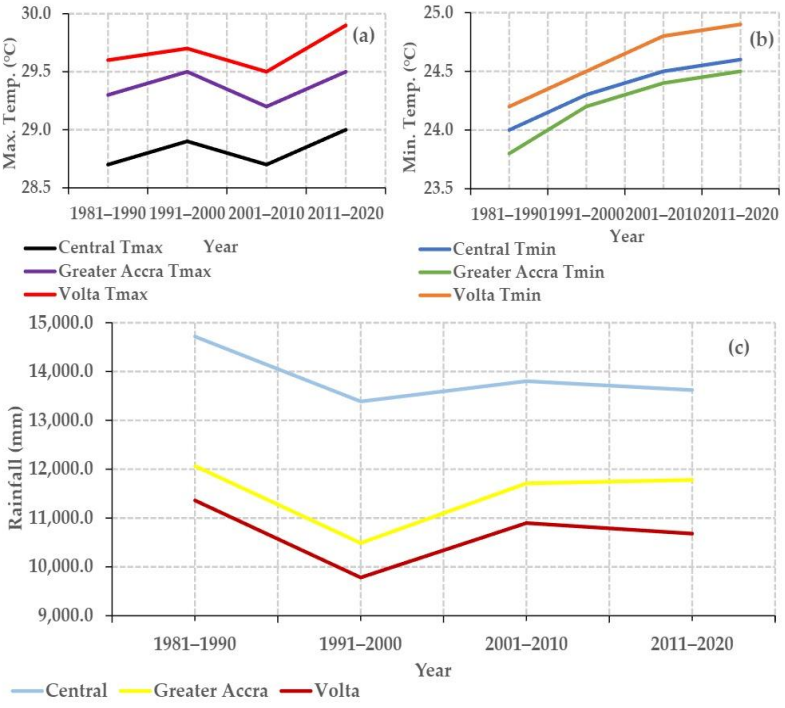


Figure 5. Average daily maximum (T_{max}) (**a**), minimum (T_{min}) (**b**), and rainfall (**c**) for the past four decades in the central, Greater Accra, and Volta areas of coastal Savannah agroecological zone of Ghana.

Table 7. Results of the Welch's *t* test analysis.

	Central			Greater Accra			Volta		
	T Stat	***p*-Value**	**Sig.**	**T Stat**	***p*-Value**	**Sig.**	**T Stat**	***p*-Value**	**Sig.**
First- and second-decades T_{max}	−3.128	0.002	*	−3.306	0.000	*	−2.328	0.002	*
Second- and third-decades T_{max}	4.216	2.518	–	6.372	1.972	–	5.055	4.404	–
Third- and fourth-decades T_{max}	−6.572	5.286	–	−7.966	1.890	–	−9.244	3.063	–
First- and second-decades T_{min}	−10.176	3.662	–	−10.706	1.497	–	−9.572	1.404	–
Second- and third-decades T_{min}	−8.544	1.554	–	−7.436	1.155	–	−7.565	4.346	–
Third- and fourth-decades T_{min}	−2.177	0.029	*	−3.130	0.002	*	−4.111	3.976	–
First- and second-decades rainfall	2.896	0.004	*	4.189	2.835	–	0.727	0.467	–
Second- and third-decades rainfall	2.896	0.004	*	−3.713	0.000	*	−3.713	0.000	*
Third- and fourth-decades rainfall	0.471	0.638	–	−0.190	0.849	–	4.135	3.594	–

* Shows significance at 95% confidence level, – indicates insignificance at 95% confidence level.

Figure 5c shows that rainfall exhibits decadal variations. Rainfall increased in the first and third decades across all three regions but decreased in the second and fourth decades, except for Greater Accra, where it increased in the fourth decade. Based on Welch's *t* test in Table 7, the central region had a significant increase in rainfall between the first and second decades. Between the second and third decades, the central region experienced a significant increase, while the Greater Accra and Volta regions observed significant decreases.

Generally, the anomalies in T_{max} and T_{min} show a stronger seasonal decadal variation across the zone (Figure 6a–f). Between 1981 and 2020, the highest positive (2.3) and negative (−1.8) dry season anomalies for T_{max} (Figure 6a) both occurred in the central region in the years of 1998 (the second decade) and 2006 (the third decade), respectively. In Figure 6b, the greatest positive (2.5) and negative (−1.9) wet season anomalies appeared in the central region and the Volta regions in 1987/2010 (both the first and third decades) and 2012 (the fourth decade), respectively. For the minor season (Figure 6c), the highest positive (2.3) occurred in the central region in 2013 (the fourth decade), while the highest negative (−1.9) ensued in the same region and the Greater Accra region in 2007 (the third decade).

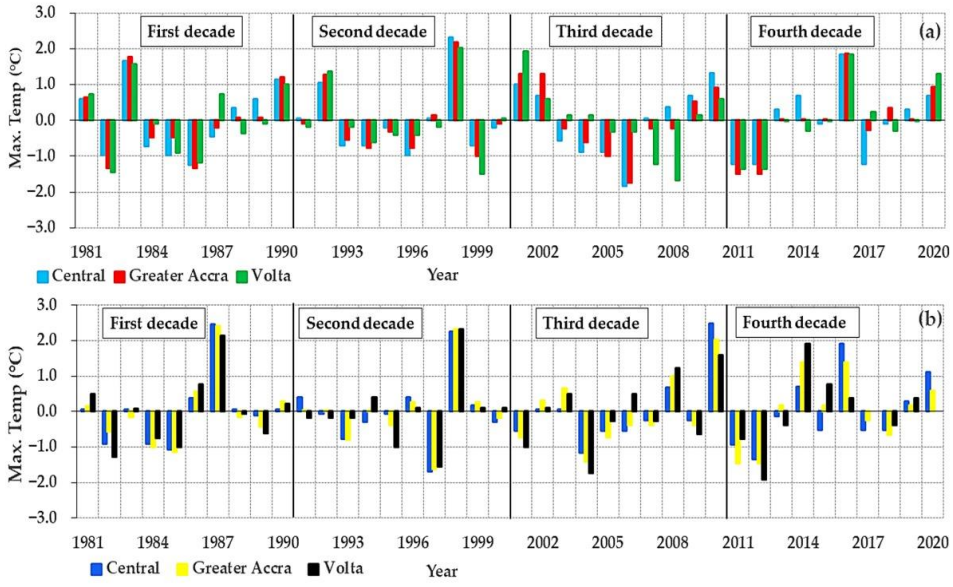


Figure 6. *Cont.*

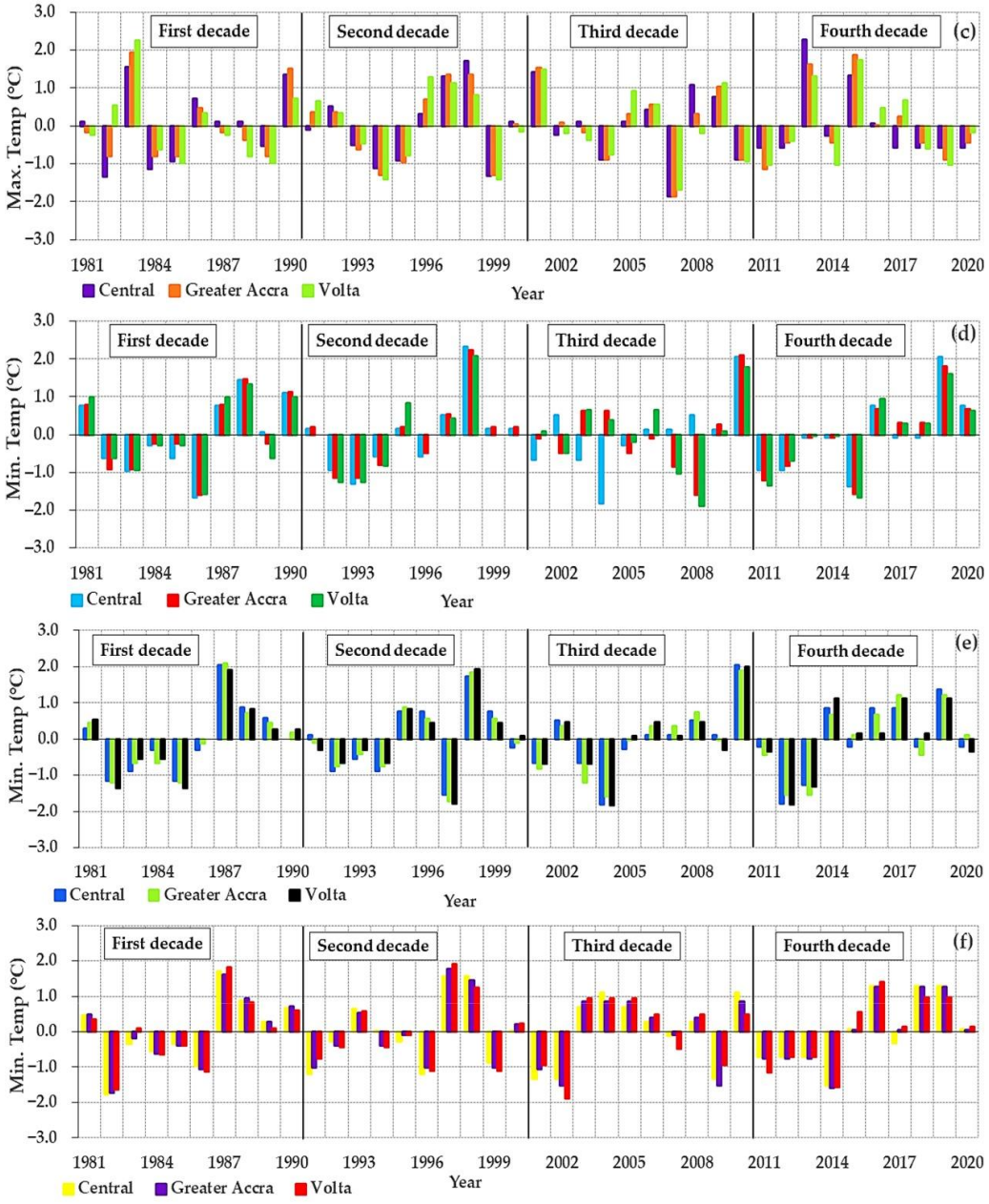


Figure 6. Standardized anomalies for mean decadal T_{max} for 1981–2021 for dry season (**a**), wet season (**b**), and minor season (**c**); T_{min} for 1981–2021 for dry season (**d**), wet season (**e**), and minor season (**f**).

From Figure 6d, the greatest positive (2.3) and negative (−1.9) anomalies for the dry season T_{min} occurred in the central and Volta regions in 1998 (the second decade) and 2008 (the third decade), respectively. For the wet season (Figure 6e), the greatest positive

(2.1) ensued in both the central and Greater Accra regions in 1987/2010 (both the first and third decades), while the greatest negative (−1.8) appeared in the central and Volta regions in 2004 (the third decade). In Figure 6f, the highest positive (1.9) and negative (−1.9) anomalies for T_{min} were both recorded in the Volta region in the years 1997 (second decade) and 2002 (third decade), respectively.

The anomalies in the mean decadal seasonal rainfall (Figure 7a–c) indicate greater improvements in the wet and minor seasons than in the dry season, despite variations. Between 1981 and 2020, the Volta and central regions recorded the highest positive (2.4) dry season rainfall in the years of 1982 and 1986, respectively, both occurring in the first decade, while the highest negative (−2.4) rainfall appeared in the Greater Accra region in 2001 (the third decade) (Figure 7a). For the wet season (Figure 7b), both the greatest negative (−2.1) and positive (2.1) rainfall anomalies ensued in the Greater Accra region in 1987 (the first decade) and 2009 (the third decade), in that order. According to Figure 7c, the Greater Accra and the central regions experienced the highest negative (−2.1) and positive (2.1) minor season rainfall anomalies in the years 1983 and 1987, respectively, both occurring in the first decade.

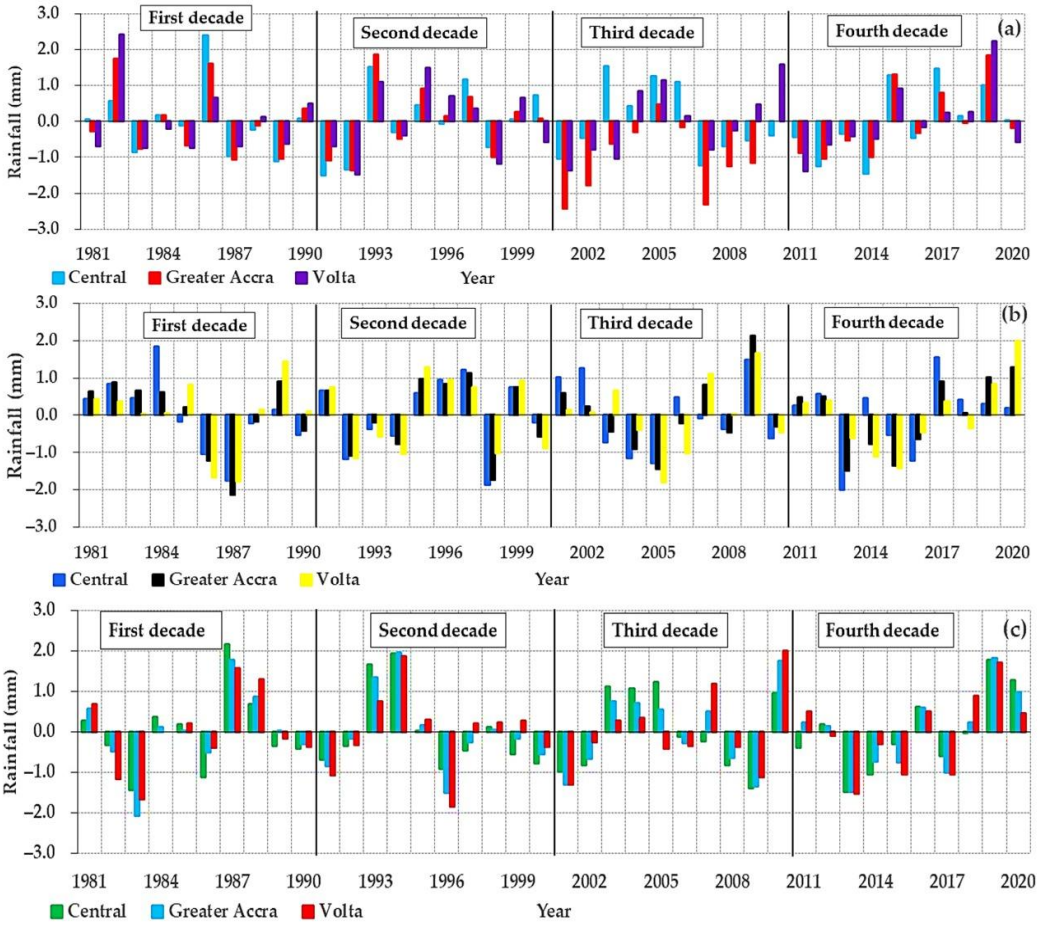


Figure 7. Standardized anomalies for mean decadal rainfall for 1981–2021 for dry season (**a**), wet season (**b**), and minor season (**c**).

3.2. Results for Future Climate Change Projection

3.2.1. Predictor Variables Selection

The selection of appropriate predictor variables is essential to the success of the SDSM method. A correlation matrix between the individual predictand and the NCEP variables was used to screen the appropriate predictors. The 26 large-scale daily predictors from the NCEP reanalysis were utilized together with the predictors with the highest correlation coefficient from the individual predictands (T_{max}, T_{min}, and rainfall) for all three regions (i.e., central, Greater Accra, and Volta). Figure 8a,b shows a summary of the screened variables of the NCEP predictors. Figure 8a shows that the pl_z, plzh, and temp, and p8zh, correlated well to predict T_{max}, T_{min}, and rainfall for the CanESM2. The p_z, temp, and p500 also correlated well with T_{max}, T_{min}, and rainfall in that order for the HadCM3 (Figure 8b). It can be said that the individual predictor variables identified for the CanESM2 and HadCM3 GCMs are controlled by different local variables in each region. Again, it can be said that surface velocities (pl_z and p_z) and mean temperature at 2 m (temp) served as potential predictors of temperature (T_{max} and T_{min}) for all the regions.

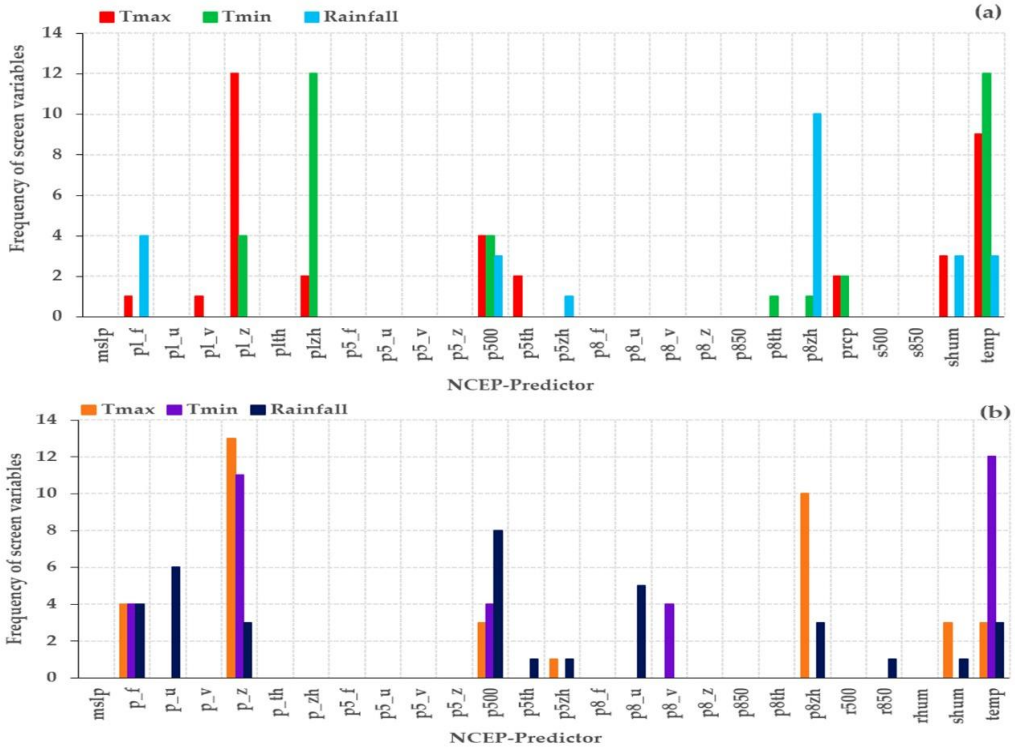


Figure 8. Screened variables of the NCEP predictors for CanESM2 (**a**) and HadCM3 (**b**) for T_{max}, T_{min}, and rainfall for all areas (central, Greater Accra, Volta, and the entire zone).

3.2.2. Model Performance Assessment during Calibration and Validation

The study used calibration periods of 30 (1981–2010) and 26 (1981–2006) years and validation periods of 11 (2011–2021) and 15 (2007–2021) years for CanESM2 and HadCM3, respectively. The statistical performance regarding the coefficient of determination (R^2), the root mean square error (RMSE), and the percent bias (PBIAS) of the model is also presented in Table 8. The CanESM2 and HadCM3 models' performances were good and ranged from 58–99%, 0.01–1.02 °C, and 0.42–11.79 °C, respectively, for R^2, RMSE, and PBIAS (for

all three regions and the entire zone) (Table 8). The performance of CanESM2 ranged from 76–99%, 0.01–1.02 °C, and 0.22–10.01 °C for R^2, RMSE, and PBIAS, respectively. The performance of the HadCM3 also ranged from 58–99%, 0.02-0.91 °C, and 0.42–11.79 °C for R^2, RMSE, and PBIAS, in that order.

Table 8. Statistical performance during calibration and validation for Tmax, Tmin, and rainfall.

Predictand	Area		CanESM2			HadCM3		
			R^2	RMSE	PBIAS	R^2	RMSE	PBIAS
T_{max}	Central region	Calibration	0.95	0.01	−0.22	0.79	0.10	0.01
		Validation	0.82	0.20	0.34	0.68	0.32	−0.42
	Greater Accra region	Calibration	0.99	0.22	0.11	0.99	0.33	0.23
		Validation	0.91	0.41	−0.23	0.98	0.56	−0.32
	Volta region	Calibration	0.99	0.02	0.02	0.99	0.11	0.01
		Validation	0.79	0.31	0.34	0.77	0.21	0.23
	Entire zone	Calibration	0.99	0.20	0.11	0.96	0.10	0.11
		Validation	0.87	0.31	0.23	0.86	0.32	0.31
T_{min}	Central region	Calibration	0.99	0.01	0.02	0.98	0.02	0.01
		Validation	0.91	0.32	0.11	0.88	0.52	0.40
	Greater Accra region	Calibration	0.99	0.21	0.23	0.99	0.12	0.21
		Validation	0.87	0.44	1.13	0.89	0.91	0.52
	Volta region	Calibration	0.99	0.03	0.02	0.99	0.13	0.02
		Validation	0.94	0.52	0.31	0.79	0.31	0.70
	Entire zone	Calibration	0.99	0.21	0.22	0.99	0.05	0.20
		Validation	0.91	0.42	0.31	0.89	0.23	0.61
Rainfall	Central region	Calibration	0.99	0.54	5.44	0.89	0.61	6.02
		Validation	0.76	0.63	6.03	0.77	0.80	7.22
	Greater Accra region	Calibration	0.95	0.82	4.01	0.89	0.81	4.41
		Validation	0.91	1.02	7.11	0.79	0.90	6.32
	Volta region	Calibration	0.92	0.42	4.12	0.88	0.40	7.01
		Validation	0.79	0.55	6.23	0.58	0.61	9.15
	Entire zone	Calibration	0.99	0.54	7.34	0.99	0.90	7.89
		Validation	0.76	0.63	10.01	0.89	0.81	11.79

Table 8 shows low performance for rainfall as compared to the T_{max} and T_{max}, especially during validation under both models. Figure 9a–h show the graphical representation of the results of the model calibration and validation for the central region (Figure 9a,b), the Greater Accra region (Figure 9c,d), the Volta region (Figure 9e,f), and the entire zone (Figure 9g,h). The low performance could be attributed to the conditional modeling behavior of rainfall and the difficulty of achieving a perfect multiple regression in the SDSM. Regarding model comparison, the CanESM2 outperformed the HadCM3 during both calibration and validation, especially for rainfall in all three regions and the entire zone (Table 8). Notwithstanding, both models performed better for T_{max} and T_{min}.

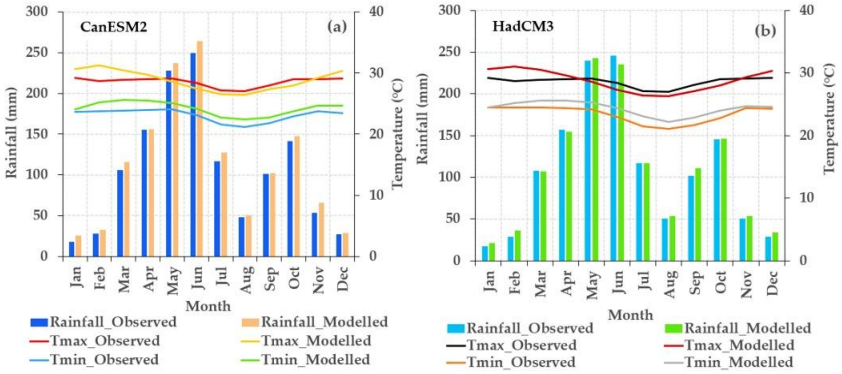


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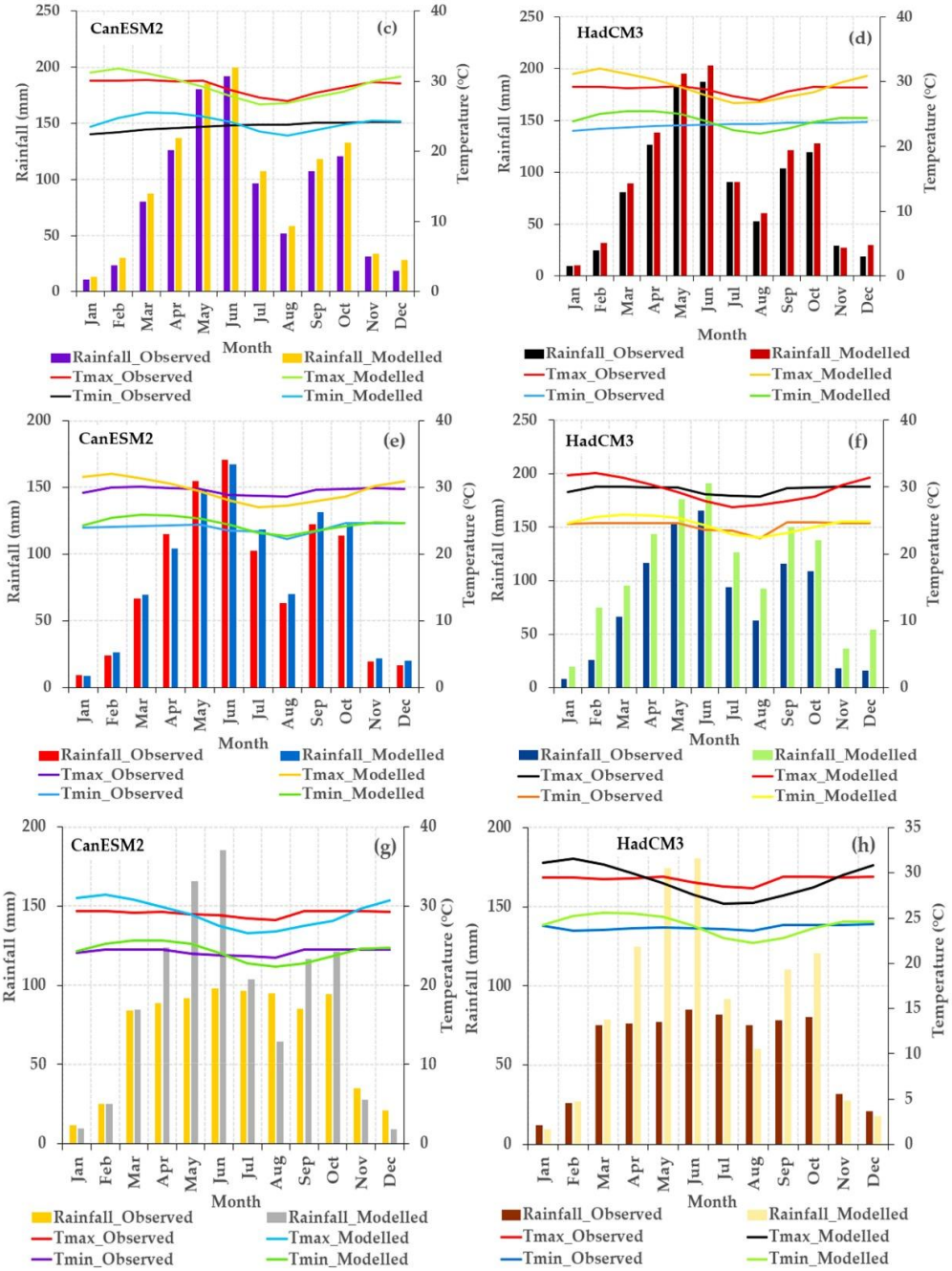


Figure 9. Calibration and validation results of mean monthly T_{max}, T_{min}, and rainfall for CanESM2 and HadCM3 for the central region (**a**,**b**), Greater Accra region (**c**,**d**), Volta region (**e**,**f**), and the entire zone (**g**,**h**).

3.2.3. Change in Projected Future Monthly Maximum Temperature (T_{max})

Figure 10a–t depict the projected future monthly T_{max} change for the central region (Figure 10a–e), Greater Accra region (Figure 10f–j), Volta region (Figure 10k–o), and entire zone (Figure 10p–t) using the CanESM2 (RCP2.6, 4.5, and 8.5) and HadCM3 (A2 and B2) models for the 2030s, 2050s, and 2080s. The overall results from the scenarios generated from the CanESM2 and HadCM3 models reveal that T_{max} will increase in most months for the 2030s, 2050s, and 2080s for all three regions and across the entire zone (Figure 10a–t). The A2 scenario reveals a higher projection for T_{max} than the B2 scenario for the regions and the entire zone (Figure 10d,e,i,j,n,o,s,t). Under the RCP2.6, 4.5, and 8.5 scenarios, T_{max} is projected to increase largely in all three regions and for the entire zone. In comparison to the RCP scenarios, T_{max} shows a greater projected increase for RCP8.5 than the other two scenarios (Figure 10a–c,f–h,k–m,p–r).

In both models and scenarios, a clear seasonal variation can be observed in the projected T_{max}. In the future, T_{max} will increase greatly in the dry season (November–March) and decrease substantially in the wet (May–July) and minor (September–October) seasons (Figure 10a–t). T_{max} is expected to increase significantly more in Greater Accra (Figure 10f–j) and Volta (Figure 10k–o) than in the central region (Figure 10a–e). Moreover, among the years, T_{max} is expected to increase considerably more in the 2050s and 2080s than in the 2030s. Regardless, greater variation in T_{max} is observed in all scenarios for the 2080s. T_{max} is expected to be highest (1.6 °C) and lowest (−1.6 °C) across the three regions (Figure 11a–o), as well as highest (1.5 °C) and lowest (−1.6 °C) for the entire zone (Figure 11p–t). In comparing the two models, the RCPs outperformed the A2 and B2 scenarios.

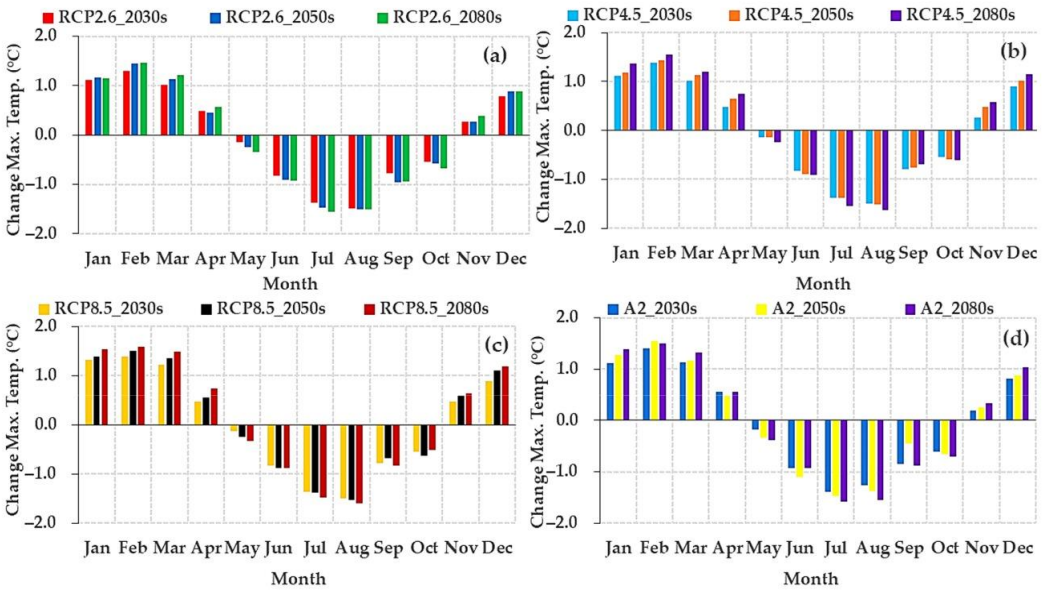


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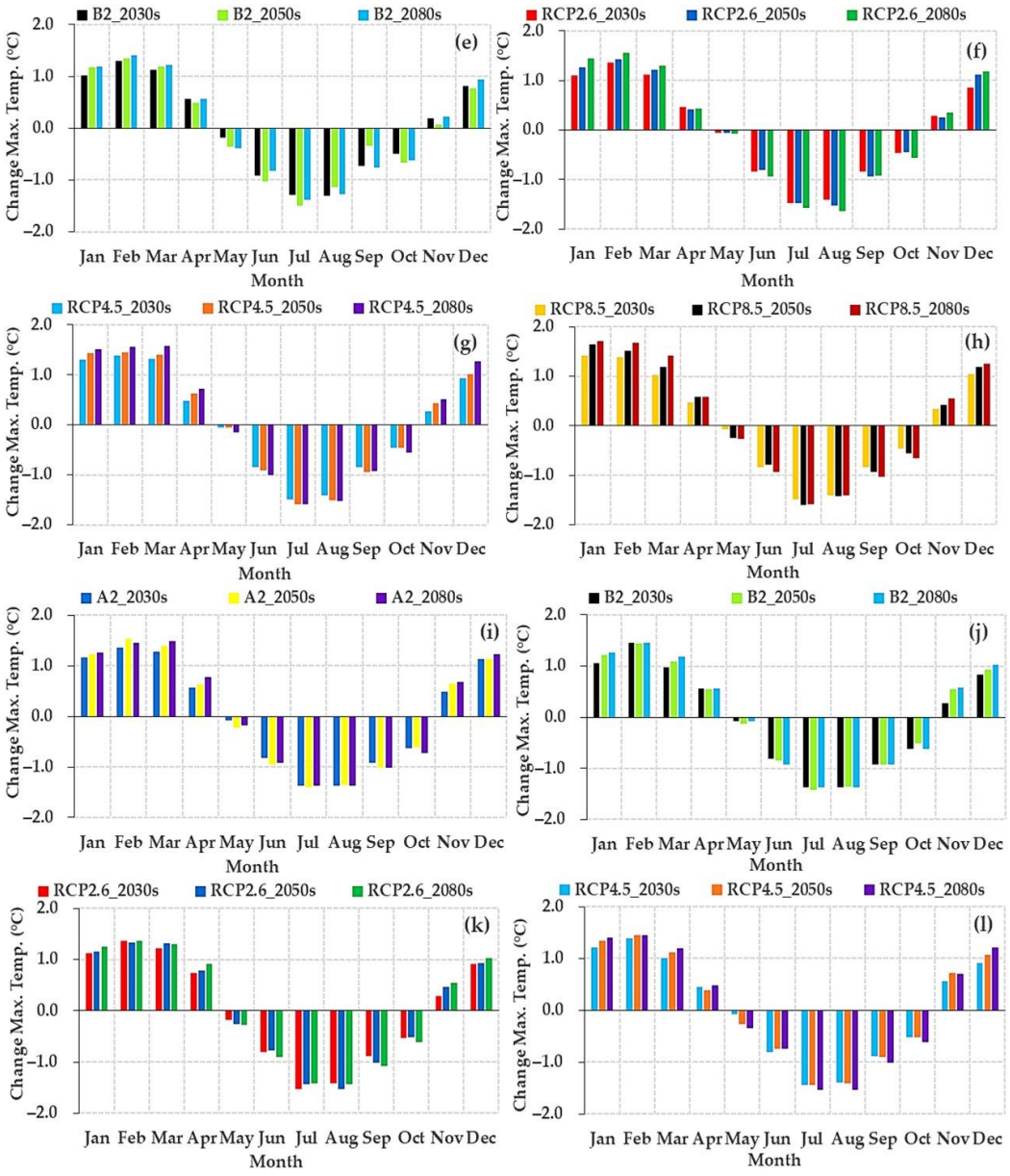


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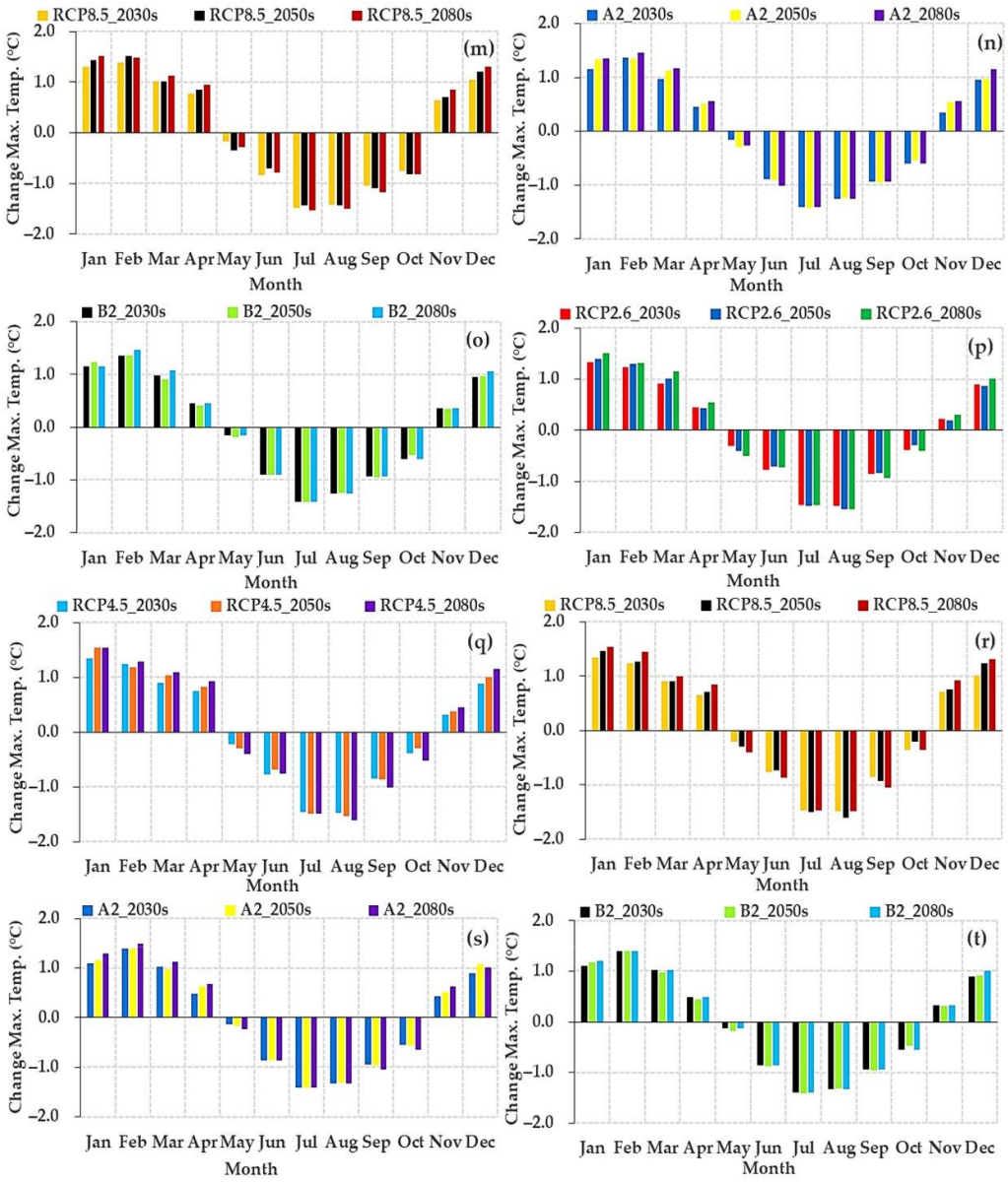


Figure 10. Future monthly change in T_{max} for CanESM2 (RCP2.6, RCP4.5, and RCP8.5) and HadCM3 (A2 and B2) for the 2030s, 2050s, and 2080s for central (**a**–**e**), Greater Accra (**f**–**j**), Volta (**k**–**o**), and the entire zone (**p**–**t**).

3.2.4. Change in Projected Future Monthly Minimum Temperature (T_{min})

Figure 11a–t depict the projected future monthly change in T_{min} for the central region (Figure 11a–e), Greater Accra region (Figure 11f–j), Volta region (Figure 11k–o), and entire zone (Figure 11p–t) under the CanESM2 (RCP2.6, 4.5, and 8.5) and HadCM3 (A2 and B2) models for the 2030s, 2050s, and 2080s. The T_{min} follows a similar pattern to that of the T_{max}. In general, T_{min} is expected to increase in the 2030s, 2050s, and 2080s under both

models for most months across the three regions and the entire zone (Figure 11a–t). T_{min} is projected to increase significantly more under the A2 scenario than under the B2 scenario for the HadCM3 model (Figure 11d,e,i,j,n,o,s,t). T_{min} is expected to increase significantly more under RCP8.5 than under the other two scenarios (Figure 11a–c, f–h, k–m, and p–r) across the three regions and the entire zone.

The results from Figure 11a–t show variation such as that of the T_{max}. Generally, T_{min} reveals a projected increase from the months of November to June, especially for the RCP scenarios. A similar pattern is observed under the A2 and B2 scenarios; however, the month of June decreases in that regard. That is, unlike the T_{max}, the T_{min} in the future will increase in the wet season, particularly in the month of June, as demonstrated by the RCP scenarios. While the T_{min} is expected to increase and decrease throughout the zone (Figure 11p–t), the projected rise and fall differ by region. T_{min} is expected to be the greatest (1.4 °C) and lowest (−2.1 °C) across the three regions, as well as the greatest (1.4 °C) and lowest (−2.3 °C) for the entire zone (Figure 11p–t). T_{min} is expected to vary the most (−2.3 and 1.4 °C) in Greater Accra and Volta and the least (−2.1 and 1.3 °C) in the central region. In general, the increase and decrease in T_{min} are considerably higher in the 2050s and 2080s across the three regions and the entire zone (Figure 11a–t). The overall comparison of the model results reveals a higher performance in the RCPs than in the A2 and B2 scenarios, like that of the T_{max}.

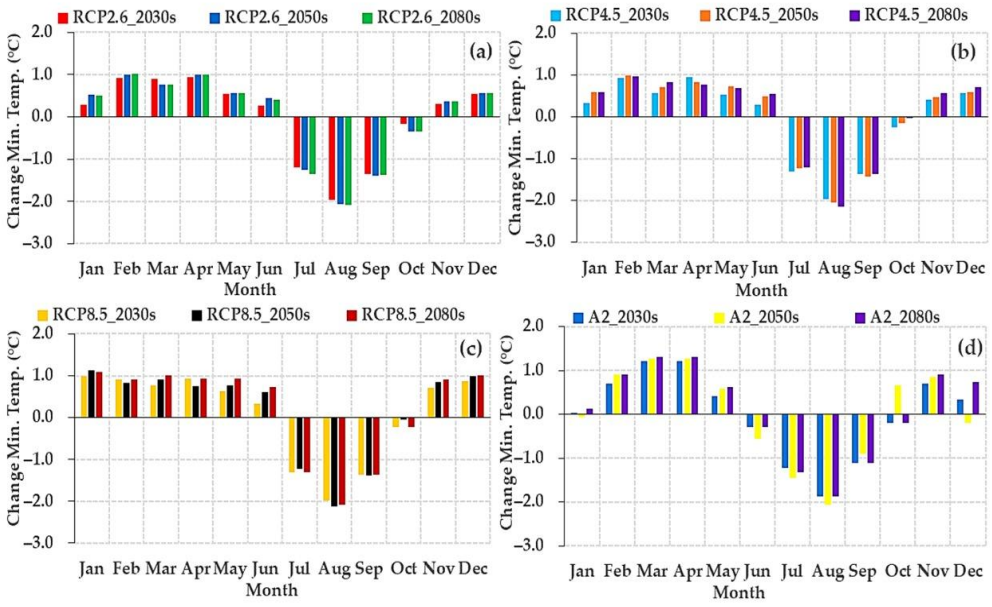


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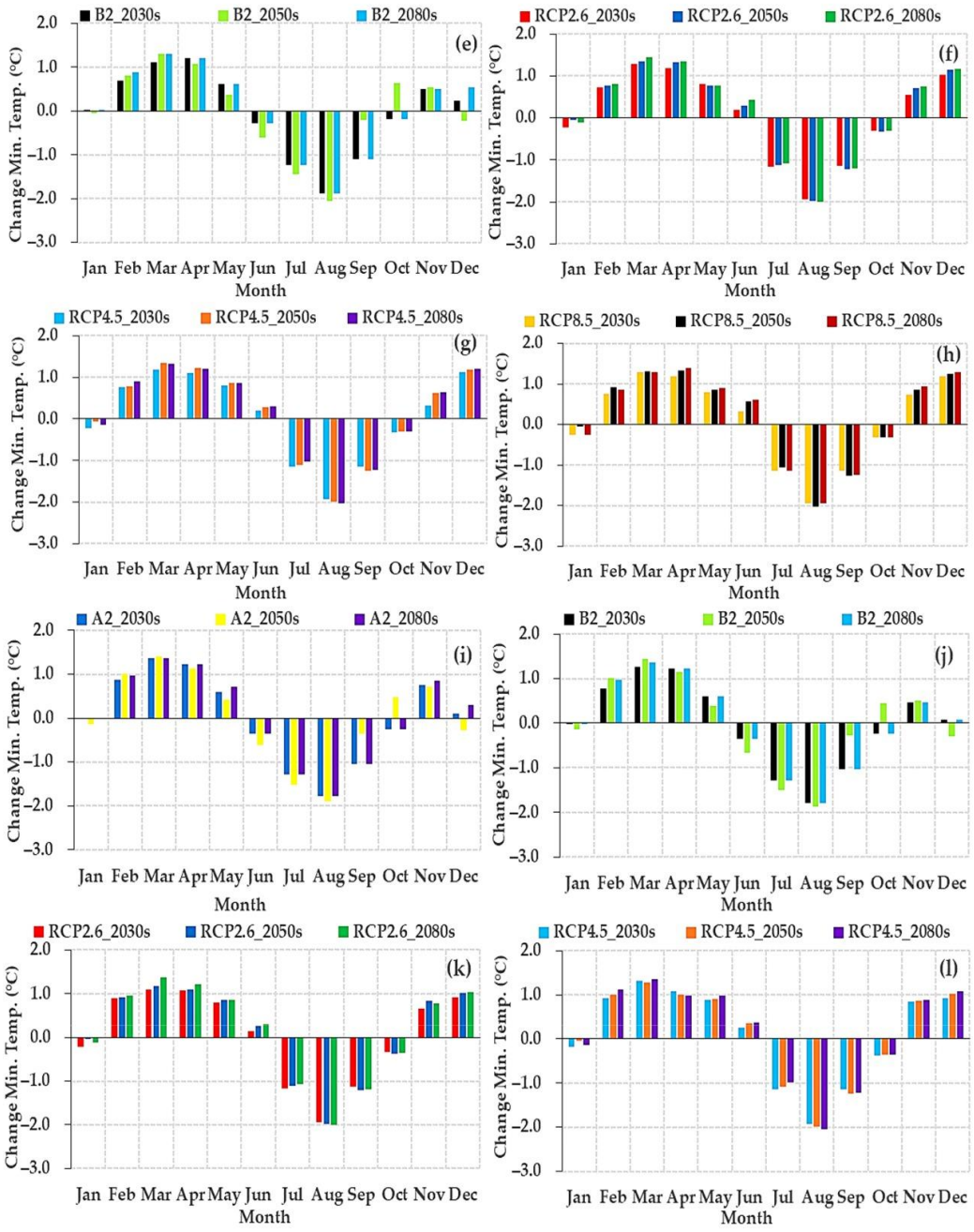


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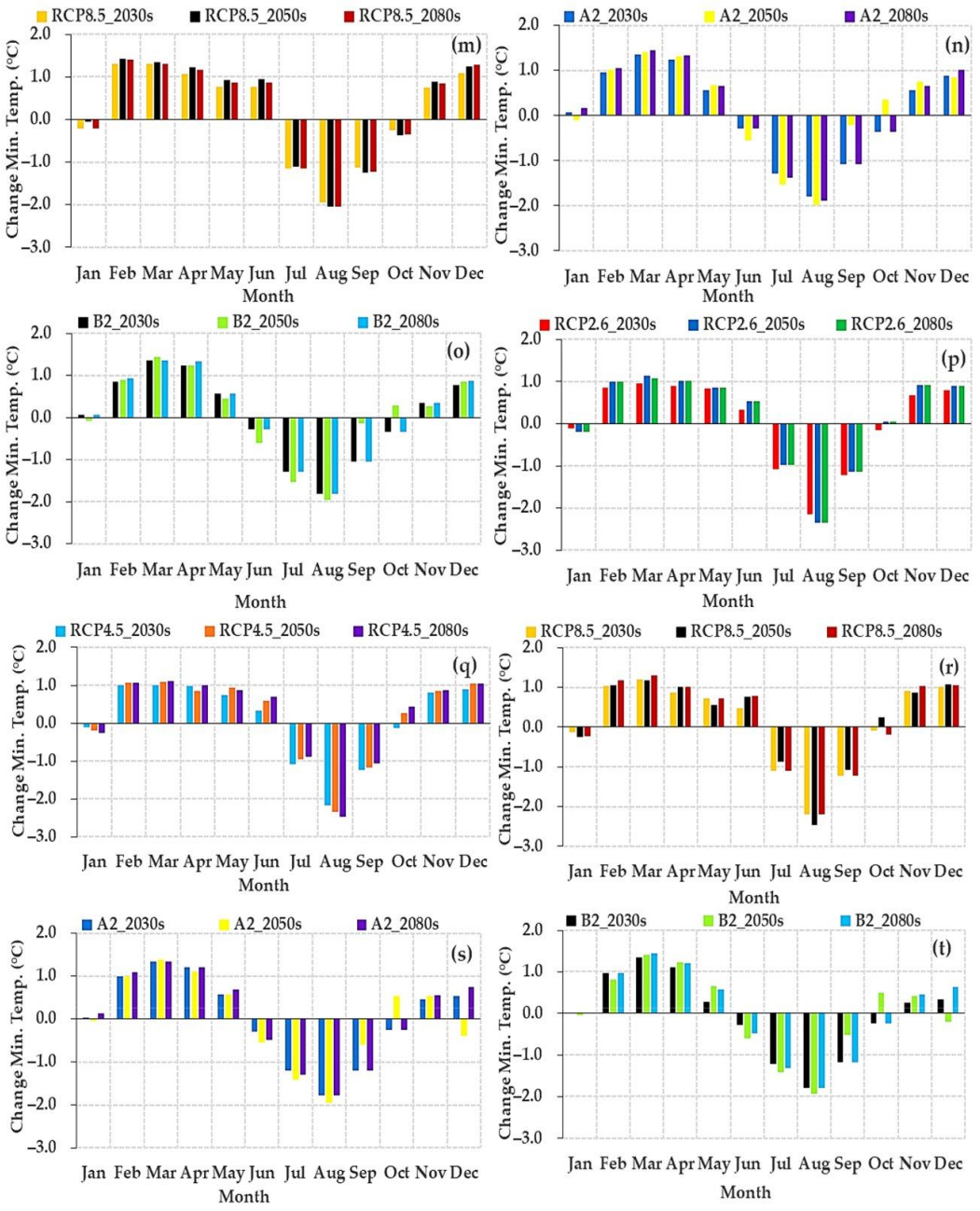


Figure 11. Future monthly change in T_{min} for CanESM2 (RCP2.6, RCP4.5, and RCP8.5) and HadCM3 (A2 and B2) for the 2030s, 2050s, and 2080s for central (**a**–**e**), Greater Accra (**f**–**j**), Volta (**k**–**o**), and the entire zone (**p**–**t**).

3.2.5. Change in Projected Future Monthly Rainfall

Figure 12a–t show the projected future monthly change in rainfall for the central region (Figure 12a–e), Greater Accra region (Figure 12f–j), Volta region (Figure 12k–o), and the entire zone (Figure 12p–t) for the 2030s, 2050s, and 2080s using the CanESM2 (RCP2.6, 4.5, and 8.5) and HadCM3 (A2 and B2 models). The overall results from Figure 12a–t indicate higher variations in rainfall in the 2030s, 2050s, and 2080s across the three regions and the entire zone under both models. In the central region, the A2 and B2 scenarios showed different projections for rainfall (Figure 12d–e). While rainfall is expected to increase and decrease for the wet season and minor and dry seasons, respectively, under the A2 scenarios (Figure 12d), the B2 scenario showed the opposite (Figure 12e). A dissimilar trend is observed for the Greater Accra region (Figure 12i,j). Here, rainfall is projected to increase under both the A2 and B2 scenarios (Figure 12i,j); however, the magnitude of change is greater for the dry season, especially from December to February. The projection for the Volta region (Figure 12n,o) follows a similar trend as the Greater Accra region. Here, rainfall is expected to increase in all months under both the A2 and B2 scenarios. Nevertheless, increases are expected to occur more in the future in the minor and dry seasons (September–March) compared to the wet season (April–July) (Figure 12n,o). The A2 and B2 scenarios for the entire zone tend to follow the zone's normal double maxima rainfall season (Figure 12s–t). Here, rainfall is projected to increase in the wet, minor, and dry seasons except in the months of December (in the 2050s and 2080s) and August (in the 2030s, 2050s, and 2080s) under the A2 scenario. This is the same under the B2 scenario, just that here the decrease in December is expected to occur in the 2050s and in all the years in August. In comparing the A2 and B2 scenarios, it was observed that the scenario performance of the A2 was superior to the B2.

Under the RCP scenarios, rainfall is expected to increase in all months except April under all the RCP scenarios and in October in the 2080s under the RCP8.5 scenario for the central region (Figure 12a–c). Under the same scenarios, rainfall reveals projected increases in all months in the Greater Accra region, with the highest change occurring in the dry season (Figure 12f–h). In the Volta region, rainfall is projected to increase and decrease between the months (Figure 12k–m). For instance, under the RCP26, rainfall shows projected increases in all months except January, April, May, and June (in the 2030s and 2050s) (Figure 12k). The RCP4.5 and 8.5 follow a similar pattern to that of the RCP2.6. However, rainfall is expected to decrease in the month of December in the 2080s for both the RCP4.5 and 8.5 scenarios (Figure 12l–m). The results of rainfall for the entire zone under the RCP scenarios reveal a clear seasonal pattern (Figure 12p–r), as was observed under the A2 and B2 scenarios (Figure 12s–t). Here, rainfall shows a projected increase in the wet (April–July) and minor (September–October) seasons and a decrease in the dry (November–February), except for March. Nevertheless, the increase in March was weak.

Therefore, rainfall is expected to vary between −98.4 and 247.7% across the three regions and −29.0 and 148.0% for the entire zone under all scenarios. Among the three regions, rainfall is projected to decrease greatly in the central region (−98.4%) followed by the Greater Accra region (−65.8%) and least in the Volta region (−3.2%) whereas the Volta region is expected to receive more rainfall (247.7%), the central region (101.0%), and the Greater Accra region (100.6%). That is, in the future, monthly rainfall will increase greatly in the Volta and Greater Accra regions and decrease immensely in the central region. The overall model performance of the A2 and B2 scenarios surpasses that of the RCP scenarios for rainfall. For the A2 and B2 scenarios, rainfall is projected to vary greatly more under the A2 than in the B2 (Figure 12d,e,i,j,n,o,s,t). Under this scenario, rainfall is projected to increase by up to 247.7% in the 2030s and 2080s under the A2 and B2 scenarios, while under the RCP scenarios, rainfall is expected to increase by up to 96.0% in the 2050s and 2080s under the RCP8.5 (Figure 12a–c,f–h,k–m,p–r).

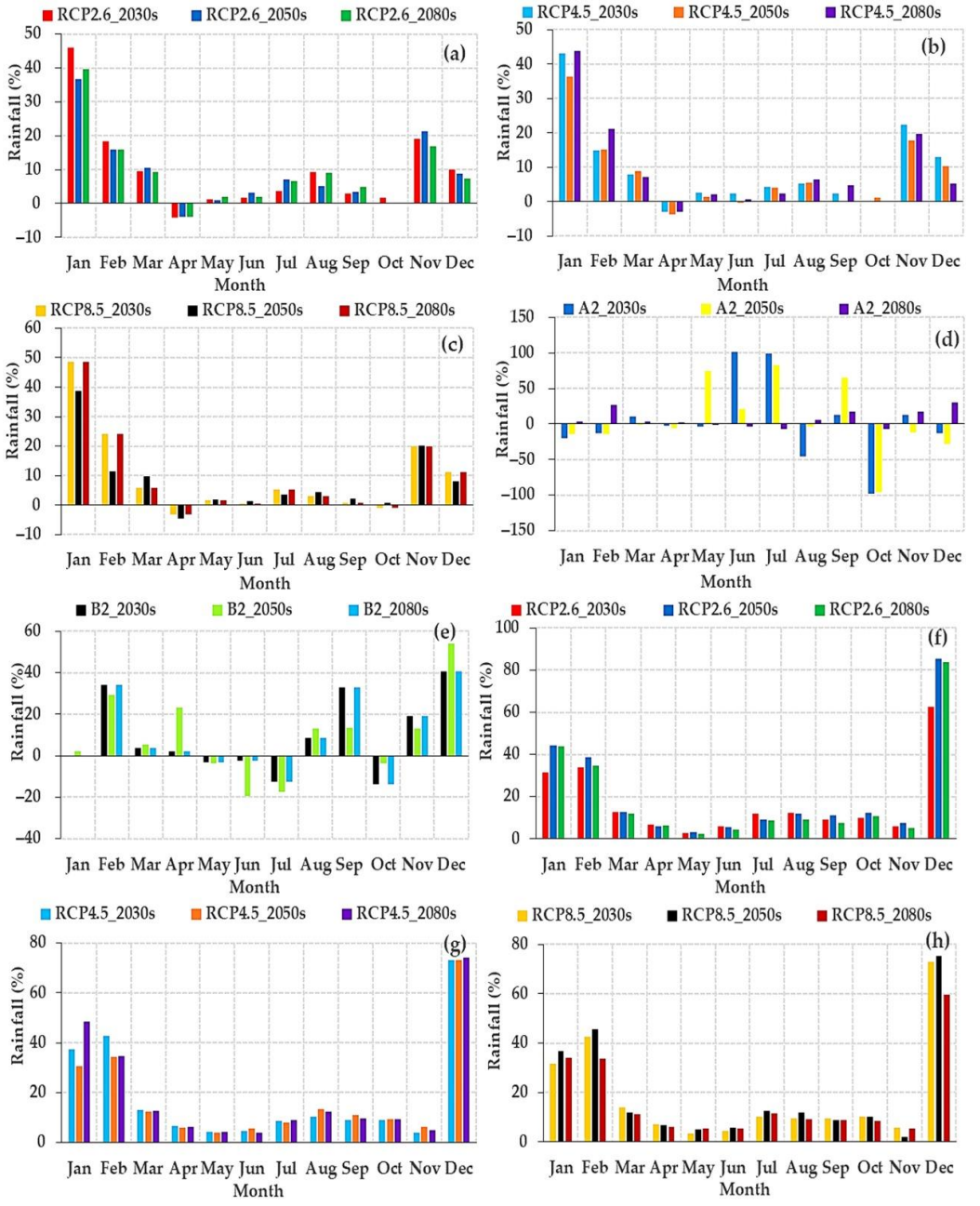


Figure 12. *Cont.*



Figure 12. *Cont.*

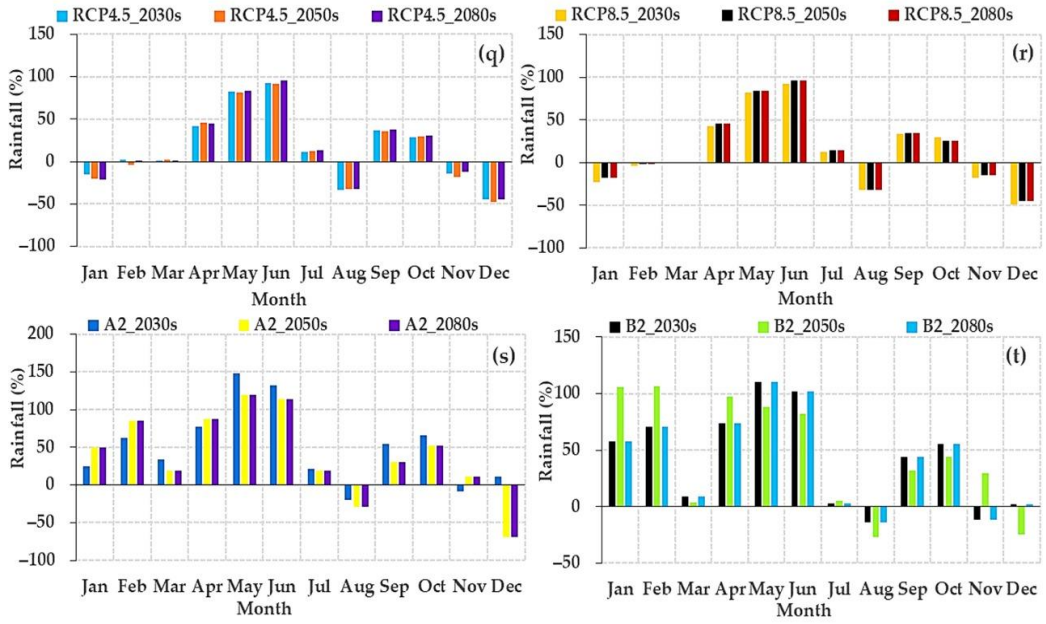


Figure 12. Future monthly change in rainfall for CanESM2 (RCP2.6, RCP4.5, and RCP8.5) and HadCM3 (A2 and B2) for the 2030s, 2050s, and 2080s for central (**a**–**e**), Greater Accra (**f**–**j**), Volta (**k**–**o**), and the entire zone (**p**–**t**).

3.2.6. Projected Future Annual Change in Maximum (T_{max}) and Minimum (T_{min}) and Rainfall

Figure 13a–c show the projected future mean annual change in $T_{\max}$ (Figure 13a), $T_{\min}$ (Figure 13b), and rainfall (Figure 13c) for the 2030s, 2050s, and 2080s for the central, Greater Accra, and Volta regions and the entire zone under the CanESM2 (RCP2.6, 4.5, and 8.5) and the HadCM3 (A2 and B2) models. The results from Figure 13a–c reveal a considerable increase in $T_{\max}$, $T_{\min}$, and rainfall under both models. As shown in Figure 13a, $T_{\max}$ is expected to rise in all scenarios except the central region and the entire zone under RCP2.6. $T_{\max}$ is projected to increase greatly under the RCP8.5 scenario compared to the other two, while the A2 scenario surpasses the B2 (Figure 13a). Among the three regions, $T_{\max}$ reveals a greater increase in the Greater Accra region, especially under the RCP8.5 and the A2 scenarios, than the other two regions. The increase is also higher in the 2080s than in the 2030s and 2050s (Figure 13a). Notwithstanding the increase, the projected mean annual change is small. For example, the highest change in the mean annual $T_{\max}$ of 1.6 °C is expected to occur in the 2080s under the RCP8.5 scenario (Figure 13a). In general, the RCP scenarios outperformed the A2 and B2 scenarios.

The $T_{\min}$ follows a similar pattern to that of the $T_{\max}$. Here, $T_{\min}$ is projected to increase in all years under all scenarios except in the 2030s under RCP4.5, A2, and B2 (Figure 13b). Under the RCP4.5 and A2, only the central region showed a decrease, while under the B2, $T_{\min}$ is expected to decrease in the central and Greater Accra regions and the entire zone (Figure 13b). The $T_{\min}$ shows a higher projected increase under all scenarios for the Greater Accra region than the other two. The $T_{\min}$ is expected to increase significantly in the 2050s under the RCP8.5 and A2 scenarios. In comparison to the $T_{\max}$, the $T_{\min}$ shows greater annual change. Here, the highest mean annual change of $T_{\min}$ is 3.2 °C and is expected to occur in the 2050s under the RCP8.5 scenario (Figure 13b). Similar to the $T_{\max}$, the overall results of the RCP scenarios surpassed the A2 and B2.

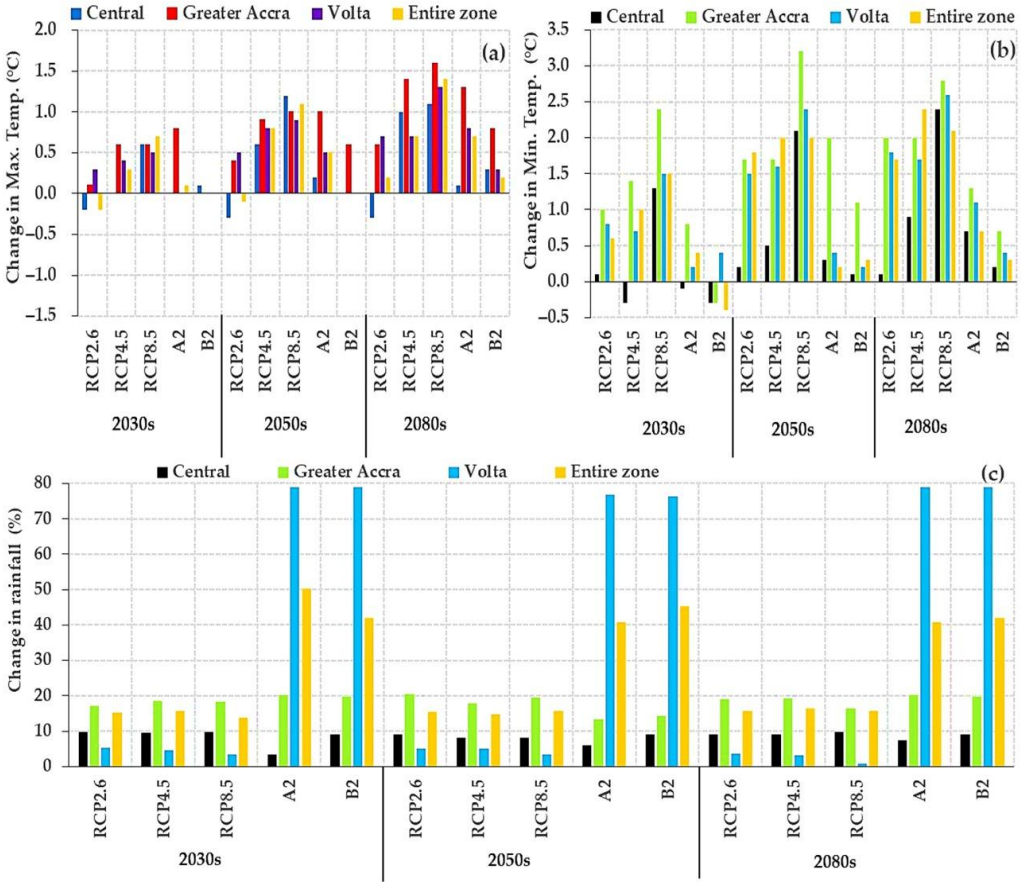


Figure 13. Mean annual change for 2030s, 2050s, and 2080s for (**a**) T_{max}, (**b**) T_{min}, and (**c**) rainfall for the central region, Greater Accra region, Volta region, and the entire zone under CanESM2 (RCP2.6, 4.5, and 8.5) and HadCM3 (A2 and B2) models.

From Figure 13c, rainfall is projected to increase in all three regions and the entire zone under all scenarios. The minimum and maximum change in mean annual rainfall are expected to be between 0.8% (in the 2080s) and 79% (in the 2030s and 2080s) under the RCP8.5 and the A2 and B2 scenarios, respectively (Figure 13c). Among the three regions, the mean annual change in rainfall is expected to be highest in the Volta region, followed by the Greater Accra region, and least in the central region. Rainfall for the three regions and the entire zone show higher projections under the A2 and B2 scenarios than in the RCP scenarios. That is, for rainfall, the A2 and B2 scenarios in the HadCm3 model outperformed the RCPs in the CanESM2.

4. Discussion

In this study, we analyzed temperature (T_{max} and T_{min}) and rainfall extreme events and their trends over space and time and employed the SDSM tool to downscale future climate change scenarios based on the CanESM2 (RCP2.6, 4.5, and 8.5) and HadCM3 (A2 and B2) for the coastal Savannah agroecological zone of Ghana. Changes in temperature and rainfall from extreme events have significant implications for water supply, agriculture,

livelihoods, and the health of the inhabitants in this region. The study identified more changepoints in T_{min} across the study locations. This finding is consistent with previous research studies conducted elsewhere on a national and global scale, such as [79,100–104].

The results revealed that the study region has warmed substantially in the past four decades. This result agrees with the earlier global research, such as [3,8,105,106]. The findings are also consistent with the previous research conducted at regional scales, such as [5,79,107,108]. According to the study's findings, the SU25, TXn, and TN90p significantly increased for all locations, regions, and the entire zone, which is consistent with the previous findings such as [24,26,35,109–114]. Over the entire African continent, Iyakaremye et al. [115] state the increased number of warm nights in most parts of Africa, while Moberg et al. [116] report increased warming for the European territory. In furtherance to this, the results revealed a significant decrease in TN10p throughout the study locations and for the entire zone, which agrees with the earlier research studies, such as [25,26,87,117,118]. The IPCC [1], in its fifth assessment report, underlines a decrease in cool nights in many land regions, which is consistent with this study.

Spatially varied results were observed for the TXx, TNx, TNn, TX10p, TX90p, and the CSDI. Positive trends were observed only in the locations of Accra, Denu, and Tema for the TXx and Cape Coast, Denu, Elmina, Moree, Prampram, and the central and Volta regions for the TNx (see Table 5 and Figure 3). The TNn also significantly increased in the locations of Ada Foah, Anloga, Keta, and Saltpond. Again, the TX10p significantly decreases only in the locations of Accra, Cape Coast, Denu, Elmina, Moree, and Tema. This decrease was reflected in the three regions (the central, Greater Accra, and Volta), as well as for the entire zone. This conforms to the IPCC's [1] assertions that cool days have decreased in many regions of the world. Moreover, the TX90p significantly increased only in the areas of Accra, Cape Coast, Denu, Elmina, Moree, Tema, and the Greater Accra region. The CSDI further showed both positive and negative trends. However, the positive trends, despite being significant, were weak. The CSDI, thus, decreased significantly in the locations of Denu, Elmina, and Moree, the three regions, and the entire zone. The variation in warming trends observed in this study is in line with the previous studies [79,119–122].

From the results, the DTR, an essential indicator of climate change [123,124], significantly decreased across the study region (−0.30 °C per decade). This finding is consistent with the earlier studies conducted in different regions, such as [26,125–131]. Barry et al. [26] state that the annual mean daily T_{min} has increased more than the annual mean daily T_{max}, which has led to a decreased DTR in the West African region, of which this study is no exception. It is worth noting that as far back as 1997, Easterling et al. [132] found a decreasing DTR trend in most parts of the world. The authors found factors such as increased cloudiness as key contributors to the decrease in DTR [132]. Nevertheless, Vose et al. [133] assert that after 1980, the increases in minimum and maximum temperatures have become more comparable, decreasing recent DTR trends. The recent increase in land-use changes through urbanization, population growth, and economic and industrial activities could be the cause of the decrease in the DTR in the zone. The coastal cities in Ghana, especially Accra (the capital), Tema, and Cape Coast, are known for their improved economic and industrial activities [73]. The incidence of urban heat island effects through urbanization and population growth has been found to decrease DTR [134,135].

The results revealed a significant decrease in RX1day, RX5day, SDII, and R10 only in the locations of Cape Coast, Elmina, Moree, and Saltpond, which was reflected in the general decrease for the central region, while the other locations were insignificant. This finding is consistent with previous research in other regions, such as [33,136–138]. In addition, the results of this study did not show any significant increase or decrease for R20, CWD, and PRCPTOT, which agrees with the earlier studies conducted elsewhere, such as [139,140]. Moreover, the CDD significantly decreased in the areas of Accra, Ada Foah, Anloga, Denu, Keta, Prampram, the Greater Accra and Volta regions, and the entire zone. This finding supports the earlier works conducted in other regions, such as [141,142].

The R95p and R99p, moreover, decreased significantly in the areas of Cape Coast, Elmina, Moree, and Saltpond, which reflected a significant decrease for the central region.

The results from the rainfall extreme indices revealed variations in the study region. For example, the decrease in RX1day, RX5day, SDII, and R10 was significant in most parts of the central region compared to the other two regions. A similar situation was observed for the R95p and R99p, while the CDD showed a significant decrease in the Greater Accra and Volta regions compared to the central region. This thus confirms the spatially variable nature of rainfall [24,29,143]. Other authors, including Abdullah et al. [79]; Vondou et al. [141]; and Santos et al. [142], reported highly variable extreme rainfall events in Bangladesh, Cameroon, and mainland Portugal, respectively. The results of the study revealed strong variations for the last four decades in the study regions, confirming the earlier work of Sanogo et al. [144] for the West African region and that of Nicholson [145] for the entire African continent.

The increase in global greenhouse gas emissions is believed to have made rainfall more variable over the West African region [146–148]. The decrease in rainfall is also attributed to land-ocean interactions and the related changes in sea surface temperature (SST) [148]. Notwithstanding, Dong and Sutton [148] believe that the increased levels of greenhouse gases in the atmosphere have a more substantial influence on the variable nature of rainfall in the West African region than the SST. Skinner et al. [149] contend that changes in SST caused by atmospheric radiative forcing are to blame for the decrease and variable nature of rainfall along most of the West African Guinea's coast areas. According to Skinner et al. [149], changes in SST reduce the monsoon westerlies and the tropical easterly jet (TEJ), as well as low-level interconnection and rising air in the middle levels of the troposphere, causing decreasing rainfall over the region. Elsewhere, Abdullah et al. [79] and Shrestha et al. [107] reported decreased annual total rainfall for Bangladesh and India, respectively, in recent decades.

During the model performance assessment for calibration and validation for future climate change scenarios for the study region, it was observed that the performance in rainfall was low compared to the T_{max} and T_{min}, especially during validation of the model. This finding is consistent with the earlier studies, such as [44,45,56]. The poor performance could be attributed to the conditional modeling behavior of rainfall and the difficulty of achieving a perfect multiple regression in the SDSM. Wilby and Dawson [96] highlighted the fact that conditional models, such as the one applied to the case of rainfall, reveal an intermediate process between local weather and regional forcing. According to Siabi et al. [44], the dynamics of local weather, such as rainfall, are highly dependent on the number of wet and dry days, which in turn rely on regional-scale predictors such as atmospheric pressure and humidity, both of which are difficult for the SDSM to capture. Therefore, when compared to T_{max} and T_{min}, the process of downscaling rainfall is more challenging [150,151]. Gulacha and Mulungu [151] assert that the SDSM is possibly not the appropriate tool to downscale rainfall. The model performance results for T_{max} and T_{min} and rainfall in our study contradict the assertions of Gulacha and Mulungu [151]. In general, the present study achieved better calibration performance in all three climate variables analyzed (see Table 8) and is consistent with the earlier studies conducted elsewhere, such as [44,45,56,65,66].

The result from the performance of the two models showed that the CanESM2 (R^2 = 76–99%) outperformed the HadCM3 (R^2 = 58–99%) during calibration and validation. This finding is consistent with the previous future climate change projection studies, such as [45,59,60,152]. It is worth noting that several research studies, such as [44,153] have also reported better performance in the HadCM3 model compared to the CanESM2. The differences in model agreements, thus, reveal the uncertainty related to climate change assessment [60,154].

Generally, the results of monthly projections for both T_{max} and T_{min} revealed an increase for the 2030s, 2050s, and 2080s under both the CanESM2 (RCP2.6, 4.5, and 8.5) and HadCM3 (A2 and B2) models for three regions and the entire zone, amidst varia-

tions. The study zone's three regions are expected to have the highest (1.6 °C) and lowest (−1.6 °C) T_{max}, while the entire zone is expected to have 1.5 °C and −1.6 °C. T_{min} will be the greatest (1.4 °C) and lowest (−2.1 °C) in each region, as well as the greatest (1.4 °C) and lowest (−2.3 °C) for the entire zone. Under the CanESM2 model, both T_{max} and T_{min} are projected to increase greatly under the RCP8.5 scenario, while that of the HadCM3 reveals a higher increase under the A2 scenarios. This finding is in line with the earlier studies, such as [44,45,56,59]. Under RCP8.5, the mean annual change in T_{max} and T_{min} is projected to be 1.6 °C (occurring in the 2080s) and 3.2 °C (occurring in the 2050s), respectively, which is similar to the change reported in an earlier study, such as [60].

The results from the projected monthly change in rainfall revealed variations among the three regions and the entire zone for the 2030s, 2050s, and 2080s under both models. Notwithstanding, the results obtained under both models showed more increases than decreases in rainfall. The decrease is more visible in the central region, while the Greater Accra and Volta regions showed an increase, thereby reflecting a general increase in rainfall in the future for the entire zone. For instance, rainfall is expected to vary between −98.4 and 247.7% across the three regions and −29.0 and 148.0% for the entire zone under all scenarios. This finding is in conformity with the earlier studies, such as [44,56]. The projected mean annual change in rainfall reveals an increase across the three regions and the entire zone. The mean annual rainfall in the zone is expected to vary between −0.8 and 79% under all scenarios. This finding agrees with studies such as [59,60].

The results of the study, therefore, have important implications for the coastal Savannah agroecological zone and the entire country. Although rainfall is projected to increase in the zone, it will be accompanied by greater variations. This situation could result in severe extreme events, including drought and floods in the zone. The incidence of both drought and flood events in the zone could have significant negative impacts on agricultural activities. For instance, a drought can lead to crop failures, losses, and the general drying of crops [155], while floods also have the tendency to damage seeds and seedlings and sweep away fertile soil [156]. The impacts of climate change on health are widely established in the scientific literature. For instance, Bosello et al. [157] assert that climate change will increase the range and abundance of vector-borne diseases, particularly malaria. There is also the possibility of a high incidence of diarrheal and intestinal diseases and cholera with the projected increase in rainfall. The projected increase in future rainfall in the zone will be beneficial for water resources, which will increase the annual river runoff.

5. Conclusions

Under a changing climate, the analysis of climate extreme indices and the projections for possible future climate change scenarios are relevant. The overall results of the study suggest that temperatures in the coastal Savannah agroecological zone of Ghana have increased and rainfall has become more variable over the last four decades, a feature that clearly supports the literature consensus on the variable nature of rainfall in the West African region. Both temperatures and rainfall are projected to increase in the future.

We noticed that most indices, such as SU25, TXn, and TN90p, significantly increased across the study locations, while others, such as TXx, TNx, TNn, TX10p, TX90p, and the CSDI, exhibited both increased and decreased trends, reflecting variations in the zone. The DTR, which is considered an essential indicator of climate change, significantly decreased across the study region. The majority of the extreme rainfall indices revealed a more significant decrease than an increase across the zone.

The general performance of the CanESM2 and HadCM3 models during calibration and validation was better, thereby supporting the encouragement for the usage of the SDSM technique in the literature for evaluating future possible climate change scenarios. The overall projection for both monthly and annual T_{max} and T_{min} showed an increase for the 2030s, 2050s, and 2080s under both the CanESM2 (RCP2.6, 4.5, and 8.5) and HadCM3 (A2 and B2) scenarios, agreeing with the consensus of a warming world and the need for increased mitigation and adaptation. Generally, both monthly and annual rainfall

are projected to increase in the zone for the 2030s, 2050s, and 2080s under both models, amidst variations.

The findings of the study have several implications for agricultural activities, water resources, health, and the general livelihoods of the inhabitants in the study zone. The findings of this study could, therefore, be helpful for the development of appropriate adaptation plans to safeguard the livelihoods of people in the zone.

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CHAPTER 4: Analysis of the influence of ENSO on rainfall variability in the coastal savannah agroecological zone of Ghana

4.1. Rainfall variability and the influence of El Niño-Southern Oscillation in the coastal savannah agroecological zone of Ghana

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Rainfall variability and the influence of El Niño-Southern Oscillation in the coastal savannah agroecological zone of Ghana

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Abstract: This study analysed rainfall variability and the influence of the El Niño-Southern Oscillation (ENSO) in the coastal savannah agroecological zone of Ghana. Daily rainfall and ENSO data from 1981 to 2021 were used. The standardized rainfall anomaly index (SRAI), cumulative departure index (CDI), individual seasonality index (SI_i), rainfall anomaly index (RAI), coefficient of variation (CV), one-way analysis of variance, inverse distance weighting interpolation, and the R-Instat software (version 0.70) were the methods applied. The results revealed more wet years in both the annual and major season rainfall across the zone, and the opposite is true for the minor season rainfall. More above-average rainfall was observed across the zone for the major season than the minor and annual. The mean individual seasonality index identified values between 0.66 and 0.72, indicating that rainfall distribution across the zone is seasonal. Both the major and minor season rainfall amounts and rainy days increased from the Central region to the Volta region. The CV for major season rainfall ranged from 17% to 22%, and the minor season ranged from 36% to 46%. The onset of rains for the major season was similar across the zone and occurred in the 1st week of April (day 92 of the year), while the cessation varied between the 4th week of July (day 183) and the last 4.4286 week (4 weeks and 3 days) of July (day 212). The corresponding onset for the minor season also appeared to be similar across the study location and occurred in the 1st week of September (with range from days 245 to 249), and a similar cessation, which occurred in the 1st week of November (day 306) across the zone. The length of the minor and major rainy seasons ranged from 57 to 61 days and 91 to 120 days, respectively. No significant difference in total annual rainfall was observed for the different ENSO phases. The variation in total annual rainfall explained by the different ENSO phases was small, between 1% and 12%. The La Niña phase was associated with greater mean annual rainfall and had greater influence on the major season rainfall than the other two phases. The greater rainfall variability could affect several livelihood opportunities and can be addressed by improving the irrigation systems in the zone.

Keywords: Rainfall variability. Onset rainfall. Cessation rainfall. ENSO. Coastal Ghana

1 Introduction

Climate change and variability have emerged as major issues in the twenty-first century (Karl and Trenberth 2003), threatening the achievement of the Sustainable Development Goals, particularly those aimed at eradicating poverty and hunger (Nilson and Visbeck 2016). Temperature and rainfall variations have an impact on many socio-ecological systems (Kakinuma et al. 2019). Rainfall variability has a significant impact on the socioeconomic livelihoods of people who rely on rain-fed agriculture, particularly in Sub-Saharan Africa (Calzadilla et al. 2013; Dinku et al. 2007; Recha et al. 2012). According to Calzadilla et al. (2013), rain-fed farming accounts for 97% of cropland in Sub-Saharan Africa. In the West African region, for example, agricultural activities employ approximately 65% of the population and contribute approximately 30–70% of the region's gross domestic product (Akumaga and Tarhule 2018; Blanc 2012). Rainfall variations are thus regarded as critical, given the rain-dependent nature of agricultural activities in the region (Sultan and Gaetani 2016; Sylla et al. 2018).

Although rainfall is considered critical in the West African region, annual amounts have been found to have decreased since the 1960s, with a 20-40% decrease in the 1990s (IPCC 2012). Rainfall in the region varies seasonally, inter-annually, and decadally (Giannini et al. 2003; Rodríguez-Fonseca et al. 2011) and is heavily influenced by the West African monsoon (Omotosho et al. 2000; Sylla et al. 2018). Trends in rainfall amounts have been well recognised across the West African region, as highlighted by Muthoni (2020) and Atiah et al. (2020), with little attention paid to variations in rainfall seasonality such as the onset, cessation, and length of the rainy season (Obarein and Amanambu 2019). Variations in the onset, cessation, and length of the rainy season are thought to be critical for crop development (Amekudzi et al. 2015; Camberlin et al. 2009; Obarein and Amanambu 2019).

Given the rain-dependent nature of agriculture in the Sub-Saharan African region (Cooper et al. 2008), several research studies on the seasonality of rainfall onset and cessation have been conducted, including those of (Akinseye et al. 2016; Camberlin et al. 2009; Dunning et al. 2016; Hachigonta et al. 2008; Ibrahim and Usman 2021; Kabanda and Nenwiini 2016; Kebede et al. 2017; Kwawuvi et al. 2022; Obarein and Amanambu 2019; Odekunle 2006; Omotosho et al. 2000; Recha et al. 2012; Sibanda et al. 2020). For example, Kebede et al. (2017) analysed the onset, cessation, and trends of dry spells in the Upper Baro-Akobo river basin in Ethiopia and found no significant variation in the onset, cessation, and duration of rainfall in the Upper Baro-Akobo river basin. Again, Obarein and Amanambu (2019) reported relatively higher interannual variability in rainfall onset than in cessation in Nigeria. In addition, Sibanda et al. (2020) pointed out a greater change in both the onset and cessation dates of the rainy season, which has significantly decreased the length of the rainy season in the Mzingwane catchment of south-western Zimbabwe. Also, Ibrahim and Usman (2021) informed us about the variation in the effective start of rainfall over 15 days and 30–60 days in the Guinea Savanna and Sudano-Sahelian Savanna zones of Nigeria.

Ghana, which is part of the Sub-Saharan African region, is no exception to agriculture's reliance on rain. In recent times, several research studies such as (Amekudzi et al. 2015; Atiah et al. 2021; Baffour-Ata et al. 2021; Bessah et al. 2020; Boansi et al. 2019; Mensah et al. 2016; Larbi et al. 2021) have attempted to characterise and determine the onset, cessation, and length of the rainy season to help smallholder farmers in Ghana whose main livelihood is dependent on their farming activities. Amekudzi et al. (2015), for example, investigated the onset and cessation dates of the rainy season over Ghana and discovered variations in rainfall onset and cessation dates across Ghana's various agroecological zones. Mensah et al. (2016) discovered that the average duration of the rainy season in Ghana was less than 200 days in the savanna and coastal zones and more than 200 days in the forest and transition zones. Similarly, Atiah et al. (2021) observe late and early onsets in the Upper West and Upper East regions, as well as late cessations and longer growing periods in Ghana's northern region. Larbi et al. (2021) also reported a projected increase in the length of the rainy season for the Vea catchment in Northern Ghana from 2020 to 2049, from 168 to 177 days. Although research on the onset, cessation, and length of the rainy season has increased in Ghana, it is still limited to the northern part of the country, as evidenced by the studies above, at the expense of other equally important parts of the country, such as the coastal zone. Given the location, rainfall variability in the coastal zone, as measured by the onset, cessation, and length of the rainy season, is critical.

Not only do the Inter-Tropical Convergence Zone (ITCZ) and the African Easterly Jet influence rainfall variability in West Africa (Le Barbé et al. 2002; Nicholson 2008; Omotosho 2008; Omotosho et al. 2000; Sylla et al. 2018), but the El Niño-Southern Oscillation (ENSO) is found to have a significant influence as well (Balas et al. 2007; Emmanuel 2022; Ibrahim and Usman 2021; Nicholson and Grist 2001). ENSO is a natural phenomenon associated with sea surface temperatures that originates in the tropical Pacific region and has global implications for agriculture, ecosystems, and other extreme weather events (Collins et al. 2010). Several research studies on the influence of ENSO on rainfall variability have been conducted in various parts of the world, including Africa (e.g., Ayantobo et al. 2022; Bhatla et al. 2020; Brönnimann et al. 2007; Cai et al. 2011; de Oliveira-Júnior 2022; Giannini et al. 2000; Grimm and Tedeschi 2009; Kijazi and Reason 2005; Manatsa and Matarira 2009; Muhire et al. 2015; Shaman 2014; Sazib et al. 2020; Thirumalai et al. 2017; Whan and Zwiers 2017).

Several research studies on the impact of ENSO on rainfall variability have been conducted in Ghana (e.g., Adiku et al. 2007; Boadi and Owusu 2017; Owusu et al. 2019a; Owusu et al. 2019b; Owusu et al. 2008; Waylen and Owusu 2014). However, researchers have primarily conducted these studies in the transition zone, deciduous forest zone, or Volta River basin, with

little to no research carried out in the coastal savannah agroecological zone (CSAZ). Waylen and Owusu (2014) re-examined the changes in rainfall climatology expectations and extremes and their relationship with ENSO in Accra, which is found in CSAZ. Despite this, the researchers made no attempt to understand the seasonality of rainfall variability, such as the onset, cessation, and length of the rainy season, and their relationship with the various phases of ENSO. There is, thus, a dearth of information regarding how ENSO and its different phases influence rainfall variability in the CSAZ. There is also a large knowledge gap in understanding the seasonality of rainfall variability, such as the onset, cessation, and length of the rainy season, as well as their relationship with ENSO's various phases. Given the distinct climatic, vegetation, and soil characteristics of Ghana's various agroecological zones and how each of them responds differently to the prevailing impacts of climate change and variability, particularly rainfall dynamics, it is imperative to analyse the influence of various ENSO phases on rainfall variability, as well as their association with seasonality effects such as the onset, cessation, and length of the rainy season in CSAZ, where no study of this nature has been conducted. This analysis is crucial given their critical role in crop development (Amekudzi et al. 2015; Camberlin et al. 2009; Obarein and Amanambu 2019). As a result, the objective of this study is to analyse rainfall variability and the influence of ENSO on Ghana's CSAZ. The study specifically analysed annual and seasonal rainfall trends, variation in seasonal rainfall amount and rainy days, the onset, cessation, and length of the rainy season, and the effect of ENSO on annual and seasonal rainfall in Ghana's CSAZ. This study is essential not only for Ghana and the smallholder farmers in the CSAZ, but also for the Sub-Saharan African region, where few research studies on variations in rainfall seasonality such as onset, cessation, and length of the rainy season have been conducted (Obarein and Amanambu 2019).

2 Materials and methods

2.1 Study area

The coastal savannah agroecological zone is one of six agroecological zones found along Ghana's central and eastern coasts (Fig. 1). The zone is part of Ghana's administrative regions of Central, Greater Accra, and Volta (Fig. 1). It has a tropical climate with both dry and wet seasons that is heavily influenced by the West African Monsoon and the ITCZ (Addi et al. 2020). The zone has two rainfall seasons: the major, which lasts from April to July (with the most rain falling in June), and the minor, which lasts from September to early November (with the most rain falling in October) (Addi et al. 2021; Ghana Statistical Service [GSS] 2013). The dry season begins in late November and lasts until the end of March. Despite having a double maxima rainfall regime, the zone receives the least amount of rainfall of the six agroecological zones in Ghana (GSS 2013). The average monthly temperature ranges between 24.7 °C in August and 32.7 °C in March (Dickson and Benneh 1995) and is considered the driest zone in the country (Gbangou et al. 2020). The majority of the zone's vegetation is grassland, with a few trees in the centre and shrubs, thickets, and mangroves in the east (GSS 2013). Because of its coastal location, the zone contributes significantly to Ghana's GDP (GSS 2013).

The zone's main economic activities are agriculture, fishing, tourism, trade, transportation, and services (Addi et al. 2021). Agriculture, although rain-dependent, contributes substantially to the socio-economic livelihoods of the people, especially those in the Central and Volta areas (GSS 2013). Crop farming is the most important agricultural activity in the zone, followed by livestock rearing, and fish farming is the least active (GSS 2013). Crops cultivated include yam, cassava, cocoyam, maize, millet, rice, pepper, tomatoes, etc., while poultry, goats, sheep, and cattle are the main livestock reared (GSS 2013). The Volta, Densu, and Ayensu are three major rivers that support agricultural activities in the zone (GSS 2013). Accra (the capital city), Cape Coast, Elmina, Moree, Saltpond, Apam, Winneba, Bortianor, Tema, Prampram, Ada Foah, Anloga, Keta, and Denu are among the major towns (Fig. 1).

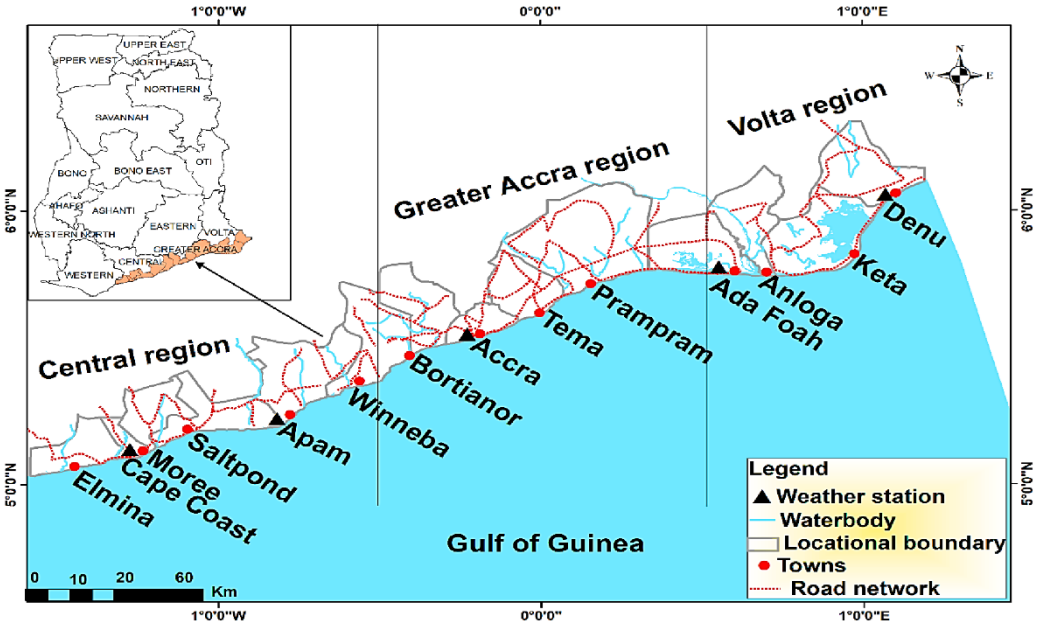


Fig. 1 Map showing the study locations in the coastal savannah agroecological zone of Ghana

2.2 Data and quality control

Daily rainfall data for 6 locations from 1981 to 2021 were acquired from the Ghana Meteorological Agency (GMet) and the National Aeronautics and Space Administration/Prediction of Worldwide Energy Resources (NASA/POWER) (https://power.larc.nasa.gov/). We obtained data for five synoptic stations from GMet: Accra, Ada Foah, Apam, Cape Coast, and Denu, while Prampram was obtained from NASA/POWER. GMet is Ghana's climatological data representative, whereas NASA/POWER is a satellite-based data set that provides global weather and agroclimatology data at 1 latitude and longitude resolution (Monteiro et al. 2018). NASA/POWER satellite data have been widely used (Kheyruri and Sharafati 2022; Monteiro et al. 2018; Mourtzinis et al. 2017; Srivastava et al. 2020) and are regarded as appropriate and reliable, particularly for filling data gaps in data-scarce regions such as developing countries (Monteiro et al. 2018).

To check for missing gaps in the data sets from the five synoptic stations, the R-Instat (version 0.70) software (http://r-instat.org/About.html) was used. The missing gaps in each data set were less than 2% in this case. As suggested by Monteiro et al. (2018), we used NASA/POWER satellite data for these five stations to fill in the gaps. The homogeneous nature of the rainfall data used in this study has been established in our previous study (see Ankrah et al. (2023a)).

ENSO data from 1981 to 2021 was obtained from the National Oceanic and Atmospheric Administration (NOAA) (https://www.cpc.ncep.noaa.gov/). We used the NOAA's Oceanic Niño Index (ONI) to identify the different ENSO phases in the Tropical Pacific Ocean, such as El Niño (warm), La Niño (cold), and Neutral (Huang et al. 2017). The ONI is recognised by NOAA as the standard index for monitoring ENSO events and has been widely applied in several research studies such as (Almeida Silva et al. 2020; de Oliveira-Júnior et al. 2022; García-Garizábal 2017; Iacovone et al. 2020; Richard and Walsh 2018; Silva et al. 2022; Tinmaker et al. 2017; Zhu et al. 2019). The index is based on a threshold of + 0.5 °C (warm) and – 0.5 °C (cold) for the 3 month running mean of the Extended Reconstructed Sea Surface Temperature version 5 (ERSSTv5) sea surface temperature (SST) anomalies in the Niño region (5°N–5°S, 120°–170°W) (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php). Following the work of Silva et al. (2020), we classified the ONI values into three categories: El Niño (> + 0.5), La Niña (≤ – 0.5), and neutral (values between – 0.5 and + 0.5).

2.3 Methods

To analyse rainfall variability in the CSAZ of Ghana, the seasonal rainfall amount and rainy days, the onset, cessation, and length of the rainy season were analysed for both the major (April to July) and minor (September to November) seasons. We

used the standardized rainfall anomaly index (SRAI), the cumulative departure index (CDI), and rainfall anomaly index (RAI) to analyse the annual and seasonal variability and long-term trends (Recha et al. 2012; Tilahun 2006). Following the study of Yamba et al. (2023), we computed the SRAI from the averages of the seasonal and annual rainfall for the data length and normalised them as follows:

$$SRAI = \frac{(r - R)}{\sigma} \tag{1}$$

where r denotes the actual seasonal or annual rainfall in a given year, R is the average rainfall of the data length, and σ is the standard deviation of the data length. Utilising the earlier estimation of the SRAI and following the study of Recha et al. (2012), we calculated the CDI from the averages of the normalised seasonal and annual rainfall data length. We thus performed a cumulative sum of the resulting values to derive trends in annual and seasonal rainfall for the zone.

We once again applied Walsh and Lawler's (1981) individual seasonality index (SI_i) to the monthly rainfall data, thereby quantifying the seasonal variations in rainfall amounts across the study locations from 1981 to 2021. The SI_i shows the sum of the absolute deviation of mean monthly rainfall from the overall monthly mean divided by the mean annual rainfall (da Silva Araújo et al. 2023; Stosic et al. 2024; Walsh and Lawler 1981). We then computed the SI as follows:

$$SI_i = \frac{1}{\bar{R}} \sum_{n=1}^{n=12} |\bar{x}_n - \bar{R} / 12| \tag{2}$$

Where $\bar{x}_n$ represents mean rainfall of month n and $\bar{R}$ is mean annual rainfall.

We calculated the mean individual seasonality index ($\overline{SI_i}$) using the following formula (da Silva Araújo et al. 2023; Stosic et al. 2024; Walsh and Lawler 1981):

$$\overline{SI_i} = \frac{1}{\bar{N}} \sum_{i=1}^{N} SI_i, \tag{3}$$

Where N represents the number of years of the considered period.

As described by Walsh and Lawler (1981), the SI_i values range from zero when there is an equal distribution of rainfall in all months to 1.83 if all the rainfall occurs in a single month. We adopted Walsh and Lawler's (1981) SI_i classes and their representative rainfall regimes as shown in Table 1.

Table 1. Rainfall seasonality index class limits and regime. Adopted from Walsh and Lawler (1981)

Rainfall regime	SI_i class limits
Very equitable	≤ 0.19
Equitable but with a definite wetter season	0.20 – 0.39
Rather seasonal with a short drier season	0.40 – 0.59
Seasonal	0.60 – 0.79
Markedly seasonal with a long drier season	0.80 – 0.99
Most rain in 3 months or less	1.00 – 1.19
Extreme, almost all rain in 1 – 2 months	≥ 1.20

We also computed the RAI to show the inter-seasonal variations in rainfall across the zone. We adopted the RAI computations in the earlier studies of Recha et al. (2012) and Tilahun (2006) for positive anomalies as:

$$\mathrm{RAI} = +3 \left(\frac{\mathrm{RF} - M_{\mathrm{RF}}}{M_{\mathrm{H10}} - M_{\mathrm{RF}}} \right) \tag{4}$$

and for negative anomalies

$$\mathrm{RAI} = -3 \left(\frac{\mathrm{RF} - M_{\mathrm{RF}}}{M_{\mathrm{L10}} - M_{\mathrm{RF}}} \right) \tag{5}$$

Where RAI denotes the rainfall anomaly index, RF is the actual rainfall for a given year, M_{RF} is the mean for the entire data length, M_{H10} and M_{L10} represent the means of the 10 highest and lowest values of rainfall in the data, respectively.

The R-Instat (version 0.70) software (http://r-instat.org/About.html) was used to calculate the mean rainfall for every 5 days (pentads) of the major and minor seasons in the zone. We employed the coefficient of variation (CV), which shows the ratio of the standard deviation to the mean expressed as a percentage (Kabanda and Nenwiini 2016; Recha et al. (2012), to

estimate the rainfall amount and rainy days across the study zone. Studies such as (Ibrahim and Usman 2021; Kabanda and Nenwiini 2016; Obarein and Amanambu 2019; Recha et al. 2012; Sibanda et al. 2020) have employed the CV for seasonal rainfall analysis.

The onset and cessation dates and length of the rainy season of the seasonal rainfall were estimated by using the R-Instat (version 0.70) software (http://r-instat.org/About.html). The suitability of the R-Instat software for rainfall onset and cessation analysis has been demonstrated in earlier work by Osman et al. (2021). The first days of the major and minor seasons are considered April 1 and September 1, respectively, and their corresponding last days are July 31 and November 30. Here, we applied a threshold of 0.85 for a rainy day, and the mean seasonal rainfall was calculated for every 5 days (pentads). This threshold is considered appropriate and has been used in studies such as Recha et al. (2012), Odekunle (2006), and Osman et al. (2012). We adopted and modified the onset of rain definition by Sibanda et al. (2020) as a day after the 1st of April and the 1st of September when the rainfall accumulation in 1 or 2 days is 20 millimetres (mm) within 3 dekads (1 dekad = 10 days), but not followed by a period of more than 10 consecutive dry days in the next 3 dekads. We followed and modified Recha et al.'s (2012) earlier work by defining the cessation of rains as occurring after July 1 and November 1 for the major and minor seasons, respectively, when the soil water balance becomes zero and the evaporation value is < 5. We kept the soil water holding capacity at 60 mm. The difference between the onset and cessation indicates the length of the season (Atiah et al. 2021; Odekunle et al. 2005).

To analyse the influence of ENSO on rainfall, we estimated the mean monthly and total annual rainfall amounts from the observed daily data for each location in the zone. The classified ENSO ONI index (i.e., El Niño, La Niña, and Neutral) phases were used to determine the influence of ENSO on annual and seasonal rainfall in the zone. Here, we employed the one-way analysis of variance (ANOVA) to test for differences, variability, and relationships between the different ENSO phases and total annual rainfall in the zone. We again used the Pearson correlation analysis to test the hypothesis that the correlation coefficient between the CDI, SI_i, RAI and the different ENSO phases is statistically significant from zero. Consequently, we tested the null hypothesis, which posits the absence of a linear relationship between the CDI, SI_i, RAI and the different ENSO phases, in contrast to the alternative hypothesis, which proposes a linear link among the variables. We also plotted the seasonal onset and cessation dates against the different ENSO phases to depict the dynamics in rainfall start and end dates for major and minor seasons in the zone.

2.4 Spatial interpolation

To analyse the spatial patterns in the major and minor season rainfall amounts, rainy days, CV, the total annual rainfall explained by the different ENSO phases in the zone, and the $\overline{SI_i}$, we used the inverse distance weighting (IDW) interpolation method built into the ArcGIS software. The IDW interpolation technique is based on the idea that things that are close together have similar properties to those that are farther apart (Ibrahim and Usman, 2021; Larbi et al., 2021). The IDW technique has been used in studies such as those of Ibrahim and Usman (2021), Kwawuvi et al. (2022), and Larbi et al. (2021).

3 Results and Discussion

3.1 Annual and seasonal rainfall trend analysis

Figures 2a–f show the standardized rainfall anomaly index (SRAI) for the zone's annual, major, and minor season rainfall. The positive and negative values represent wet and dry years and seasons. As highlighted by Yamba et al. (2023), the SRAI is essential for the determination of dry and wet years, which is crucial for understanding the length of the growing season. Figs. 2a–f reveal more wet years in both the annual and major season rainfall across the zone, and the opposite is true for the minor season rainfall. In Accra, the highest positive (anomaly: 2.5) annual rainfall occurred in 2021 and the highest negative (–2.4) ensued in 1998 (Fig. 2a). For the major season, the highest positive (1.8) appeared in 2009 and negative (–2.5) in 1987. The corresponding minor season had the highest positive (3.1) and negative (–1.6) in 2021 and 1983, respectively. In Ada Foah (Fig. 2b), the year 2010 recorded the highest positive (1.9), while the highest negative (–2.2) ensued in 1998. The years 1985 and 1997 both recorded the highest positive (1.7) major season rainfall and the highest negative (–2.3) in 1982 (Fig. 2b). The highest positive (2.5) and negative (–1.8) minor season rainfall also occurred in 2008 and 2018, respectively (Fig. 2b). In Apam, the year 2021 had the highest positive (2.4) annual rainfall, while 1998 had the highest negative (–2.5) (Fig. 2c). The highest positive (1.8) major season rainfall occurred in 2009 and the negative (–2.3) in 1998. The minor season recorded the highest positive (2.5) rainfall in 2021 and the negative (–1.4) in 1996 (Fig. 2c). In Cape Coast, the year 1984 saw the highest positive (3.3) annual rainfall and 2013 with the highest negative (–2.3) (Fig. 2d). The year 1984 again saw the highest positive (3.1) major season rainfall and the highest negative (–1.7) occurring in 1998 (Fig. 2d). For the minor season, the highest positive (2.6) occurred in 2021 and the negative (–1.4) in 2009 (Fig. 2d). In Prampram, the highest positive (2.0) annual rainfall ensued in 2019 and the negative (–2.3) in 1992 (Fig. 2e). For the major season, the highest positive (1.7) occurred in 2009 and the negative (–2.0) in 1987, while the highest positive (2.2) minor season rainfall appeared in 2010 and negative (–1.7) in 1983 (Fig. 2e). In Denu, the highest positive (2.0) annual rainfall occurred in 2019 and the negative (–2.1) in 2002 (Fig. 2f). The

highest positive (3.0) for the major season also appeared in 2019 and the negative (–1.8) in 2003, while the highest positive (2.4) for the minor season ensued in 2010 and the negative (–1.9) in 1996 (Fig. 2f).

The results presented above have shed light on the frequency of both wet and dry periods throughout the zone. According to the results, more wet incidences occur annually across the zone. However, there exist variations in these incidences for the major and minor seasons of rainfall. It emerged that the major season is associated with more wet incidences and the minor season with more dry incidences. The finding agrees with the earlier study by Ankrah et al. (2023b) that reported increased incidences of drought and wetness events in coastal Ghana. The wet and dry incidences could pose substantial challenges to agricultural activities in the zone considering their strong influence on the length of the growing season, as stressed by Yamba et al. (2023). Several research studies, such as those of Gobin and Van de Vyver (2021), Mbiriri et al. (2019), Ojara et al. (2022), and Yadeta et al. (2020), have highlighted the substantial effects of wet and dry incidences on agriculture and crop yields. For instance, the findings of Gobin and Van de Vyver (2021) showed that the 2016 wet incidences in Belgium resulted in 39%, 45%, and 53% yield losses for cereals, maize, and potato, while the 2018 dry incidences caused 74% and 42% in maize and potato yield reductions, respectively.

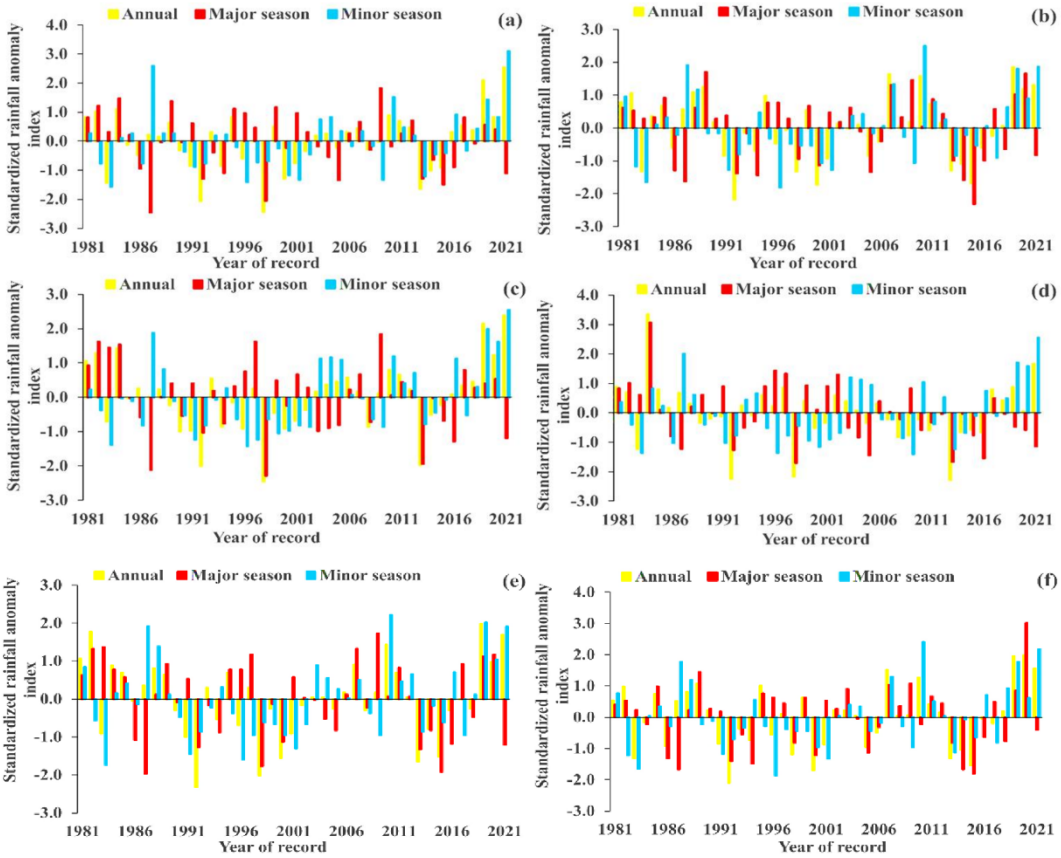


Fig. 2 Standardized rainfall anomaly index for annual, major and minor seasons rainfall at **(a)** Accra, **(b)** Ada Foah, **(c)** Apam, **(d)** Cape Coast, **(e)** Prampram, and **(f)** Denu

Figures 3a–f illustrate the cumulative departure index (CDI) for the zone's annual, major, and minor season rainfall, Table 2 presents the correlation analysis for the CDI and the different ENSO phases. The upward and downward patterns of the CDI represent above-average and below-average rainfall, respectively. A CDI threshold of zero (black dashed line) was established for the study. A threshold greater than zero signifies above-average rainfall, while a value less than zero indicates below-average rainfall, and a value around zero reflects near-average rainfall.

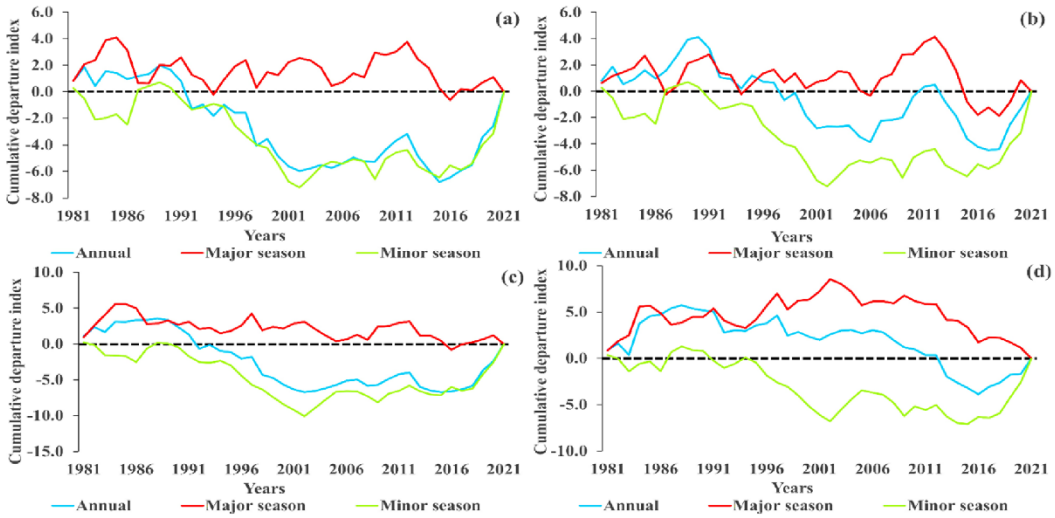
The major season in Accra (Fig. 3a) saw above-average rainfall for the majority of the years analysed, while the minor season and annual saw below-average rainfall trends. The major season rainfall at Ada Foah (Fig. 3b) followed a pattern similar

to that of Accra (Fig. 3a); however, Accra experienced few below-average major season rainfalls (in the years 1994 and 2016) as compared to Ada Foah, which had many years with below-average rainfalls (1987, 1994, and 2015–2019). During the period 1981–1997, Ada Foah experienced above and near average annual rainfall, and afterwards had below average rainfall until 2021, except for 2012, where near average rainfall ensued. The minor season in Ada Foah (Fig. 3b) experienced above-average rainfall only in 1981 and 1987–1990, with the remaining years being below average. At Apam (Fig. 3c), the major season rainfall experienced above-average rainfall for the majority of the years except for 2016, while the annual rainfall was above-average only from 1980–1991. The majority of the years showed below-average rainfall for the minor season, except for 1981 and 1989 (Fig. 3c).

At Cape Coast (Fig. 3d), above-average rainfall occurred throughout the period under analysis for the major season rainfall. While the annual followed a similar pattern to the major season, it experienced below-average rainfall from 2013–2021. The minor season rainfall was above and near average in the 1980s until 1994 and below average afterwards. Except for 2005 and 2015–2018, major season rainfall at Prampram (Fig. 3e) has been above-average for the majority of the years. Above-average annual rainfall appeared from the 1980s until 1997, followed by above-average rainfall in the minor season occurring only in 1981 and 1987–1991. At Denu (Fig. 3f), the major season rainfall had above-average rainfall from 1981–1986, 1989–1991, 2009–2013, and 2020–2021, while the annual rainfall experienced above-average rainfall from the 1980s until 1991 and had below-average rainfall afterwards. The minor season also experienced below-average rainfall for the majority of the years, except for 1981 and 1988–1990. A decreasing trend was observed in both annual and seasonal rainfall across the zone.

Table 2 shows that no correlation occurred between the CDI of the annual, major, and minor seasons rainfall and the El Niño phase across the locations. However, a medium positive correlation prevailed between the CDI of the minor season rainfall and the La Niña phase in the locations of Ada Foah and Apam, while a strong positive correlation for the same variables ensued in the locations of Prampram and Denu. A very strong positive correlation is also observed between the CDI of the minor season rainfall and the Neutral ENSO phase in the locations of Ada Foah and Denu. This indicates that the La Niña and the Neutral ENSO phases have a medium-to-very strong positive influence on the minor season rainfall in some locations of the study region.

From the above, it can be said that more above-average rainfall occurred across the zone in the major season than the minor and annual over the period of analysis. Generally, the minor season revealed near and above-average rainfall in the 1980s and the early 1990s, while the 2000s showed below-average rainfall across the zone. The annual rainfall also revealed a pattern similar to the minor season, except for Cape Coast (Fig. 3d), which experienced above-average annual rainfall for the majority of the years. Also, a totally different major season rainfall pattern is observed in Denu (Fig. 3f) when compared with the other locations in the zone, clearly revealing the existence of local variations in the zone. This finding is consistent with the earlier studies conducted elsewhere, such as those of Ayanlade et al. (2017), Hein et al. (2019), Nathan et al. (2020), Recha et al. (2012), and Tilahun (2006), who employed the cumulative departure index to analyse annual rainfall, seasonal rainfall, or both. Tilahun (2006), for example, reported variations in above and below average annual rainfall in Ethiopia's semi-arid regions. Similarly, Recha et al. (2012) and Ayanlade et al. (2017) discovered variations in above and below average seasonal and annual rainfall in Kenya's Tharaka district and southwestern Nigeria. Hein et al. (2019) further pointed out the fluctuations in the early and late growing seasons in the ShweBo and KyautSe in the dry zone of Myanmar.



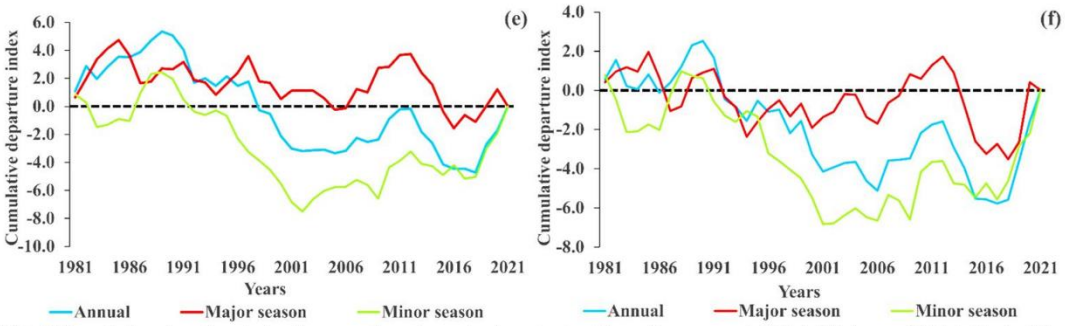


Fig. 3 Cumulative departure index for annual, major and minor seasons from the mean rainfall at **(a)** Accra, **(b)** Ada Foah, **(c)** Apam, **(d)** Cape Coast, **(e)** Prampram, and **(f)** Denu. Note: The black dashed line represents the established threshold

Table 2. Correlation coefficient between the cumulative departure index and the different ENSO phases

Locations	El Niño			La Niña			Neutral		
	Correlation (*p*-value)	Correlation (*p*-value)	Correlation (*p*-value)	Correlation (*p*-value)	Correlation (*p*-value)	Correlation (*p*-value)	Correlation (*p*-value)	Correlation (*p*-value)	Correlation (*p*-value)
	Annual	Major	Minor	Annual	Major	Minor	Annual	Major	Minor
Accra	–0.09 (0.71)	–1.13 (0.62)	–1.38 (0.58)	0.35 (0.12)	0.07 (0.78)	0.38 (0.11)	0.76 (0.24)	–0.93 (0.06)	0.86 (0.14)
Ada Foah	–0.02 (0.93)	–0.09 (0.72)	0.02 (0.95)	0.40 (0.09)	0.25 (0.30)	0.48 (0.04*)	0.53 (0.47)	–0.81 (0.19)	0.95 (0.04*)
Apam	–1.25 (0.62)	–0.20 (0.43)	–0.11 (0.68)	0.31 (0.20)	–0.05 (0.85)	0.47 (0.04*)	0.63 (0.37)	–0.12 (0.88)	0.71 (0.29)
Cape Coast	0.30 (0.22)	0.21 (0.41)	0.07 (0.79)	0.01 (0.97)	–0.32 (0.19)	0.38 (0.11)	0.59 (0.41)	–0.62 (0.38)	0.92 (0.80)
Prampram	–0.02 (0.94)	–0.07 (0.80)	–0.04 (0.88)	0.33 (0.17)	0.23 (0.34)	0.51 (0.03*)	0.43 (0.57)	–0.81 (0.19)	0.73 (0.27)
Denu	–0.03 (0.92)	–0.12 (0.63)	–0.01 (0.96)	0.38 (0.11)	0.39 (0.10)	0.52 (0.02*)	0.87 (0.13)	–0.07 (0.94)	0.99 (0.00*)

* Correlation is significant at the 0.05 level.

Figure 4 displays the time series of the SI_i rainfall, while Fig. 5 illustrates the spatial distribution of $\overline{SI_i}$ rainfall across the study locations. Table 3 shows the correlation analysis for the SI_i and the different ENSO phases. Fig. 4 demonstrates that, between 1981 and 2021, no extreme rainfall regime (i.e., almost all rain in 1-2 months) occurred across the study locations. In Accra, the values ranged from a low of 0.39 (equitable but with a definite wetter season) in 2021 to a high of 1.03 (most rains in 3 months or less) in 1983. In Ada Foah, the values varied from a low of 0.41 in 2021, indicating a rather seasonal period with a short dry season, to a high of 0.90 in 1983, indicating a markedly seasonal period with a long dry season. The seasonality regimes in Apam (low: 0.44; high: 0.97) and Cape Coast (low: 0.48; high: 0.93) are similar to those in Ada Foah, occurring in 1981 and 2021, respectively. In Prampram, a low and high value of 0.45 and 0.91 occurred in 1990 and 1983, respectively, with the same seasonality regimes as those of Apam and Cape Coast. The values (low: 0.41; high: 0.93) in Denu also follow the same seasonality regime as the previously indicated locations, but they occurred in 2021 and 1992, respectively. According to the $\overline{SI_i}$ (Fig. 5) that all the study locations have values between 0.66 and 0.72, indicating that rainfall distribution across the zone is seasonal.

The previous study by Yamba et al. (2023), which revisited and reclassified the agro-climatic zones of Ghana and discovered a seasonal rainfall regime in the coastal zone of Ghana, aligns with the above findings. Yamba et al. (2023) associated the seasonal contrasts in rainfall in the climate zones with the north and south oscillation of the Inter-Tropical Convergence Zone (ITCZ) in Ghana. As highlighted by Amekudzi et al. (2015) and Yamba et al. (2023), the ITCZ modulates the West African monsoon winds, which cause major and minor seasons in Ghana. Yamba et al. (2023) further attributed the seasonal rainfall in Ghana's coastal zone to the low moisture content resulting from the area's relatively flat nature and the monsoon winds blowing parallel to the coastal land. Elsewhere, studies such as those of Da Silva Araújo et al. (2023) and Stosic et al. (2024) have analysed the rainfall regimes of Pernambuco State, Brazil, and Serbia, respectively. The findings of

Stosic et al. (2024), for instance, revealed the higher influence of the North Atlantic oscillation and the East Atlantic pattern on rainfall seasonality in Serbia.

According to Table 3, a strong negative correlation prevailed between the SI_i and the El Niño phase in the locations of Accra and Apam, with the other locations having no correlation. A similar strong negative correlation occurred between the SI_i and the La Niña phase in the previously mentioned locations, and a medium correlation ensued in Prampram. No correlation is observed between the SI_i and the Neutral phase across the locations. The influence of large-scale teleconnection patterns on rainfall seasonality has been evaluated by several studies, including those by Stosic et al. (2024) and Tošić et al. (2014). The findings of Stosic et al. (2024), for instance, showed a negative correlation between the Western Mediterranean Oscillation and SI_i in Serbia, while that of Tošić et al. (2014) found a negative correlation between the East Atlantic pattern and precipitation in northern Serbia.

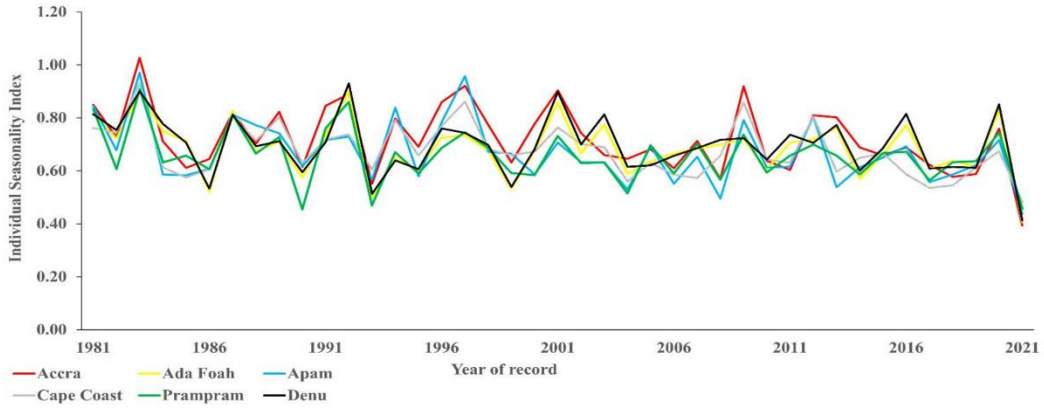


Fig. 4 Rainfall seasonality index for the study locations from 1981 to 2021

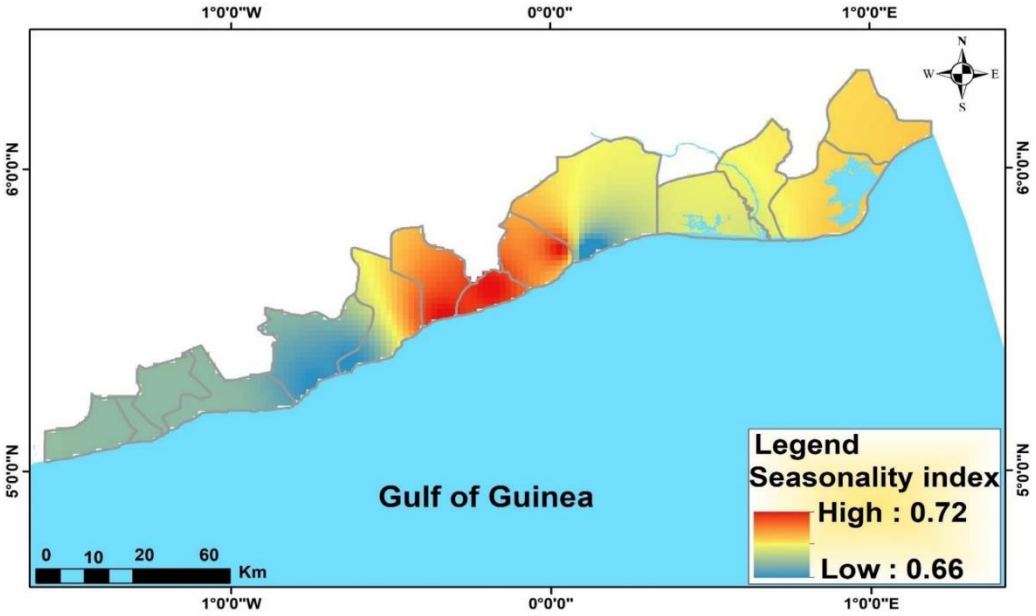


Fig. 5 Spatial distribution of mean rainfall seasonality index values interpolated across the CSAZ

Table 3. Correlation coefficient between the individual seasonality index for the study locations and the different ENSO phases

Locations	El Niño		La Niña		Neutral	
	Correlation	*p*-value	Correlation	*p*-value	Correlation	*p*-value
Accra	– 0.52	0.02*	–0.57	0.01*	–0.13	0.87
Ada Foah	–0.29	0.25	–0.41	0.09	–0.04	0.10
Apam	–0.56	0.02*	–0.53	0.02*	–0.06	0.95
Cape Coast	–0.41	0.09	–0.32	0.19	–0.19	0.81
Prampram	–0.35	0.16	–0.48	0.04*	–0.05	0.95
Denu	–0.29	0.24	–0.41	0.08	–0.02	0.10

* Correlation is significant at the 0.05 level

Figures 6a–f show the RAI for the annual, major, and minor seasons of rainfall at various locations in the zone, while Table 4 presents the correlation analysis for the RAI for the major and minor of seasons rainfall and the different ENSO phases. The positive and negative values represent wet and dry years, respectively (Muhire et al. 2015). Figures 6a–f show that the annual and major seasons have more wet years than dry years, while the minor season has the opposite pattern. In Accra (Fig. 6a), the highest positive (anomaly: 6.6) and negative (–5.5) for the annual rainfall occurred in 2021 and 1981, respectively. The major season for the same location experienced the highest positive (anomaly: 4.7) and negative (–5.3) anomalies in 2009 and 1987, respectively, while the minor season experienced the highest positive (anomaly: 7.2) and negative (–4.2) anomalies in 2021 and 1983, respectively (Fig. 6a). In Ada Foah, the annual rainfall anomaly peaked at positive (4.4) and negative (–4.9) in 2019 and 1992, respectively (Fig. 6b). For the major season, the highest positive values (4.6) appeared in 1989 and negative values (–4.9) in 2015, while the minor season has (5.4) and (-4.6) values in 2010 and 1996, respectively (Fig. 6b). In Apam (Fig. 6c), the highest positive (5.9) and negative (–5.8) annual anomalies ensued in 2021 and 1998, respectively. The major season in Apam (Fig. 6c) recorded the highest positive (4.6) and negative (–5.2) values in 2009 and 1998, respectively, while the minor season recorded (5.2) and (–4.0) values in 1996 and 2021, respectively. In Cape Coast (Fig. 6d), the highest positive (9.0) and negative (–5.7) annual rainfall anomalies occurred in 1984 and 2013, respectively. The highest positive (7.3) and negative (–4.1) occurred in 1984 and 1998, respectively, for the major season, and (5.6) and (–3.7) appeared in 2021 and 2009, in that order, for the minor season (Fig. 6d). In Prampram, the highest positive (4.9) and negative (–5.2) annual rainfall anomaly occurred in 2019 and 1992, respectively (Fig. 6e). The major season had the highest positive (4.3) in 2009 and negative (–4.3) in 1987, while the minor season revealed a value (4.9) in 2010 and (-4.5) in 1983 (Fig. 6e). In Denu (Fig. 6f), the annual rainfall anomaly reached the highest positive (4.6) and negative (–4.9). The major season recorded a high positive (7.9) in 2020 and a negative (–4.1) in 2015, whereas the minor season had the value (5.3) in 2010 and (–4.7) in 1996 (Fig. 6f). Across the zone, the year 2020 recorded the highest positive anomaly for the major season rainfall, which occurred in Denu, and that of the minor season in 2021 in Accra. Accra recorded the highest negative anomaly for the major season in 1987 and for the minor season in 1996.

According to Table 4, a perfect positive correlation occurred between the RAI of the annual rainfall and the El Niño in the locations of Ada Foah, Apam, Cape Coast, and Denu and a very strong positive correlation in Prampram. Between the major season rainfall and the El Niño phase, a strong positive correlation ensued in Ada Foah and Denu and a medium positive in Prampram. Accra and Denu showed a strong positive correlation during the minor season, while Ada Foah, Apam, and Prampram showed a medium positive correlation. A perfect positive correlation prevailed between the RAI for the annual rainfall and the La Niña phase in all locations, except Accra, where no correlation occurred. For the major season and the La Niña, a strong positive correlation ensued in the locations of Ada Foah, Cape Coast, and Denu, and a medium positive in Prampram. The RAI of the minor season and the La Niña phase showed a very strong positive correlation in all locations, except for Cape Coast, where a medium positive correlation ensued. The RAI of the annual rainfall and the Neutral phase also showed a perfect positive correlation in all locations, with the exception of Accra, where no correlation was observed. For the major season and the Neutral phase, a very strong positive correlation appeared in the locations of Ada Foah, Apam, and Prampram, with no correlation in the remaining locations. A very strong positive correlation prevailed between the RAI of the minor season rainfall and the Neutral phase in the locations of Accra, Apam, and Denu.

This finding is consistent with the previous study by Ankrah et al. (2023b), which found more drought incidences in the 1980s and 1990s in these areas. Nicholson et al. (2018) also reiterated the numerous drought periods in the 1970s and 1980s in the West African region and which is consistent with this study. From Figures 3a–f, it can be seen that while both the major and minor season rainfall show inter-annual variability, the variations in the minor season rainfall are greater than in the major season. This finding is in line with the earlier study of Recha et al. (2012) who reported greater inter-annual rainfall variability in the Tharaka district in Kenya. The finding is also consistent with the earlier study of Longobardi and Boulariah (2022) who found greater inter-annual rainfall variability in the Campania region in southern Italy. The finding supports the general scientific consensus of the of the seasonal, inter-annual, and decadal variability of the West African climate (Giannini et al. 2003; Omotosho et al. 2000; Rodríguez-Fonseca et al. 2011; Sylla et al. 2018). The variability in the West African rainfall is

greatly influenced by the West African Monsoon flow (Nicholson 2008; Omotosho 2008; Omotosho et al. 2000; Sylla et al. 2018). In the study region, the seasonal movement of the ITCZ plays an important role in the major and minor season rainfall distribution (Addi et al. 2021). The variability in rainfall in the West African region is also linked to ENSO (Ibrahim and Usman 2021; Nicholson and Grist 2001; Owusu et al. 2019a). The West African monsoon flow impacts rainfall variability in the study area, but other localized features such as vegetation types, topographic and landscape dynamics, coastal characteristics, and upwelling cold waters off the coast of Accra also have a major effect (Acheampong 1982; Amekudzi et al. 2015; Braimah et al. 2022; Owusu 2018). Acheampong (1982) reiterated that the rainfall distribution pattern in coastal Ghana differs significantly from the distribution along the whole West African coast. Owusu (2018) highlighted the increasing deforestation in Accra caused by urbanisation and its effect on rainfall variability. Braimah et al. (2022) stated that the rapid depletion of vegetation in southern Ghana, especially coastal Ghana, leads to reduced rainfall levels and increased variability in the area. Generally, the major and minor seasons rainfall in the zone varied greatly around the mean and conform to the earlier study in the Tharaka district in Kenya by Recha et al. (2012). The greater inter-annual rainfall variations could affect several livelihood opportunities, especially those of the smallholder farmers in the zone. The results from the correlation analysis established that the different ENSO phases have relationships with rainfall variability (RAI) across the study locations. Several research studies, such as those of Xu et al. (2004), Barros et al. (2008), Karori et al. (2013), Zhang et al. (2013), Lee and Julien (2016), and Son et al. (2016), have evaluated the influence of ENSO on rainfall variability and their relationship. The findings of Zhang et al. (2013), for instance, found a significant relationship with El Niño and seasonal precipitation in the east River basin in south China. The findings of Xu et al. (2004) also established a statistically significant relationship between precipitation anomalies and ENSO in the southern zone and part of the middle zone of Southeast Asia and the Pacific region.

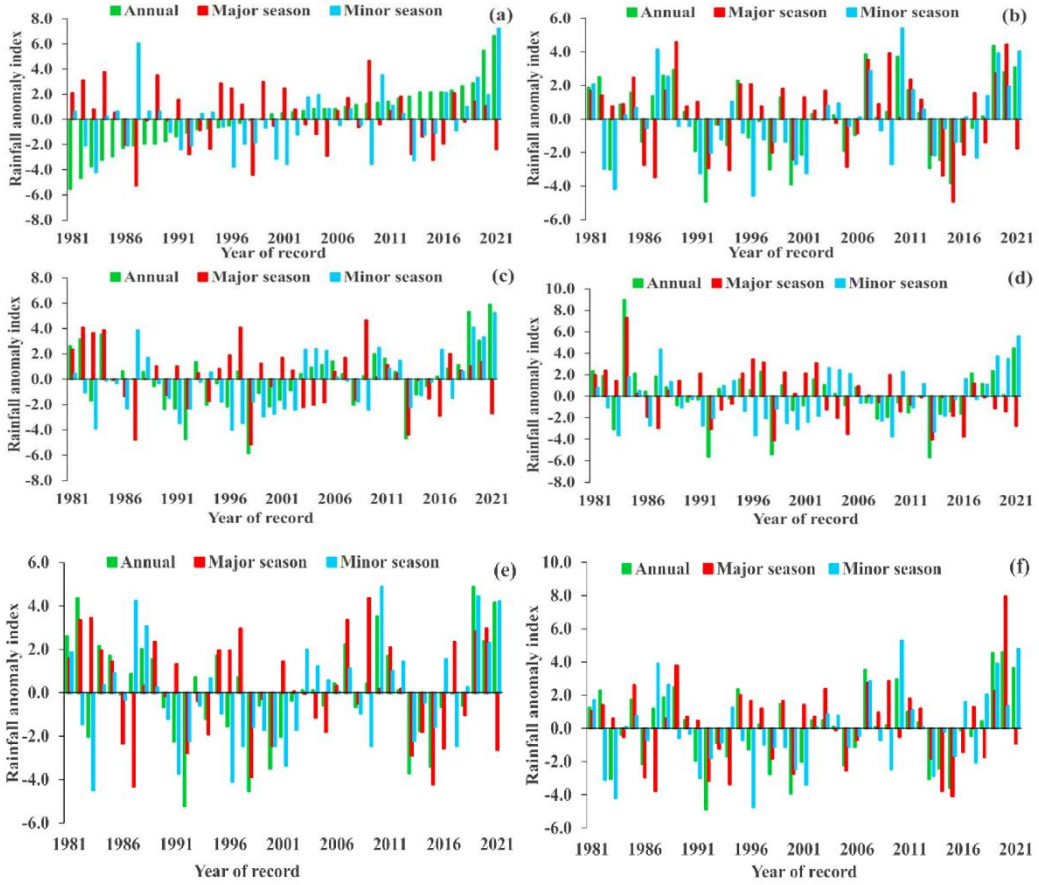


Fig. 6 Rainfall anomaly index for major and minor season rainfall at **(a)** Accra, **(b)** Ada Foah, **(c)** Apam, **(d)** Cape Coast, **(e)** Prampram, and **(f)** Denu

Table 4. Correlation analysis for the rainfall anomaly index and the different ENSO phases

Locations	El Niño			La Niña			Neutral		
	Correlation (*p*-value)	Correlation (*p*-value)	Correlation (*p*-value)	Correlation (*p*-value)	Correlation (*p*-value)	Correlation (*p*-value)	Correlation (*p*-value)	Correlation (*p*-value)	Correlation (*p*-value)
	Annual	Major	Minor	Annual	Major	Minor	Annual	Major	Minor
Accra	0.22 (0.38)	0.33 (0.19)	0.52 (0.03*)	0.38 (0.11)	0.30 (0.21)	0.78 (0.00*)	–.088 (0.12)	–0.89 (0.11)	0.99 (0.01*)
Ada Foah	1.00 (0.00**)	0.59 (0.00*)	0.50 (0.03**)	1.00 (0.00**)	0.54 (0.02*)	0.77 (0.00**)	1.00 (0.00**)	0.99 (0.01**)	0.91 (0.09)
Apam	1.00 (0.00*)	0.23 (0.37)	0.50 (0.03*)	1.00 (0.00**)	0.36 (0.13)	0.79 (0.00**)	1.00 (0.00**)	0.98 (0.03*)	0.99 (0.01**)
Cape Coast	1.00 (0.00**)	0.31 (0.22)	0.41 (0.09)	1.00 (0.00**)	0.64 (0.00**)	0.46 (0.04*)	1.00 (0.00**)	0.92 (0.08)	0.97 (0.03*)
Prampram	0.99 (0.00**)	0.49 (0.04*)	0.49 (0.04*)	1.00 (0.00**)	0.46 (0.04*)	0.79 (0.00**)	1.00 (0.00**)	0.97 (0.03*)	0.92 (0.08)
Denu	1.00 (0.00**)	0.61 (0.01**)	0.53 (0.02*)	1.00 (0.00**)	0.59 (0.01**)	0.72 (0.00**)	1.00 (0.00**)	0.95 (0.05)	0.96 (0.04*)

* Correlation is significant at the 0.05 level, ** Correlation is significant at the 0.01 level.

3.2 Variations in seasonal rainfall amount, number of rainy days, and the onset, cessation, and length of the rainy season

The coastal savannah agroecological zone is the driest and receives the lowest rainfall among the agroecological zones in Ghana (Asare-Nuamah and Botchway 2019). Table 5 shows the variations in major and minor season rainfall and rainy days, while Figures 7a–h depict the spatial variations in major and minor season rainfall amounts, annual averages of rainy days, and CV across the zone. According to Table 5, Cape Coast received the most rainfall (780.9 mm) with the most annual average rainy days (114) during the major season, while Ada Foah received the least (533.8 mm) with annual average rainy days (109). On the contrary, Apam had the highest rainfall (326.9 mm) with annual average rainy days (81) during the minor season and the lowest (265.5 mm) with annual average rainy days (69) in Denu. In Table 5, the CV for the minor season rainfall was higher than for the major season. For example, Denu had the highest CV (22%) for the major season and Accra had the lowest (17%), while Accra and Prampram had the highest (46%) and lowest (36%), respectively, for the minor season.

In Figure 7a, it is observed that major season rainfall amounts increase from the Central region to the Volta region. However, the corresponding CV appeared to be greater in the Volta region, followed by the Central region, and lowest in the Greater Accra region, especially in Accra (Fig. 7b). The number of annual average rainy days also increased from the Central region to the Volta region (Fig. 7c), and the opposite was true for the related CV (Fig. 7d). The rainfall amount for the minor season (Fig. 7e) follows the same pattern as that of the major season (Fig. 7a), while the corresponding CV appeared to be greater in the Greater Accra region, especially in Accra. This is followed by the Central region, and the lowest is in the Volta region (Fig. 7f). The minor season annual average rainy days increased from the Central region to the Volta region (Fig. 7g), while the corresponding CV is greater in some parts of the Greater Accra and Central regions, followed by the Volta regions, and lowest in the other areas of the Central region (Fig. 7h). See Figure 1 to understand the regional divisions across the study locations.

Across the study locations, the CV for major season rainfall ranged from 17% to 22%, while the CV for minor season rainfall ranged from 36% to 46%. The CV for the rainy days also varied between 95% and 114% for the major season, whereas that of the minor season ranged from 102% to 106%. The CV identified in this study is consistent with the earlier studies elsewhere, such as Ibrahim and Usman (2021); Kabanda and Nenwiini (2016); Obarein and Amanambu (2019); Recha et al. (2012); and Sibanda et al. (2020). For instance, Recha et al. (2012) and Sibanda and Ahmed (2020) reported a CV in rainfall of greater than 30% in the Tharaka district in Kenya and the Mzingwane catchment of south-western Zimbabwe, respectively. Similarly, Kabanda and Nenwiini (2016) pointed out a CV of rainfall of up to 39% in the Vhembe district of South Africa. When the CV in rainfall amount is compared to the CV in rainy days, it is found that the CV in rainy days is greater than the CV in rainfall amount for both the major and minor seasons. This finding agrees with those of Recha et al. (2012), who reported a higher CV on rainy days than rainfall amounts in Tharaka district, Kenya.

The results from the CV analysis reveal a clear local seasonal rainfall variability across the zone. The variability of major season rainfall was greatest in Denu in the Volta region of the zone and lowest in Accra in the Greater Accra area. For the minor season, Accra and Prampram in the Greater Accra part of the zone had the highest and lowest variability, respectively. The local rainfall variability in the zone could be attributed to so many factors, such as local convective activities caused by vegetation types and topographic dynamics (Braimah et al. 2022; Owusu 2018). Research studies such as those of Almazroui et al. (2018), Li et al. (2022), Shetty et al. (2022), and Tawde and Singh (2014) have analysed the influence of topography on rainfall variability in their respective areas of application. For instance, in Chongqing, China, Li et al. (2022) reported that

areas in the more complex mountainous regions have higher rainfall amounts, intensities, and frequencies compared to those in the lower areas. In their experimental study, Almazroui et al. (2018) found that both topography and surface heating are essential in determining the spatial patterns and intensity of extreme rainfall over Jeddah, Saudi Arabia.

Table 5. Rainfall amount and coefficient of variation for major and minor seasons in the study locations from 1981 to 2021

Location	Major season				Minor season			
	Rain (mm)	CV	Rainy days (Annual averages)	CV	Rain (mm)	CV	Rainy days (Annual averages)	CV
Accra	599.7	0.17	111	0.97	285.8	0.46	77	1.06
Ada Foah	533.8	0.20	109	1.04	269.1	0.37	70	1.03
Apam	646.7	0.19	111	0.97	326.9	0.43	81	1.06
Cape Coast	780.9	0.19	114	0.95	318.3	0.39	84	1.00
Prampram	545.7	0.19	113	0.97	303.9	0.36	78	1.02
Denu	537.9	0.22	108	1.14	265.5	0.38	69	1.03

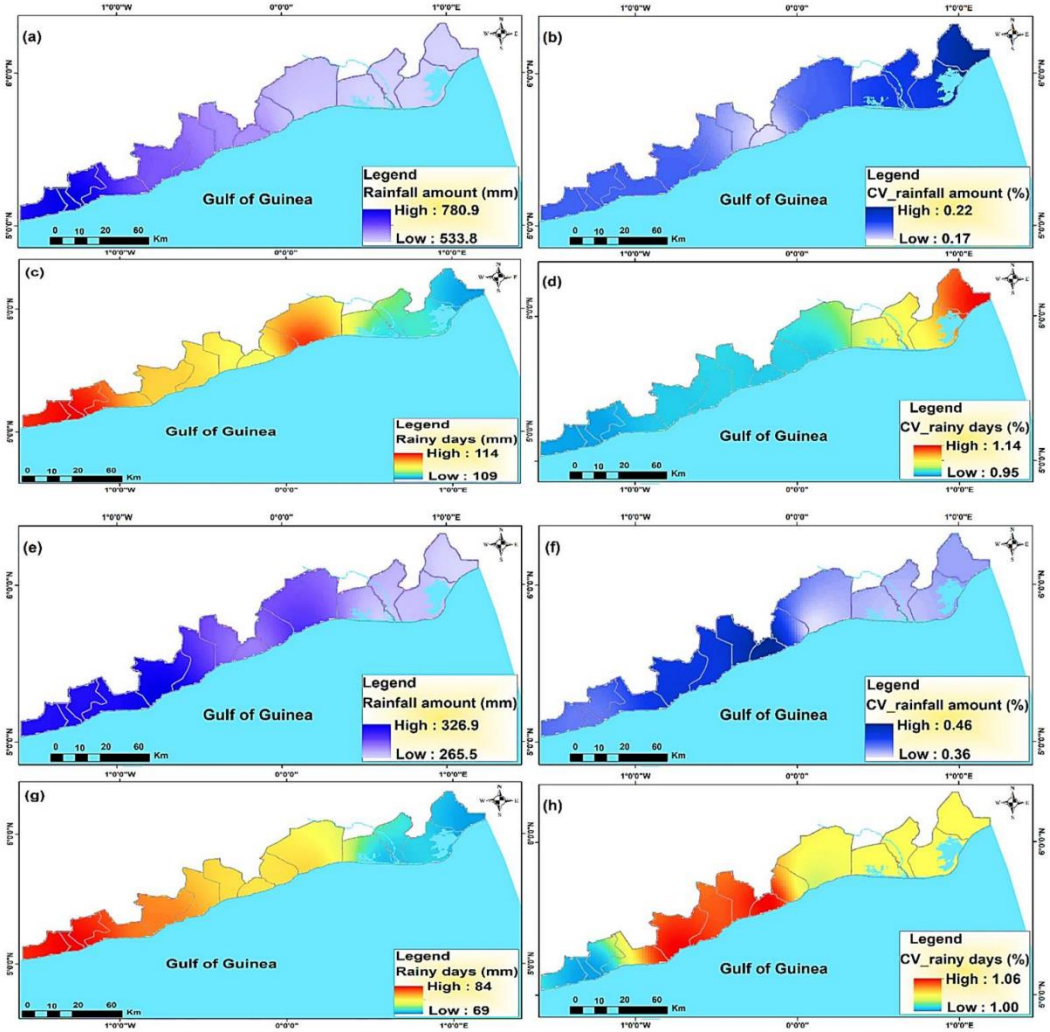


Fig. 7 Spatial variations in major season rainfall amount and CV **(a, b)**, rainy days and CV **(c, d)**, and minor season rainfall amount and CV **(e, f)**, and rainy days and CV **(g, h)**

On average, the major season's rainfall onset dates (1st week of April) appeared to be similar across the study locations and correspond to day 92 of the year, while the cessation dates vary between the 4th week of July (day 183 of the year) in Ada Foah and Denu and the last 4.4286 week (4 weeks and 3 days) of July (day 212 of the year) in Accra (Table 6). The onset dates (1st week of September) for the minor season also appeared to be similar across the study location and correspond to day 245 of the year in most locations and day 249 of the year in Apam, while the cessation date, which occurred on the 1st week of November (day 306 of the year), is similar across the locations (Table 6). The length of the major season rainfall ranged from 91 days in Ada Foah and Denu to 120 days in Accra, whereas that of the minor season varied from 57 days in Apam to 61 days in the other locations (Table 6). A summary of the onset and cessation dates, as well as the length of the rainy season, for each individual year for both the major and minor seasons is displayed in (Online Resource 1).

Table 6. Average onset, cessation dates and the length of season across the study locations from 1981 to 2021

	Onset date		Cessation date		Length of season (in days)	
Locations	Major season	Minor season	Major season	Minor season	Major season	Minor season
Accra	1st week of April	1st week of September	The last 4.4286 week of July	1st week of November	120	61
Ada Foah	1st week of April	1st week of September	1st week of July	1st week of November	91	61
Apam	1st week of April	1st week of September	4th week of July	1st week of November	117	57
Cape Coast	1st week of April	1st week of September	4th week of July	1st week of November	113	61
Prampram	1st week of April	1st week of September	4th week of July	1st week of November	113	61
Denu	1st week of April	1st week of September	1st week of July	1st week of November	91	61

Figures 8a–d show the major and minor season rainfall onset and cessation days across the study locations. In Figure 8a, the major season rainfall onset varies between the 1st week of April (day 92 of the year) for most years in the study locations and the 3rd week of May (day 142) in Prampram in the year 2000. The minor season onset (Fig. 8b) ranges from the 1st week of September (day 245) in most of the locations to the last 4.4286 week (4 weeks and 3 days) of October (day 302) in Cape Coast in 2009. The cessation day for the major season (Fig. 8c), on the other hand, varies between the 1st week of July (day 183 of the year) in Denu for most years and the last 4.4286 week (4 weeks and 3 days) of July (day 212), also occurring in most years in the other locations, whereas that of the minor season ranges from day the 1st week of November (day 306) in Apam for most years to the last 4.4857 week (4 weeks and 2 days) of November (day 334) in Cape Coast in 2020–2021 (Fig. 8d). Figures 8a–d also show cases of early onset and late cessation across the study locations. Fig. 8a shows that the onset of the major season rainfall across the study locations could occur as early as the 1st week of April and as late as the 3rd week of May, while that of the minor season rainfall across the zone could occur as early as the 1st week of September and as late as the last week of October (Fig. 8b). The cessation of the major season rainfall could be as early as the 1st week of July or as late as the last week of July (Fig. 8c), while that of the minor season could also happen as early as the 1st week of November and as late as the last week of November (Fig. 8d).

The results presented reveal variations in the major and minor seasons' rainfall onset and cessation across the zone. Notwithstanding, the variations in the minor season rainfall were greater than in the major season. This finding is consistent with the earlier studies conducted in other parts of Ghana, such as Amekudzi et al. (2015) and Atiah et al. (2021). For example, Amekudzi et al. (2015) reported higher variations in rainfall onset and cessation across the different agroecological zones of Ghana. The finding again agrees with other studies conducted elsewhere, such as those of Recha et al. (2012), Asakereh et al. (2023) and Omay et al. (2023). Between the onset and cessation of rains, it was established that the cessation of rains in the zone is associated with greater variability, especially for the minor season compared to the onset. As the results have established, on average, the major season rainfall onset is in the 1st week of April across the zone, whereas that of the minor season is in the 1st week of September (see Table 6). The study locations exhibit early onset and late cessation of both major and minor season rainfall, which aligns with previous studies by Amekudzi et al.(2015) in the savannah zone of Ghana and Atiah et al. (2021) in northern Ghana. As highlighted by Atiah et al. (2021), the onset and cessation of rainfall have a considerable impacts on the farmers' planting calendar, especially in rain-fed agriculture systems. Farmers must thus sow seed prior to or at the start of the growing season. The sowing of seed later than the fifth and sixth pentads of April and September could hinder crop growth or lower yields.

Factors such as vegetation types, topographic dynamics, and increased convective activities (Acheampong 1982; Amekudzi et al. 2015; Boateng 1966; Braimah et al. 2022; Houze 2006; Owusu 2018), as well as meteorological conditions (Acheampong 1982; Boateng 1966; Hall and Peyrillé 2006), could explain the rainfall variations observed in the study locations. Denu in the Volta region had a higher CV than Accra in the Greater Accra region, possibly due to the area's increased vegetation growth compared to Accra, the capital city. Acheampong (1982) found that the removal of forest vegetation east of

Cape Three Points influenced the variability of rainfall in the Accra Plains. Acheampong (1982) further reiterated that if the original dense forest vegetation still persisted, more forest transpiration would enhance humidity in the atmosphere, perhaps leading to higher rainfall. Owusu (2018) also corroborated this argument by stating that urbanisation has led to the removal of a substantial amount of forested vegetation in Accra, causing increasing variability in rainfall patterns for the area. Elsewhere, Singh et al. (2024) observed that rainfall generally increases from the forest border towards the centre and decreases from the forest boundary in Central India's terrestrial vegetation. The researchers highlighted the crucial significance of forests in the distribution of monsoonal rainfall in Central India (Singh et al. 2024). Topographic dynamics substantially affect the orographic rainfall of an area (Amekudzi et al. 2015). Increased convective events in the Togo-Akwapim ranges result in more rainfall on the windward side, while the leeward side, which includes the study locations, receives less and more variable rainfall (Amekudzi et al. 2015). Yadav et al. (2024) found comparable evidence of an orographic impact on rainfall in the Indian Himalayan area.

Acheampong (1982) emphasised that the coastal area of Ghana east of Cape Three Points, including the study region, has low and variable rainfall due to factors such as the physical characteristics of the land and the sea, unfavourable local circulation in the atmosphere, which is connected to the overall atmospheric patterns, and the combination of these elements. Two distinct wind systems, the northeasterly winds and the southwesterly winds, also influence the variability in rainfall in the study locations (Baidu et al. 2017). The northeasterly winds (Harmattan) originate from the Sahara desert and are dry and dusty, resulting in no rainfall. In contrast, the southwesterly winds originate from the Gulf of Guinea, carrying moist air to the coastal and inland regions of the country, leading to rainfall (Baidu et al. 2017). The north and south oscillating patterns of the two wind systems result in bimodal rainfall seasons: a major one from April to July and a minor one from September to November. These patterns influence the timing of the rainy season's onset, cessation, and length in the study locations (Amekudzi et al. 2015). Boateng (1966) contended that cold waters at Cape Three Points on Ghana's western coast affect southwesterly moist winds from the Gulf of Guinea, causing them to blow parallel to the east coast (the study area) and leading to minimal rainfall. Sea surface temperature, dynamic stability, land surface feedback, and transient tropical waves are additional elements that influence rainfall variability in the area (Hall and Peyrillé 2006).

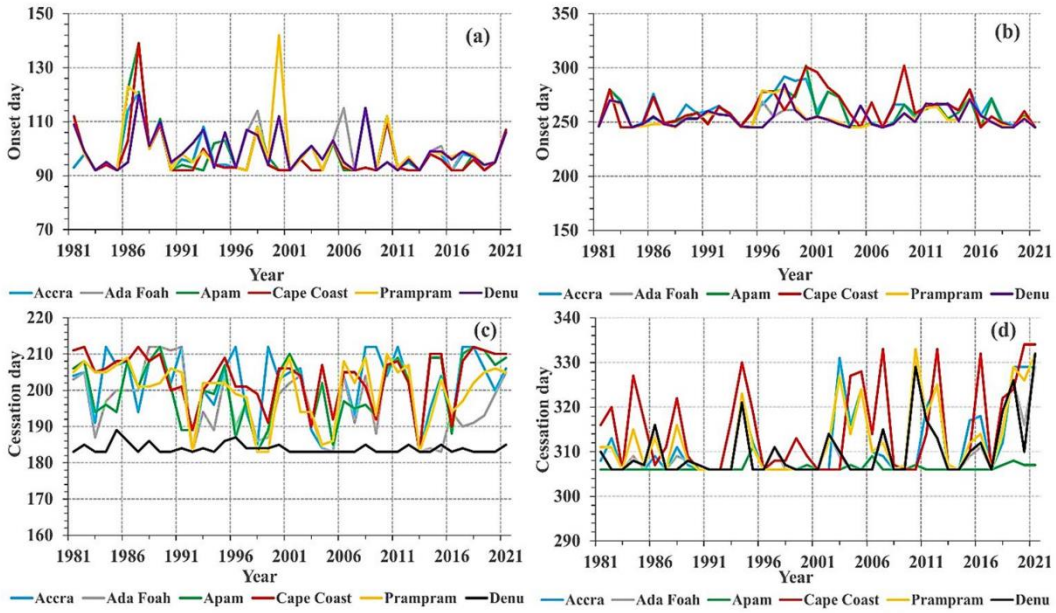


Fig. 8 Onset and cessation days for major and minor season rainfall across the location. Onset for major **(a)** and minor **(b)** seasons, and cessation for major **(c)** and minor **(d)** seasons

3.3 The influence of ENSO on annual rainfall

Online Resource 2 displays the influence of the different ENSO phases on annual rainfall in the study locations, and Figures 9 and 10a–f show the graphical representation of the variability in total annual and average annual rainfall. Notably, we utilised the one-way analysis of variance (ANOVA) to test the assumptions of whether or not there exist differences in the means of

the total annual rainfall received in the zone based on the different ENSO phases. Here, we tested the assumption of homogeneity of the variances using Levene's test, which was acceptable across the study locations. For instance, in Online Resource 2, the test was tenable in Accra ($F(2, 38) = 1.024$, $p = 0.369$), Ada Foah ($F(2, 38) = 0.144$, $p = 0.866$), Apam ($F(2, 38) = 1.042$, $p = 0.363$), Cape Coast ($F(2, 38) = 0.418$, $p = 0.661$), Prampram ($F(2, 38) = 0.139$, $p = 0.870$), and Denu ($F(2, 38) = 0.181$, $p = 0.835$). According to the correlation matrix in Online Resource 2, it is observed that the La Niña phase of the ENSO reveals a positive but weak correlation with total annual rainfall across the study locations. The El Niño and Neutral phases, on the other hand, also show a negative and weak correlation with total annual rainfall in all the locations except for Apam, where a positive and weak correlation occurred under the El Niño phase.

From Online Resource 2, the ANOVA test revealed no statistically significant difference in total annual rainfall for the different ENSO phases across the study locations. Thus, there is enough evidence to accept the null hypothesis ($p > 0.05$ in all locations) that there is no statistically significant difference in total annual rainfall across the locations based on the different ENSO phases. This finding disagrees with previous research studies conducted in other parts of Ghana, such as Boadi and Owusu (2017), Owusu et al. (2019a), and Waylen and Owusu (2014), who found significant associations between ENSO events and total annual rainfall. For instance, Owusu et al. (2019) reported a statistically significant difference in total annual rainfall between the El Niño and La Niña phases in the Ho municipality of Ghana. Following this, we used the Tukey Honestly Significant Difference (HSD) Post-Hoc test to analyse the pairwise differences among the group means in total annual rainfall for the different ENSO phases. At a 95% confidence interval, the Tukey HSD test revealed no statistically significant difference in total annual rainfall among the different ENSO phases across the study locations (Online Resource 2).

The R^2, which shows the percentage of variation in total annual rainfall as explained by the different ENSO phases, varies across the study locations (Online Resource 2). For example, in Accra, 5% ($R^2 = 0.051$) of the variability in total annual rainfall is caused by the different ENSO phases. It is 12% ($R^2 = 0.122$) at Ada Foah, 1% ($R^2 = 0.014$) at Apam, 3% ($R^2 = 0.032$) at Cape Coast and Prampram ($R^2 = 0.030$), and 11% ($R^2 = 0.114$) at Denu. The variability in total annual rainfall attributable to the different ENSO phases is generally small in the study locations, with the exception of Ada Foah and Denu, which revealed variability greater than 10%. Although small, the above findings support the earlier studies conducted in other parts of Ghana. For example, Owusu et al. (2019a) pointed out that between 1955 and 2015, ENSO events accounted for 15% of the variability in total annual rainfall in the Ho municipality of Ghana. Likewise, between 1991 and 2010, Boadi and Owusu (2017) reported that ENSO events and lake water level accounted for 72.4% of the inter-annual variability in hydropower generation from the Akosombo Dam in Ghana. The finding also supports the wider literature consensus on the influence of ENSO on rainfall variability across different regions of the world (Ayantobo et al. 2022; Brönnimann et al. 2007; Cai et al. 2011; Emmanuel 2022; Grimm and Tedeschi 2009; Kijazi and Reason 2005; Muhire et al. 2015; Sazib et al. 2020; Whan and Zwiers 2017). As the ENSO influence on total annual rainfall variability in the zone is found to be small, it is possible that the ITCZ seasonal oscillation and other localised conditions serve as the dominant factors for rainfall variability in the zone. As indicated elsewhere in this study, rainfall in West Africa is greatly influenced by the seasonal movement of the ITCZ and the African Easterly Jet (Le Barbé et al. 2002; Nicholson 2008; Omotosho 2008; Sylla et al. 2018). The north (southerly warm moist winds from the Gulf of Guinea) and south (dry and cold north-east trade winds from the Sahara desert) movements of the ITCZ cause more and no rainfall, respectively, in Ghana. Other localised effects could include the orographic effects of mountains and those from lakes and large waterbodies.

Across the zone, it is observed that the La Niña phase is associated with greater mean annual rainfall than the El Niño and the Neutral phases (Fig. 9). As shown in Figure 10a, the mean annual rainfall in Accra increased from a long-term average of 1027.8 mm to 1067.7 mm in the La Niña years during the study period. At Ada Foah (Fig. 10b), the value increased from 985.2 mm to 1048.6 mm, while at Apam it increased from 1186.2 mm to 1198.6 mm (Fig. 10c). At Cape Coast, it increased from 1340.0 mm to 1372.7 mm (Fig. 10d) and from 1051.4 mm to 1083.1 mm for Prampram (Fig. 10e). At Denu, the value rose from a long-term average of 978.4 mm to 1042.4 mm (Fig. 10f). This finding is consistent with the previous studies such as Owusu et al. (2019a) and Owusu et al. (2008) who found lower mean annual rainfall amounts during the El Niño phase in the Ho municipality and the Volta River basin, respectively in Ghana. The finding also agrees with the earlier global study of Mason and Goddard (2001), who reported that globally, El Niño is associated with below-normal precipitation while La Niña has above-normal precipitation. The present study disagrees with the earlier study of Emmanuel (2022), who reported higher precipitation amounts in the West African region during the El Niño phase and lower during the La Niña phase. This contrasting result could be due to the altitudinal-dependent dry season period of the La Niña phase, as used in the study of Emmanuel (2022).

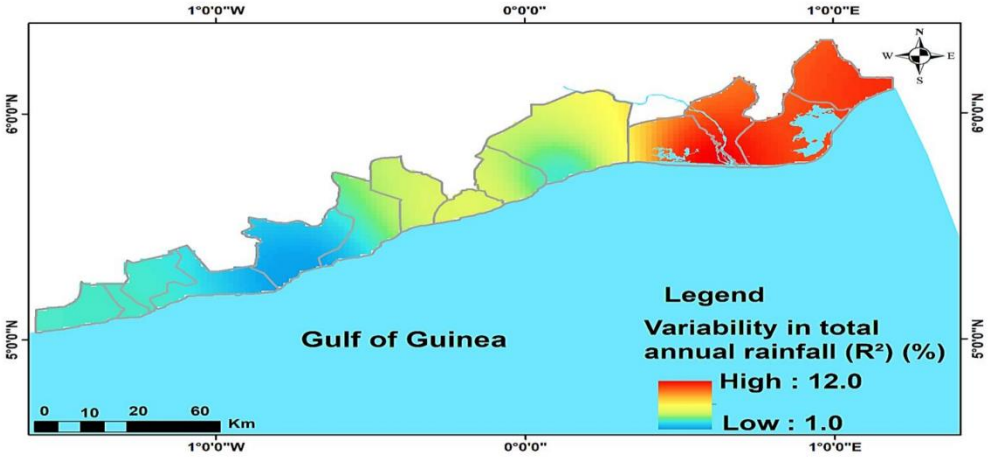


Fig. 9 Percentage of variability in total annual rainfall explained by the different ENSO phases across the coastal savannah agroecological zone of Ghana

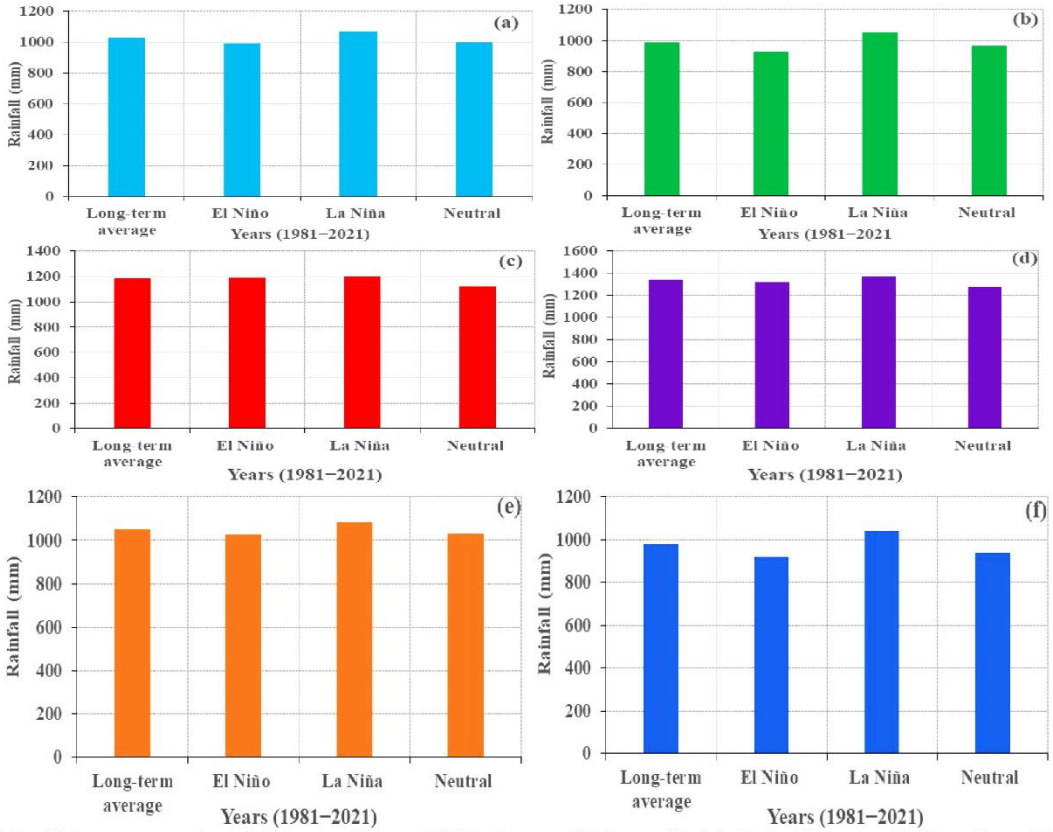
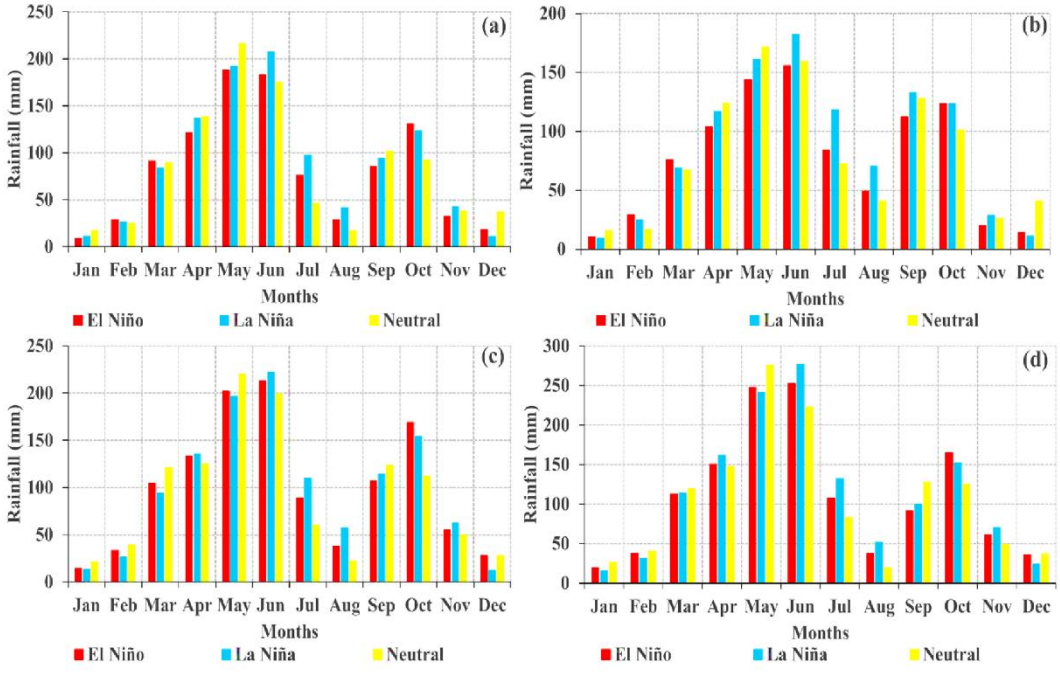


Fig. 10 Average annual rainfall for the different ENSO phases at **(a)** Accra, **(b)** Ada Foah, **(c)** Apam, **(d)** Cape Coast, **(e)** Prampram, and **(f)** Denu from 1981–2021

3.4 The influence of ENSO on seasonal rainfall

Figures 11a–f show the mean rainfall patterns for the major (April–July) and minor (September–November) seasons for the different ENSO phases across the study locations for the study period. From Figure 11a–f, it can be seen that the major season rainfall peaks in June for the La Niña phase for most of the locations, except for Accra (Fig. 11a) and Cape Coast (Fig. 11d), where rainfall reached highest in May for the Neutral phase. On the other hand, the peak for the minor season rainfall varies between September and October for the majority of the locations for the El Niño and La Niña phases. Across the zone, the highest (277.0 mm) major season rainfall was recorded at Cape Coast (Fig. 11d) for the La Niña phase, while that of the minor season (169.0 mm) ensued in Apam (Fig. 11c) for the El Niño phase. Online Resource 3 displays graphical representations of the variations in major and minor season rainfall onset and cessation dates during the different ENSO phases across locations.

The findings show that the La Niña phase has a greater influence on the major season rainfall pattern across the zone than the El Niño phase does for the minor season. This finding is consistent with the previous studies, such as those of Owusu et al. (2019) and Owusu et al. (2008) in the Ho municipality and the Volta River basin of Ghana, respectively. Across the zone, higher rainfall amounts are recorded in the major season in the months of April-May-June-July and less in the minor season. The different rainfall amounts for the major and minor seasons for the La Niña and El Niño phases thus confirm the earlier global findings of Mason and Goddard (2001). Notwithstanding, the differential rainfall amounts associated with the El Niño and La Niña phases in the zone support the earlier assertion by Nicholson et al. (2000) that El Niño and La Niña signals in the West African region are quite complex. While the La Niña and the El Niño phases showed dominance in the major and minor seasons, respectively, the influence of the Neutral phase on both the major and minor season rainfall is worth mentioning. For instance, the rainfall in the month of May across the zone is influenced by the neutral phase (Fig. 11a–f). The higher rainfall amounts associated with the neutral phase could be attributed to the influence of the ITCZ. The seasonal patterns and variability in rainfall across the zone could impact crop cultivation by the smallholder farmers. Owusu et al. (2019b) reported on the devastating effects of the 2015 El Nino event on smallholder farmer activities and livelihoods in Ghana's transition zone. As stressed by Feng et al. (2013), seasonal rainfall patterns and variability have greater influence on agricultural production than that of total annual rainfall and its variability in the tropics.



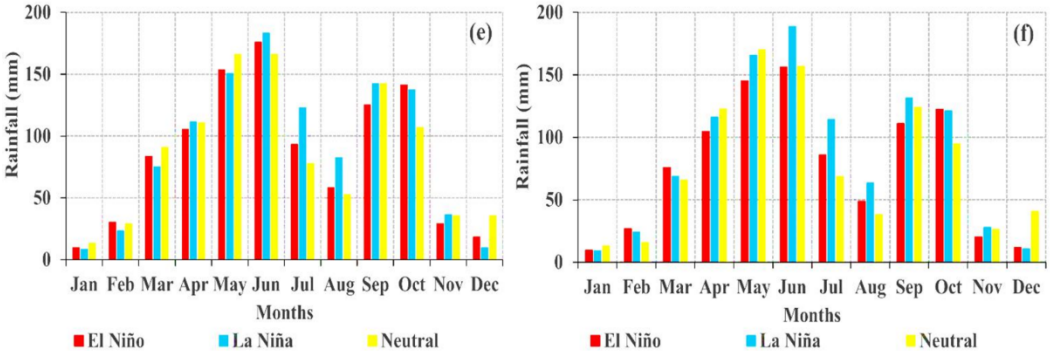


Fig. 11 Mean seasonal rainfall for the different ENSO phases at **(a)** Accra, **(b)** Ada Foah, **(c)** Apam, **(d)** Cape Coast, **(e)** Prampram, and **(f)** Denu

4 Conclusion

This study analysed rainfall variability and the influence of ENSO on Ghana's CSAZ. Here, we employed the SRAI, CDI, SI_i, and RAI to analyse the annual and seasonal variability and long-term trends, whereas the onset and cessation dates and length of the rainy season of the seasonal rainfall were estimated by using the R-Instat (version 0.70) software. The ANOVA test was used to test for the differences, variability, and relationships between the different ENSO phases and total annual rainfall in the zone through the ONI index. The Pearson correlation analysis was also used to test the hypothesis that the correlation coefficient between the CDI, SI_i, RAI and the different ENSO phases. The main findings of this study are that rainfall exhibits greater inter-annual variability in Ghana's CSAZ, which adds to the literature consensus of a highly variable nature of rainfall in the West African region and in other regions of the world. Also, the variability in total annual rainfall attributable to the different ENSO phases is generally small across Ghana's CSAZ. Despite its small size, the finding adds to the growing body of literature on the influence of ENSO on rainfall variability across the globe.

The results established that both the SRAI and the RAI have more wet years in both the annual and major season rainfall across the zone, and the opposite is true for the minor season rainfall. The correlation analysis established that the different ENSO phases have positive correlations with rainfall variability (RAI) across the zone. The results established that there was more above-average major season rainfall across the zone than minor and annual over the period of analysis. Largely, it was revealed that the minor season had near and above-average rainfall in the 1980s and the early 1990s, while the 2000s showed below-average rainfall across the zone. The annual rainfall also revealed a pattern similar to the minor season, except for the location of Cape Coast, which experienced above-average annual rainfall for the majority of the years. It was again revealed that the years 2020 and 2021 recorded the highest positive major and minor season rainfall anomalies, respectively, across the zone, while the highest negative major and minor season rainfall anomalies occurred in 1987 and 1996, in that order. The correlation analysis between the CDI and the different ENSO phases showed that the La Niña and the Neutral ENSO phases have a medium-to-very strong positive influence on the minor season rainfall in some locations of the study region. The results again showed that the $\overline{SI_i}$ for all the study locations have values between 0.66 and 0.72, indicating that rainfall distribution across the zone is seasonal.

The results further established that across the zone, the major season rainfall amount and rainy days increased from the Central region to the Volta region. The corresponding CV pattern, however, shows the opposite. While the minor season rainfall amount and rainy days followed the same pattern as the major season, the related CV revealed greater variability in the Greater Accra and the Central regions and the lowest in the Volta region. That is, while the major season rainfall showed greater variability in the Volta region than the other two, it showed the opposite in the minor season. The results also revealed greater variations in the major and minor seasons' rainfall onset and cessation across the zone. Nevertheless, the variations in the minor season rainfall were greater than in the major season. It was, moreover, revealed that, on average, the major season's rainfall onset dates appeared to be similar across the zone and occurred in the 1st week of April (day 92 of the year), while the cessation varied between the 4th week of July (day 183) and the last 4.4286 week (4 weeks and 3 days) of July (day 212). The corresponding onset for the minor season also appeared to be similar across the study location and occurred in the 1st week of September (with range from days 245 to 249, and a similar cessation, which occurred in the 1st week of November (day 306) across the zone. The length of the minor and major rainy seasons ranged from 57 to 61 days and 91 to 120 days, respectively.

Concerning the influence of ENSO on rainfall variability in the zone, the ANOVA test revealed no statistically significant differences in total annual rainfall for the different ENSO phases across the zone. The percentage of variation in total annual rainfall as explained by the different ENSO phases varied between a low of 1% in some parts of the Central region and a high

of 12% in some parts of the Greater Accra region. Furthermore, it was established that the La Niña phase is associated with greater mean annual rainfall than the El Niño and Neutral phases and has a greater influence on the major season rainfall pattern across the zone. Nonetheless, the neutral phase of the ENSO's influence cannot be overlooked, as it appeared to correspond to the seasonal oscillation of the ITCZ in the zone.

The greater variability in rainfall amount, rainy days, onset, and cessation across the zone, especially during the minor season, could affect several livelihood opportunities, especially those of the smallholder farmers in the zone. The variability can therefore be addressed by enhancing irrigation systems in the zone. For instance, the Densu River can serve as a source of irrigation for some areas in the Greater Accra region; the Ayensu River can serve the same purpose for some parts of the Central region; and the Volta River for those in the Volta region. A timely climate forecast and information from the Ghana meteorological agency could also be helpful, especially for the smallholder farmers in the zone.

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Code availability Not applicable.

Author Contributions JA conceptualised the idea of the study, prepared materials, analysed data, and wrote the first draft of the manuscript. All authors commented on the previous version of the manuscript. Supervision was done by AM and HM. All authors read and approved the final manuscript.

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CHAPTER 5: Analysis of the impacts of climate change and climate variability on marine and freshwater fish harvest and their effects on the socio-economic livelihoods of the communities in the coastal savannah agroecological zone of Ghana

5.1. Climate variability, coastal livelihoods, and the influence of ocean change on fish catch in the coastal Savannah zone of Ghana

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Climate Variability, Coastal Livelihoods, and the Influence of Ocean Change on Fish Catch in the Coastal Savannah Zone of Ghana

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Abstract: Coastal zones, despite their contribution to global economies, continue to suffer the negative impacts of climate variability, which limit the livelihoods of people, particularly small-scale fishermen. This study examined climate variability, coastal livelihoods, and the influence of ocean change on the total annual fish catch in Ghana's Coastal Savannah zone. The mixed-methods approach was used to analyze primary data (semi-structured questionnaires and interviews), secondary data (sea surface temperature (SST) and salinity (SSS), and fish catch), and statistical tests (chi-square, binary logistic regression, and multiple regression). Findings revealed a significant increase in climate variability awareness among fishermen, attributed to the influence of broadcast media. However, they lack sufficient information regarding the transformation of cities, the urbanization process, and its impact on the global climate. Increasing temperatures and sea level rise emerged as the most prevalent impacts of climate variability over the past two decades in the zone. Although the fishermen lack awareness regarding the changes in SSS and their effects on fish, the findings of the multiple regression analysis established that changes in SSS exert a more pronounced effect on the decreasing fishing catch in the zone compared to those in SST. Empirical fish catch records supported the fishermen's claim of a substantial decrease in total fish catch in the zone over the past 20 years. Aside from climate variability impacts, the involvement of many people and light fishing emerged as additional factors contributing to the decreasing fish catch in the zone. High premix fuel prices or shortages and "saiko" activities were the main obstacles that hindered the fishermen's activities. "Saiko" is an unlawful activity in which foreign industrial trawlers sell fish directly to Ghanaian canoes or small-scale fishermen at sea. The fishermen lack sufficient means of supporting their livelihoods, as there is a lack of viable alternative livelihood options. Additionally, the majority of the fishermen experience symptoms of fever and headaches. The binary logistic regression analysis showed that the fishermen's income insufficiency could be substantially reduced if they were to have their own houses, canoes, or fish all year. This situation highlights the need for heightened support from policymakers for improved sustainable livelihood prospects as well as health and well-being.

Keywords: climate variability; coastal livelihood; small-scale fisheries; coastal zone; sea surface temperature; sea surface salinity; oceanic change

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1. Introduction

The impacts of climate variability are evident in all areas, including the world's coastal zones [1]. Coastal zones provide numerous benefits such as food provision, fishing, employment, tourism, recreation and leisure, and habitat for aquatic species [2,3]. As a result, they are recognized among the regions of the world that favor population concentration [2,4].

Small and Nicholls [5] emphasized an estimate that 30% of the global population are at or near the coast. Coastal zones thus serve as an important region that contributes significantly to the sustainable development of global economies [6]. Nevertheless, Ahmed [7] asserts that the sustainability of the world's coastal zones remains uncertain due to the greater threats imposed by climate variability. The combined effects of climate variability and sea level rise, as evidenced by extreme changes in coastal high water levels, could pose threats to both the biophysical and socio-economic systems of the coastal zones [8,9]. The findings of Church et al. [10] and Nicholls et al. [11] have brought attention to the potential rise in mean sea level by one meter or more by the year 2100, as well as between 0.38 and 0.77 m within the same timeframe, as reported by the Intergovernmental Panel on Climate Change [12]. These projections indicate significant implications for coastal zones and their environments. Coastal zones, including their infrastructure, economies, and livelihoods, could be negatively impacted by climate variability and sea-level-rise-related hazards such as coastal erosion, inundation and flooding, shoreline change, intrusion of saline waters, and disruption of aquatic habitats and fisheries, among others [4,13]. Although climate variability and oceanographic changes have numerous effects on the coastal zone, their effects on fish and fisheries continue to be significant. Fisheries serve as an important source of protein [14,15], and account for 17.3% of the global total animal proteins [16].

Aside from their contribution to global food security, fisheries also provide livelihood opportunities to several million people, especially in small-scale fisheries in developing countries [17,18]. For instance, Stacy et al. [18] reported that 2.5 million households are involved in small-scale fisheries in Indonesia. In Africa, about 12.3 million (2.1%) of the people aged between 15 and 64 are engaged in fisheries, which account for more than USD 24 billion or 1.26% of the gross domestic product (GDP) of all African countries [19]. In West Africa, marine artisanal fisheries support the livelihoods of about 6.7 million people, with a catch value of USD 3.5 billion per year [20]. In Ghana, the fisheries sector provides livelihoods to about 2.6 million people, which account for 10% of the entire population and contribute to about three percent of the country's GDP [21]. The sector also contributes 53.9% of the country's total animal proteins [16]. Marine artisanal fisheries remain the main source of Ghana's fish production, livelihood activity, and account for 80% of the total annual fish catch [17,22].

In recent years, the effects of climate variability have had a negative impact on the fish and fisheries sectors [23–27]. The changing global climate affects the physical and biogeochemical characteristics of the ocean, such as temperature, pH, oxygen content, and wind patterns [28]. Sea surface temperature (SST), for example, is considered an important environmental factor for fish habitats [29]. In the northwestern Pacific Ocean, an SST front is reported to affect the distribution of Pacific saury (Cololabis saira) [29]. Between 1982 and 2006, SST in West Africa increased by 0.52 °C, 0.46 °C, and 0.24 °C [30]. The changes in SST thus affect the primary productivity, eco-physiology, and ecology of marine species, which result in shifts in species distribution, phenology, ecosystem functions, and trophic interactions [24,31]. The changes in fish distribution and primary production are projected to cause widespread restructuring of the global catch potential [24]. As a result, Cheung et al. [32] reported an increase and a decrease in catch potential at higher latitudes and in tropical regions, respectively. In West Africa, Lam et al. [33] reported a projected decrease in fish landings by 2050 for the regions along the Gulf of Guinea and a slight increase for those in the Canary Current large marine ecosystem. Barange et al. [34] also predicted an increase of 23.9% in fish catch potential for the Gulf of Guinea regions and a decrease of 14.6% for those along the Canary Current areas. Despite the discrepancies in their studies, all models have revealed the sensitivity of the West African fisheries to climate variability [24]. Apart from climate and oceanographic changes that affect global fish and fisheries, negative anthropogenic activities such as overfishing, unregulated fishing, transshipment, pollution, and habitat degradation are also found to have negative impacts on fish and fisheries [31,35,36]. Alder and Sumaila [37] and Atta-Mills et al. [38] informed us about the increasing pressure of foreign fleets on the West African marine ecosystems.

In Ghana, Atta-Mills et al. [38] attributed the decline in fish stocks to overfishing, a lack of good governance, and the use of destructive approaches.

In recent times, research studies on climate variability and the livelihoods of coastal artisanal fisheries have increased in many regions (e.g., [39–48]), including Ghana (e.g., [23,49–56]. Despite the increase, research on climate variability and the livelihoods of Ghana's coastal artisanal fisheries is limited to a few sections of the country's coast. Most studies focus on fishing communities in the western region (Rain Forest zone), at the expense of other equally important fishing communities in the Central, Greater Accra, and Volta regions (Coastal Savannah zone). Ankrah [23] and Koomson et al. [50] made efforts for the Coastal Savannah zone; however, their studies were limited to only coastal Winneba. Their studies, while significant, failed to recognize local variations and the diverse characteristics of individual fishing communities throughout the Coastal Savannah zone. Again, Ayilu et al. [51] focused on the livelihoods of four coastal fishing communities in the Greater Accra region in addition to those studied in the Western region; the researchers did not attempt to recognize the perceived impacts of climate variability on the fishers' livelihoods. In addition, while Okyere et al. [52] covered the entire Ghanaian coast, their work was limited to the capacity deficit of fishers, which focused more on leadership and governance at the expense of the fisher's livelihood opportunities. Their work also had limited coverage, as they selected only five fishing communities in the entire coastal stretch of Ghana. The limited locational study may have an impact on policy intervention and direction because policymakers should understand the diverse characteristics of individual communities to make an appropriate decision. Currently, there exists a dearth of information regarding the impact of climate variability on the livelihood of coastal artisanal fisheries in the Volta region, as far as our knowledge extends. These studies failed to demonstrate a comprehensive understanding of the effects of local oceanic component changes on fishery yields.

To fill these gaps, the aim of the present study is to analyze climate variability impacts on the livelihoods of fishers in the Coastal Savannah zone of Ghana. The study specifically examined fishers' perceived causes and knowledge about climate-related and oceanic impacts, sources of livelihood aside from fishing, and the influence of SST and sea surface salinity (SSS) on the total annual fish catch. This research not only adds to the existing body of knowledge on climate variability and its impact on fisheries but also has the potential to inform the development of effective policies aimed at protecting the livelihoods of coastal fishers in the zone. It also highlights the opportunity and added value of improved fishermen's climatological literacy and the importance of informal knowledge in science.

2. Materials and Methods

2.1. Study Area

Three coastal portions of the Central, Greater Accra, and Volta regions constitute the Coastal Savannah zone of Ghana. The zone thus forms 20 out of the 26 coastal metropolitan, municipal, and district assemblies (MMDAs) and occupies three out of the four coastal regions of the country [22]. The zone, which contains the three regions, forms about 70% of the country's 560 km^2 coastline and a total of 203 landing beaches, which account for 69% of the country's total fish landing sites [22]. The remaining 89 (31%) belong to the Western region, as indicated in the earlier work of Owusu and Adjei [55]. Among the three regions, the Central region has a total of 97 (33%) fish landing sites, followed by the Greater Accra region with 59 (20%), and the lowest with 47 (16%) in the Volta region. Although agricultural, commerce, and tourism activities exist, fishing is considered an important occupation and a major source of livelihood for about 2.6 million people, which accounts for 10% of the entire population [17,21,22].

The main fish species caught across the zone include Atlantic little tuna (*Euthynnus alleratus*), Scad Mackerel (*Caranz rhoncus*), Chub Mackerel (*Scomber colias*), Frigate mackerel (*Auxis thazard*), Sardinella (*Sardinella* spp.), Threadfin (*Galeoides decadactylus*), Burrito (*Brachydeuterus auritus*), Anchovy (*Engraulis encrasicolus*), Cassava fish (*Pseudotolithus sene-*

galensis), and Bumper (*Chloroscombrus chyrsurus*), among others [22]. The zone has a total of 114 (61%) out of the 186 fishing communities and 73,916 (69%) out of the 107,518 fishermen across the country [22]. Among the three regions, the Central region has the most (44 (39%)) fishing communities, followed by the Greater Accra (42 (37%)), and the Volta (28 (24%)). On the number of fishermen, the majority (33,373 or 45%) are found in the Central region, followed by Greater Accra with 25,844 (35%), and the lowest (14,599 or 20%) in the Volta region [22]. The types of fishing gear used by the fishermen across the zone include purse seines, beach seines, lines, set nets, Ali nets, and drifting nets [22].

The elevation across the zone ranges from the lowest point of −3.8 m on the coast to the highest point of 641.2 m inland [57]. It has a maximum and minimum mean annual temperature of 27.9 °C and 26.6 °C, respectively [57,58]. Although the zone has a bimodal rainfall regime [59], it is considered the driest and receives the lowest rainfall across the country, with the average annual rainfall ranging from a low of 978.4 mm to a high of 1339.9 mm [57].

This study was conducted in 15 communities across the zone (Table 1). These communities were selected due to their significant contributions, number of fishermen, and greater reliance on fishing for livelihood [22]. Prior to the selection of the 15 communities, we read the information report sheet of the 2016 Ghana marine canoe frame survey, an official document by the fisheries and scientific survey division of the fisheries commission under Ghana's ministry of fisheries and aquaculture development [22]. Several other communities (see Figure 1) met the selection criteria and held equal significance for the study. Nevertheless, these communities were not reachable due to constraints on resources and the time needed to conduct the study.

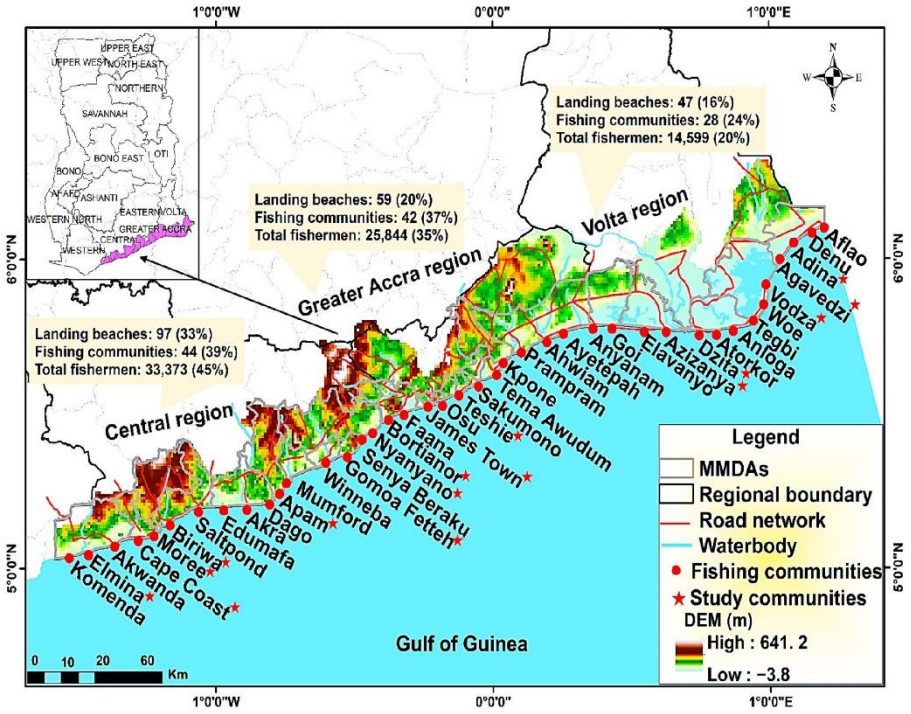


Figure 1. Map showing the study communities in the Central, Greater Accra, and Volta regions of Ghana. Note: the statistics relating to landing beaches, fishing communities, and the number of fishermen were sourced from Dovlo et al. [22].

Table 1. Characteristics of the selected fishing communities used in the study. Source: Dovlo et al. [22].

S/N	Community	MMDAs	Region	Number of Fishermen	Landing Beach(es)
1	Elmina	Komenda-Edina-Eguafo-Abrem District	Central	1512	Elimina Main
2	Cape Coast	Cape Coast Metropolitan Assembly	Central	556	Abrofo Mpoano and Duakor
3	Moree	Abura-Asebu-Kwamankese District	Central	997	Etuei
4	Biriwa	Mfantsiman Municipal Assembly	Central	836	Abaka Ekyir
5	Apam	Gomoa West District	Central	741	Apam Main
6	Gomoa Fetteh	Gomoa West District	Central	643	Mbanyin and Mbaa Mpoano
7	Nyanyano	Gomoa East District	Central	1920	Nyanyano
8	Bortianor	Ga South Municipal Assembly	G/Accra	1240	Bortianor
9	James Town	Ashidu Keteke Sub-Metropolitan Area	G/Accra	1515	Ga Mashie
10	Teshie	Ledzokuku-Krowor Municipal Assembly	G/Accra	1044	Sangonaa
11	Azizanya	Ada East District	G/Accra	800	Mataheko
12	Dzita	Keta Municipal Assembly	Volta	756	Agledome
13	Vodza	Keta Municipal Assembly	Volta	800	Vodza
14	Agavedzi	Ketu South Municipal Assembly	Volta	744	Agavedzi
15	Adina	Ketu South Municipal Assembly	Volta	1493	Adina

2.2. Methodology

This study employed both primary and secondary data sources. The primary data sources were obtained from semi-structured questionnaire administration and interviews. The secondary data used in this study included the monthly mean beach SST measured in °C and daily beach SSS in ‰ from the coastal stations of Winneba, Tema, and Keta located in the Coastal Savannah zone (period from 2000–2020). In addition, the study used marine artisanal fish catch data (in metric tons) in the zone for the same period. The above data were obtained from the Ghana Fisheries Commission's Scientific and Survey Division. The Ghana Fisheries Commission's Scientific and Survey Division is responsible for the evaluation of Ghana's marine ecosystem and fisheries, etc. Regarding the marine environment, the Scientific and Survey Division thus monitors and measures oceanographic variables, including the measurement of SST, SSS, and dissolved oxygen, among others. The oceanographic measurements are collected across several coastal stations along Ghana's coastal areas, including Keta, Tema, Winneba, and Takoradi, among others. On fisheries (fish stock and statistics), the Scientific and Survey Division performs numerous activities, including the estimation of annual fish production, while on fishing gear, it conducts studies on gears and improves on the existing ones (https://www.mofad.gov.gh/agencies/fisheries-commission/fisheries-commission-at-a-glance/, accessed on 30 May 2023).

This study falls under the case study research design [60,61] and uses the mixed-method (both qualitative and quantitative) approach [62] to analyze climate variability impacts on the livelihoods of fishers in the Coastal Savannah zone of Ghana. The case study design, as reiterated by Crowe et al. [60], is used to explore the in-depth nature of complex issues. Yin [61] further highlighted that the case study design is more suitable for obtaining information on highly explanatory questions. The research design followed in this study is one of several considered appropriate due to the complexities in the understanding and explanation of the concept of climate variability's related impacts on fisheries and livelihoods. The data collection process used in this study was guided by the climate-related risk [63] and sustainable livelihood [64] frameworks and was conducted between February and April 2023.

By employing a simple sample selection technique, a semi-structured questionnaire was administered to 350 fishermen in each of the 15 communities (see Table 1) used in this study, for a total of 5250 participants. Again, the purposive sampling technique was employed to interview 15 leaders of the fishing groups, with one leader from each of the 15 communities. A total of 5265 participants were thus sampled for the study. The study

followed Yamane's [65] formula for sample size to estimate the minimum sample size for the communities used in this study as follows:

$$n = \frac{N}{1 + N(e)^2} \quad (1)$$

where n denotes the sample size, N represents the population size, and e indicates the error term.

Using Equation (1) and assuming a 5% error and a 95% confidence interval, the minimum sample size required for the communities ranged from 232.64 in Cape Coast to 331.03 in Nyanyano, making the sample of 350 used in this study representative.

Leaders of the fishermen's groups as used here denote fishermen who are natives and have lived in their respective fishing communities for more than 40 years, have bought their own canoes, are actively involved in fishing, and have employed other fishermen. These people were considered key informants based on their level of involvement in the fishing activity and length of stay in the community, and they had a broader understanding of the climatic and livelihood conditions.

This study was directed at only fishermen and no other fisher groups (e.g., fish sellers and fish mongers) because of the components of ocean (sea) changes included in the semi-structured questionnaire. That is, the fishermen are those who go fishing on the sea and could share their perspectives regarding oceanic parameters such as SST and SSS, etc. The participants for the questionnaire administration were randomly selected based on a set of criteria: they lived in the community and had been fishing for at least 10–20 years; they had knowledge about climate variability impacts on coastal environments and fishermen; and they were aware of the major challenges that limited their fishing activity. The reasons behind the selection process were to focus on Indigenous fishermen, or those who have established a longstanding presence within their respective communities, as opposed to individuals who have only recently migrated for the purpose of engaging in fishing activities. For the interview, one must be a native, have lived for more than 40 years in the respective fishing community, operate their own canoe, employ other fishermen, and depend solely on fishing for their livelihoods. The number of years lived and being a native of the community distinguished the participants for the questionnaire administration from those for the interview.

The semi-structured questionnaire employed in this study consisted of four sections, including socio-demographic characteristics, perceived causes of climate variability, perceived climate-related impacts, and alternative livelihood engagement opportunities aside from fishing. Some key questions asked included, but were not limited to: Have you heard about climate variability? If yes, where did you hear it, and what is causing it? In your view, which of the following factors is causing climate variability? Which of the following impacts has been the most common in this area over the last two decades? In your opinion, does climate variability have any impact on fish populations? Do you think changes in SST affect fish and fish stocks? How do you perceive the total number of fish caught over the last two decades? The questionnaire consisted of both closed-ended and open-ended questions. Whereas the closed questions offered the participants options to select from a range of answers, the open-ended questions gave them a chance to express and share their experiences regarding climate variability and the related impacts on coastal environments and on their livelihoods. On average, a questionnaire takes about 20 to 30 min of a participant's time.

Six field assistants were taken through the questionnaire, the use of the KoboToolbox software version 2021.2.4 (https://www.kobotoolbox.org/), and some ethical issues in data collection. There was diversity in the selection of the field assistants based on the distinct languages (i.e., Fante, Ga-Dangme, and Ewe) spoken in the 15 selected communities. The questionnaire was administered to the respondents via mobile phones utilizing the KoboToolbox between February and April of 2023. The KoboToolbox software (https:

//www.kobotoolbox.org/) is a robust and insightful data collection tool that allows both online and offline data collection from one's mobile phone.

Data from the questionnaire administration were exported in Excel format and imported into the Statistical Package for the Social Sciences (SPSS) software (version 26.0) for analysis. Consequently, a suitable statistical analysis was executed. In this study, variables such as age, marital status, education, household size, all-year fishing (fishing trips), house ownership, and canoe ownership were considered independent variables. These variables were considered to independently influence, based on the literature, the income status (sufficiency or insufficiency) of fishermen [66–70], even though other factors such as fishing knowledge, fish gear used, fish prices, and fishing costs have an influence on a fishermen's income status [69,71,72]. Here, the chi-square test of independence was employed to evaluate the associations between independent variables and the livelihood opportunities of fishermen and others, with the Cramer's V statistic showing the strength of the associations. Again, the binary logistic regression test was used to evaluate the effects of the independent variables on the livelihood opportunities (i.e., income sufficiency) of the fishermen. The decision to employ binary logistic regression in this study was based on its wide utilization in the existing body of literature concerning climate variability and the livelihood opportunities of fishermen. Several studies, including Macusi et al. [72], Malakar et al. [73], and Muallil et al. [74], have utilized this approach. We selected the statistical procedures based on the categorical nature of the variables in this study, most of which were dichotomous. The purpose was to understand the potential of these variables in predicting the likelihood of a decrease in the insufficiency status of income among fishermen. The multiple linear regression test was also used to determine if changes in SST and SSS predicted the decreased total annual fish catch in the zone.

Questions raised during the interview included, but were not limited to, whether the number of fish caught by their group keeps increasing every year or is the opposite; the major challenges they and other groups face that affect their fishing activity; and the livelihood opportunities (i.e., their satisfaction with the income they make from fishing and whether it is enough to cater for their family's expenses; the ease of obtaining loans from banks; and whether they and their group engage in other income-earning activities aside from fishing). Before the start of the interview, the participant was presented with a consent form detailing their rights, including that the interview was voluntary, and they had the right to withdraw or request that their already-captured responses be withdrawn or deleted from the research. The participant was assured of anonymity and confidentiality by not revealing their personal traits, such as their name. The abbreviations FL1, FL2, FL3, FL4, FL5, FL6, FL7, FL8, FL9, FL10, FL11, FL12, FL13, FL14, and FL15 were used to represent the fishing group's leaders' names, which were then followed by their respective communities. For example, the abbreviations FL1: Elmina, FL2: Cape Coast, FL3: Moree, FL4: Biriwa, FL5: Apam, FL6: Gomoa Fetteh, FL7: Nyanyano, FL8: Bortianor, FL9: James Town, FL10: Teshie, FL11: Azizanya, FL12: Dzita, FL12: Vodza, FL14: Agavedzi, and FL15: Adina represent the fishing group's leaders in the communities of Elmina, Cape Coast, Moree, Biriwa, Apam, Gomoa Fetteh, Nyanyano, Bortianor, James Town, Teshie, Azizanya, Dzita, Vodza, Agavedzi, and Adina, respectively. The interview started only when the participant agreed and signed the consent form. The interview occurred at a location where the participant was engaged, particularly at their home, and in the instance where the participant was at the shore, the interview was carried out at the place where they were free and without any third party. The interview was conducted using the language the leaders were familiar with (e.g., Fante, Ga-Dangme, Ewe, and Twi). The interviews were taped only with the mutual consent of the interviewer and the participant. Additionally, comprehensive notes were taken, resulting in a cumulative duration of 375 h, with each of the 15 leaders of the fishing groups being interviewed for 25 min.

Prior to starting the interview, the researchers engaged in a comprehensive analysis of positionality and social interactions, considering their potential influence on the process of acquiring data and the subsequent interpretation of results [75]. The first author, a native of

the study area, adopted an insider, or emic ontological position, to conduct interviews with the fishing group leaders [75,76]. The leaders of the fishing group developed confidence and perceived the first author as harmless. The leaders of the fishing group were transparent and provided detailed insights on the pattern of fish catch, the major challenges they faced that impacted their fishing activities, and their livelihood opportunities. The first author's perception as harmless by the fishing group leaders motivated the researcher to pose more detailed questions. This position did not have any impact on the qualitative results but rather contributed to the comprehension of the detailed shared knowledge and experiences of the leaders of the fishing group. In this study, the researchers took measures to maintain objectivity, cultural neutrality, and impartiality towards the biases of the fishing group's leaders during the interview transcription process, despite the presence of insider positionality [75,76].

This study gained insights from the presentation of the findings in the qualitative study carried out by Arku et al. [77]. The study aimed to achieve three primary research goals: determining the pattern of fish catch, identifying the major challenges encountered by fishing leaders and their groups that impact their fishing activities, and assessing their livelihood opportunities, including income sufficiency, accessibility to bank loans, and alternative activities that engage their livelihoods apart from fishing. The study of interviews performed with leaders of fifteen fishing groups was driven by these aims. The data analysis in this study employed an engaging and inductive qualitative approach, as described by Arku et al. [77] and Strauss and Corbin [78], to directly create themes. The interviews conducted with the fishing group leaders were transcribed from their respective local languages into the English language. The interview notes were thoroughly examined, and the recorded audio was repeatedly reviewed to guarantee the reliability and accuracy of the results [77,79]. The interview transcripts were classified into themes based on the fishing group's leaders' observations regarding the pattern of fish catch, the major challenges they faced that impacted their fishing activities, and their livelihood opportunities. The interview transcripts contain direct quotations that represent the themes and constructs that offer contextual information regarding the answers of the leaders of the fishing group. These responses were obtained through interviews conducted between February and April 2023.

2.3. Ethical Considerations

Prior to the start of the research, the research ethics protocol was followed, and approval was obtained from the ethics committee of the Faculty of Arts and Humanities at the University of Porto. The research, including the data collection instruments, was reviewed for ethical conformity and to ensure that it did not involve any risk or disadvantage to the participants. This was approved with resolution No. 31/CEFLUP/.

3. Results

3.1. Socio-Demographic Characteristics of Respondents

The socio-demographic characteristics of the respondents across the entire zone and the individual study communities are shown in Figure 2a–f and Table 2, respectively. Across the zone, the greatest proportion (41% or 2170) of respondents were between the ages of 30 and 40, while the lowest (8% or 393) were above the age of 50 (Figure 2a). All the respondents were male (100% or 5250), and a large proportion of respondents (91% or 4791) were married, with just a few (9% or 459) being single (Figure 2b). Again, across the zone, the majority (55% or 2875) of respondents had primary school education, while none (0 or 0.0%) had senior secondary/high school or higher education (Figure 2c). Furthermore, a greater proportion (52% or 2749) of respondents across the zone had a household size of >5, while the smallest (12% or 610) had a household size of 3 (Figure 2d). The majority (44% or 2335) of respondents had resided in the zone for 41–50 years, with the least (8% or 393) having lived there for 51 years or more (Figure 2e). In addition, a higher proportion (47%

or 2472) of respondents across the zone had been fishing for 21–30 years, while the lowest (13% or 694) had been fishing for 10–20 years (Figure 2f).

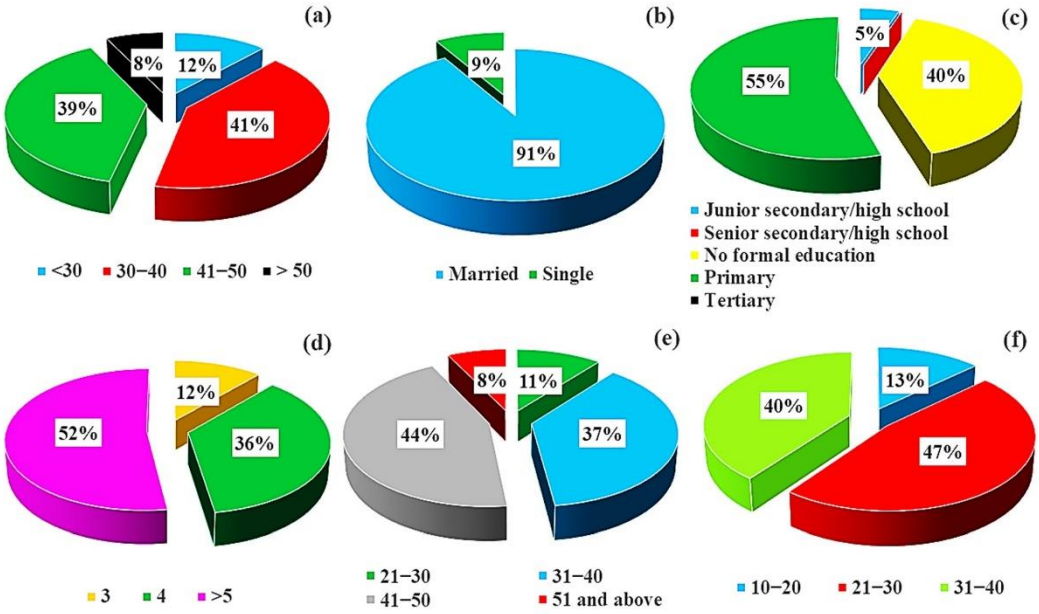


Figure 2. Socio-demographic characteristics of respondents across the zone: (**a**) age, (**b**) marital status, (**c**) level of education, (**d**) household size, (**e**) length of stay in community, and (**f**) years of fishing.

Table 2. Respondents' socio-demographic characteristics for the individual communities.

Variables	Elmina	Cape Coast	Moree	Biriwa	Apam	Gomoa Fetteh	Nyanyano	Bortianor	James Town	Teshie	Azizanya	Dzita	Vodza	Agavedzi	Adina
Age															
<30	61	8	26	34	80	45	50	38	88	36	12	14	61	24	60
30–40	122	163	148	172	124	199	172	142	129	104	204	104	110	146	131
41–50	136	159	146	124	109	80	106	151	109	163	118	208	131	169	141
>50	31	20	30	20	37	26	22	19	24	47	16	24	48	11	18
Marital Status															
Married	322	344	334	332	292	324	318	328	276	324	346	336	289	330	296
Single	28	6	16	18	58	26	32	22	74	26	4	14	61	20	54
Level of education															
JSS	0	44	24	17	25	17	29	27	9	18	0	23	8	25	12
SSS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
No formal	173	120	152	131	150	184	152	139	178	148	166	113	86	120	85
Primary	177	186	174	202	175	149	169	184	163	184	184	214	256	205	253
Tertiary	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Household size															
3	58	8	22	28	62	39	48	30	91	44	21	14	61	24	60
4	110	122	167	153	130	171	140	119	123	95	135	120	82	123	106
>5	182	220	161	169	158	140	162	201	136	211	194	216	207	203	184
Length of stay in community (in years)															
21–30	42	6	18	16	80	45	50	37	74	29	10	14	63	24	60
31–40	126	139	141	157	126	186	160	130	120	96	188	82	80	117	106
41–50	151	185	161	157	107	93	118	164	132	178	136	230	159	198	166
>51	31	20	30	20	37	26	22	19	24	47	16	24	48	11	18
Years of fishing															
10–20	56	21	18	16	137	45	50	37	74	29	52	14	61	24	60
21–30	145	174	172	200	146	220	210	168	150	122	182	132	128	174	149
31–40	149	155	160	134	67	85	90	145	126	199	116	204	161	152	141

Note: JSS represents junior secondary or high school, and SSS is senior secondary or high school.

According to Table 2, the ages of the respondents differ greatly across the study communities. Nevertheless, it appears that most respondents are between the ages of 30–40 and 41–50, followed by <30 years, and the lowest being those >50 years. Dzita, for example, appears to have the majority (59% or 208) of respondents aged 41 to 50 years, followed by Azizanya (58% or 204) and Gomoa Fetteh (57% or 199) for the age range 30 to 40 years, and the lowest in Cape Coast (2% or 8). In terms of marital status, married respondents outnumbered single respondents across the study communities. Azizanya had the largest (99% or 346) number of

married respondents among the communities, followed by Cape Coast (98% or 344), Dzita (96% or 336), and the lowest in Azizanya (1% or 4) for single respondents.

Most respondents had either completed primary school or had no formal education, with junior secondary or high school coming next in terms of education level. Most respondents with primary education (73% or 256) appeared in Vodza, then (72% or 253) in Adina, and (0% or 0) for senior secondary/high school and tertiary level in all the communities. The number of households varied substantially among communities. Despite variations, most respondents had household sizes ranging from 4 to >5. Cape Coast had the highest number of respondents (63% or 220) with a household size >5, followed by Dzita (62% or 216) with a household size >5, while Cape Coast had the fewest (2% or 8) with a household size 3.

According to Table 2, the majority of respondents had lived in their communities between the years of 31–40 and 41–50. Dzita had the largest proportion (66% or 230), Agavedzi was second (57% or 198), and Cape Coast had the lowest (2% or 6). Furthermore, most of the respondents in the communities had been fishing between the years 21–30 and 31–40. Gomoa Fetteh had the highest proportion (63%, 220) of respondents who had fished for 21 to 30 years, followed by Nyanyano (60% or 210), and Dzita had the lowest proportion (4% or 14).

3.2. Perceived Causes and Knowledge about Climate Variability

Figure 3a–g demonstrates the respondents' perceived causes and knowledge of climate variability across the entire zone and the individual study communities, respectively. A significant proportion of respondents across the zone (100% or 5250) were aware of climate variability (Figure 3a). Again, a higher number (81% or 4228) identified television as their primary source of information regarding climate variability, followed by radio (19% or 1008) and newspapers (0% or 14) (Figure 3b). Furthermore, a larger number (45% or 2347) of respondents attributed climate variability to negative human actions, followed by both negative human actions and natural events (27% or 1416), and the lowest (5% or 282) to the punishment of God (Figure 3c). Deforestation was additionally recognized as the most significant (72% or 3776) factor contributing to climate variability across the zone, followed by natural events (28% or 1467), and the least significant (0% or 0) factors being urbanization and vehicular fumes or carbon monoxide (Figure 3d).

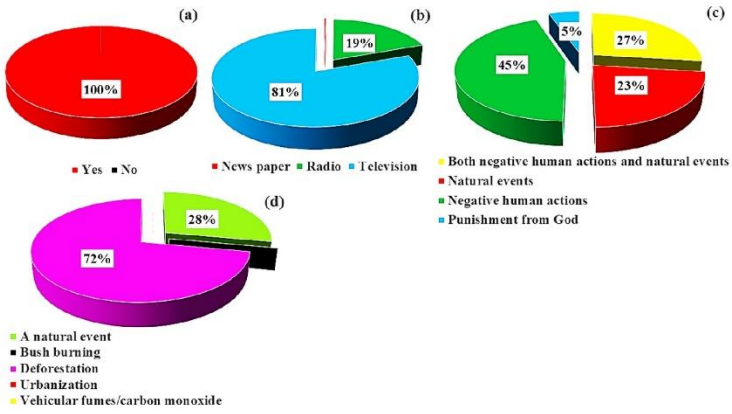


Figure 3. *Cont.*

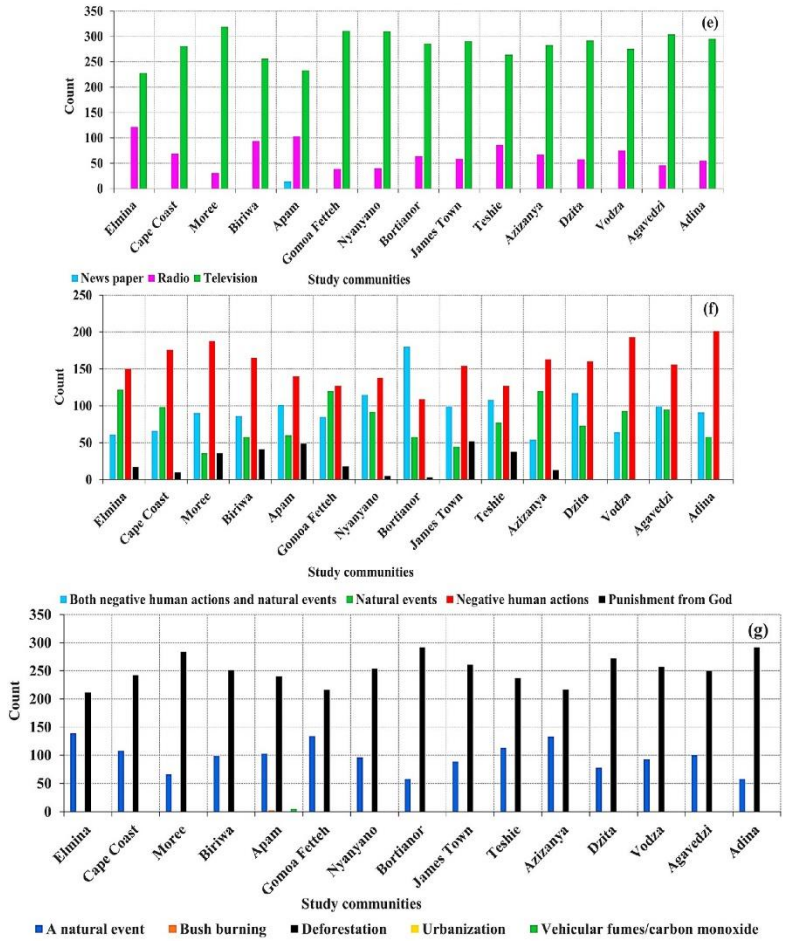


Figure 3. Respondents' perceived knowledge about climate variability: (**a**) awareness about climate change; (**b**) sources of climate change information; (**c**) causes of climate change; (**d**) factors contributing to climate change across the zone; and (**e**) sources of climate change information; (**f**) causes of climate change; and (**g**) factors contributing to climate change among the study communities.

A similar situation can be found in the individual study communities. For example, all (100% or 350) respondents in each study community are aware of climate variability. The sources of information about climate variability in the communities ranged from a high of 91% or 319 for television in Moree to a low of 4% or 14 for newspapers in Apam (Figure 3e). Adina had the most (57% or 201) attribution to negative human actions for the causes of climate variability, whereas Dzita, Vodza, Agavedzi, and Adina had the lowest (0% or 0) attribution to God's punishment (Figure 3f). Respondents in their individual communities recognized deforestation as the primary contributor to climate variability, with the highest response (83% or 292) shown for both Bortianor and Adina (Figure 3g). Bush burning, urbanization, and vehicular fumes or carbon monoxide were perceived by the respondents in most of the communities as the lowest (0% or 0) contributors (Figure 3g).

3.3. Perceived Climate-Related and Oceanic Impacts

Figure 4a–i and Table 3 depict the respondents' views of climate-related and oceanic impacts across the entire zone and the individual study communities, respectively. Respondents across the zone perceived rising temperatures as the most common (34% or 1759) impact of climate variability over the last two decades, followed by sea level rise (32% or 1700), and storms and waves as the least common (0% or 3) (Figure 4a). Increased carbon dioxide (CO_2) concentrations in the atmosphere and sand mining were identified as the most (53% or 2774) and least (0% or 3) significant factors, respectively, contributing to the most common impacts of climate variability over the last two decades (Figure 4b). Again, a considerable majority (96% or 5040) of respondents acknowledged the impact of climate variability on fish populations (Figure 4c), whereas a minority (4% or 210) did not.

Similarly, a large portion (81% or 4273) of respondents across the zone accepted that changes in SST impact fish and fish stocks, with only a small minority (19% or 977) opposing it (Figure 4d). Figure 4e shows that the vast majority (100% or 5248) of respondents were unaware of the impact that changes in SSS have on fish and fish stocks. Furthermore, a significant proportion (100% or 5250) indicated that the total number of fish caught in the zone has decreased significantly over the last two decades (Figure 4f), with the majority (100% or 5247) attributing the decreased fish catch to other factors in addition to climate variability (Figure 4g). According to Figure 4h, the majority (48% or 2523) of respondents believe that the low fish catch in the zone is due to many people fishing across Ghana's sea, followed by the use of light in fishing (23% or 1196), and the lowest being the catching of fingerlings (0% or 22). High premix fuel prices or shortages were also indicated by the majority (60% or 3134) of respondents as the main obstacle limiting fishing activities, followed by saiko activities (25% or 1293), and the lowest (0% or 3) being poor fishing equipment (Figure 4i). The term "premix fuel" refers to a particular blend of oil and gasoline used by responders to power their canoes or boats, which is heavily subsidized by the Ghanaian government. The term "saiko" refers to the unlawful trade in fish at sea by foreign industrial trawlers to Ghanaian canoes or small-scale fishermen.

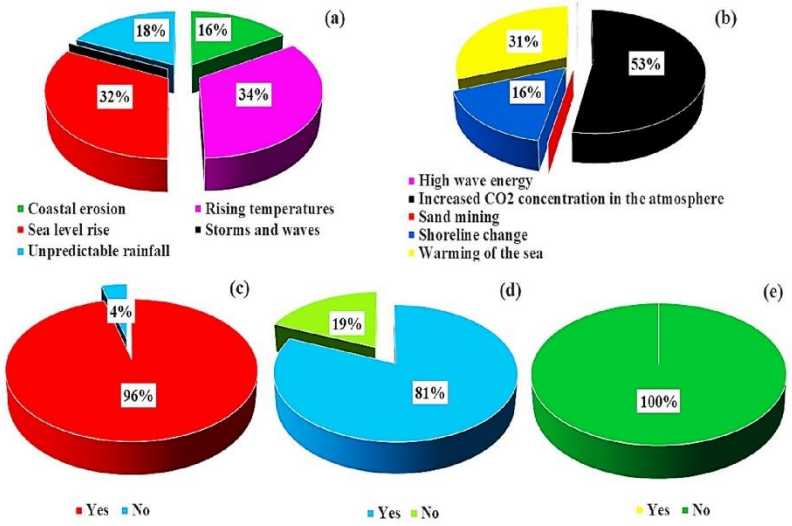


Figure 4. *Cont.*

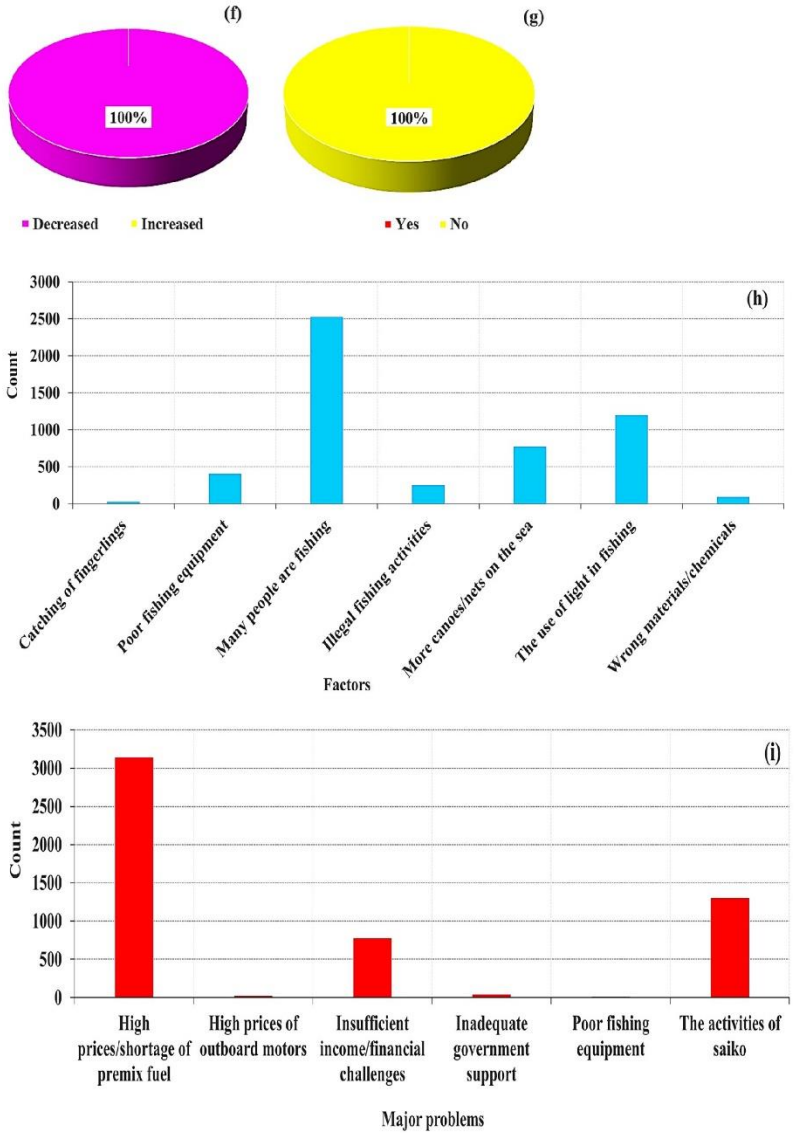


Figure 4. Respondents' perceived climate-related impacts across the zone: (**a**) most common impact of climate change over the last two decades; (**b**) factors contributing to the most common impact; (**c**) impact of climate change on fish population; (**d**) impact of SST on fish and fish stocks; (**e**) SSS on fish and fish stocks; (**f**) total number of fish caught over the last two decades; (**g**) climate change as the only cause of decreased fish catch; (**h**) other factors causing low fish catch; and (**i**) major problems that limit fishing activities.

Table 3. Perceived climate-related and oceanic impacts.

Variables	Elmina	Cape Coast	Moree	Biriwa	Apam	Gomoa Fetteh	Nyanyano	Bortianor	James Town	Teshie	Azizanya	Dzita	Vodza	Agavedzi	Adina
Most common impact of climate change over the last two decades															
							Coastal erosion								
	22	36	32	96	70	18	4	14	41	37	158	105	82	87	50
							Rising temperatures								
	97	103	160	81	143	198	206	173	151	99	54	27	93	54	120
							Sea level rise								
	187	165	82	124	75	35	23	16	85	158	110	204	138	187	111
							Storms and waves								
	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0
							Unpredictable rainfall								
	44	46	76	49	59	99	117	147	73	56	28	14	37	22	69
Factors contributing to the most common impacts															
							High wave energy								
	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0
							Increased CO_2 concentration in the atmosphere								
	143	153	248	145	210	301	323	320	238	167	84	44	130	79	189
							Sand mining								
	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0
							Shoreline change								
	22	36	32	96	67	18	4	14	41	37	158	105	82	87	50
							Warming of the seas								
	185	161	70	109	64	31	23	16	71	146	108	201	138	184	111
Impact of climate change on fish population															
Yes	340	344	337	320	347	335	334	5	342	350	320	322	330	324	350
No	10	6	13	30	3	15	16	345	8	0	30	28	20	26	0
Impact of SST on fish and fish stocks															
Yes	282	298	311	279	265	304	300	328	315	284	168	271	317	282	269
No	68	52	39	71	85	46	50	22	35	66	182	79	33	68	81
Impact of SSS on fish and fish stocks															
Yes	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
No	350	350	350	350	348	350	350	350	350	350	350	350	350	350	350
Total number of fish caught over the last two decades															
							Decreased								
	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350
							Increased								
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Climate change as the only cause of decreased fish catch															
Yes	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0
No	350	350	350	350	347	350	350	350	350	350	350	350	350	350	350
Other factors causing low fish catch															
							Catching of fingerlings								
	0	0	0	0	22	0	0	0	0	0	0	0	0	0	0
							Poor fishing equipment								
	39	0	46	56	78	29	16	49	31	0	10	0	0	0	50
							Many people are fishing								
	223	233	169	241	139	165	123	149	84	66	213	182	164	210	162
							Illegal fishing activities								
	0	0	0	23	85	0	0	0	0	0	0	45	74	0	18
							More canoes/nets on the sea								
	82	75	3	0	8	2	0	0	0	0	127	123	90	140	120
							Use of light in fishing								
	0	0	132	28	0	154	211	152	235	284	0	0	0	0	0
							Use of wrong materials/chemicals								
	6	42	0	2	15	0	0	0	0	0	0	0	22	0	0
Major problems that limit fishing activities															
							High prices/shortage of premix fuel								
	180	170	221	182	220	242	291	250	228	177	206	177	237	157	196
							High prices of outboard motors								
	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0
							Financial challenges								
	10	13	65	115	42	49	26	33	63	139	10	52	51	43	62
							Inadequate government support								
	0	0	0	0	33	0	0	0	0	0	0	0	0	0	0
							Poor fishing equipment								
	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0
							The activities of saiko								
	160	167	50	53	52	59	33	67	59	34	134	121	62	150	92

Respondents' views differ substantially among the study communities. For example, Nyanyano had the highest (59% or 206) response on the most common impact of climate variability over the past two decades on rising temperatures, while Dzita had the second highest (58% or 204) response on sea level rise, and most communities had the lowest (0% or 0) response on storms and waves (Table 3). According to Table 3, increased concentrations of CO_2 in the atmosphere were identified as the major factor leading to the most common impact of climate variability over the last two decades, with Nyanyano receiving the greatest number of responses (92% or 323). Again, most respondents in the communities recognized the impact of climate variability on fish populations, with Teshie and Adina having the greatest proportion (100% or 350) of responses (Table 3).

Likewise, most of the respondents in the individual communities were able to identify changes in SST and their impact on fish and fish stocks, with Bortianor having the highest (94% or 328) and lowest (6% or 22) number of responses. According to Table 3, the majority (100% or 350) of respondents in the study communities perceive that changes in SSS have no impact on fish and fish stocks. Furthermore, in the study communities, all respondents (100% or 350) indicated a substantial decrease in the total number of fish caught over the last two decades. Table 3 shows that the other factors contributing to limited fish capture

vary considerably among study communities. Nonetheless, the highest factor (81% or 284) was the use of light in fishing, which occurred in Teshie.

When asked about their experience with the above issues, particularly the number of fish caught in the zone and the factors that contribute to it, during the interview, most of the fishing group's leaders characterized the fish catch as "decreased" and conveyed concerns regarding the diverse factors that contribute to the decrease in fish catch. For instance, a fishing group leader sharing their observation about the decrease in fish catch and citing various factors that have contributed to the decrease expressed the following.

> *The annual catch of fish has decreased due to factors such as increased sea surface temperature, a lack of trawlers, and increased fishing activity in many parts of the country, which makes it difficult to catch fish deep down* (FL1: Elmina).

Additionally, a fishing group leader reported that:

> *Fish abundance fluctuates annually, and if more fish are caught this year, it will not be enough for the next two years until the third year* (FL2: Cape Coast).

A fishing group leader further indicated that:

> *Fish catch has decreased due to factors such as sea temperature, which affects the fish's behavior and the total catch. The practice of light fishing, which can kill fish, is also causing a divide among fishermen. Some communities, like Saltpond, Gomoa Fete, Winneba, and Nyanyano, oppose light use, while others, like Elmina, Apam, and the Western part of the country, support it* (FL3: Moree).

Another fishing group leader again revealed that:

> *The total catch has decreased. The fishery closure season by the government should be in April or May, when the sea surface temperature increases, rather than June or July, when fish come to the surface for more catch* (FL4: Biriwa).

Likewise, a fishing group leader established that:

> *The number of fish caught has substantially decreased due to global change. In addition, some fishermen use harmful chemicals in fishing, and what do you expect? We use light in fishing, which is not harmful. The light attracts more fish, increasing the catch and ensuring survival and repayment of borrowed money from fish sellers* (FL5: Apam).

Similarly, the leader of a fishing group stated that:

> *The number of fish caught has decreased drastically. We no longer catch the same number of fish as we did when I was younger. In the past, people did not use lights to fish, and there were few fishing nets, but this is no longer the case* (FL6: Gomoa Fetteh).

Moreover, a fishing group leader indicated that:

> *Fishermen in this area oppose the practice of light fishing. The light draws in both fingerlings and mature fish, leading to their capture. Saiko activities, involving foreigners, also contribute to this issue* (FL7: Nyanyano).

In addition, a fishing group leader revealed that:

> *We do not get fish these days. In the past, you took your canoe and returned with many fish. There are many regulations now, like the fishery closed season, where we cannot go to the sea for months. While we do not object to the closed season, its implementation is flawed. The date for closure should not be in July; it should be before the sea temperature increases.* (FL8: Bortianor).

A fishing group leader also expressed that:

> *The annual fish catch has decreased due to climate change and the bad attitude of some fishermen, who fish with light, attracting both fingerlings and mature fish* (FL9: James Town).

A fishing group leader indicated that:

> *We used to get more fish, including salmon and herring. We do not get them anymore because those who fish with light have caught them all* (FL10: Teshie).

Regarding the same issue, a fishing group leader conveyed:

In the past, we used to catch bigger fish, but now we only catch small ones. There are more canoes nowadays, and many people are fishing. On the high seas, people catch fish, select the mature ones, and throw the dead fingerlings back into the sea, driving other fish away. Light fishing is now prevalent and beneficial, although some fishermen argue it is illegal (FL11: Azizanya).

A fishing group leader noted:

The total catch has decreased, and some species have gone extinct. Factors responsible for this include low-quality fishing equipment, overfishing, illegal fishing activities, and climate change (FL12: Dzita).

Moreover, a fishing group leader lamented that:

The annual catch of fish has decreased due to sea pollution, making it difficult to catch them, especially with the low-quality fishing equipment that we use (FL13: Vodza)

One fishing group leader shared his observation as follows:

The catch amount has decreased. I do not think there will be any fishermen who will not accept this as a fact. This, I believe, is not only the result of climate change but also of our harmful activities (FL14: Agavedzi).

A fishing group leader also commented, saying that:

I get less fish these days compared to the past. The number of fishermen and canoes has increased. The climate change incident has also caused some fish to migrate. Many fishermen are unaware of the potential for fish migration, despite the harmful activities of some, particularly those that use chemicals (FL15: Adina).

In addition, while many problems limit respondents' fishing activities, it appears that those with high premix fuel prices or shortages were the most concerned, with a considerable proportion (83% or 291) of responses coming from the Nyanyano community. When asked during the interview to identify the major challenges that limit their fishing activities, most of them indicated "high prices or shortages of premix fuel" as well as the activities of "saiko". One fishing group leader expressed concern that:

The saiko activities are the main problem, as is the premix fuel price instability. We do not have any to buy. We buy car petrol [gasoline] instead (FL1: Elmina).

Similarly, the leader of a fishing group stated that:

The saiko activities are disturbing and need to be stopped. We do not have access to premix fuel, and we purchase small amounts at higher prices. We now use the gasoline from the car at the station (FL2: Cape Coast).

Likewise, a fishing group leader established that:

We have serious issues with saiko activities. Last week, they seized the nets of my friends on the sea. The unstable nature and increased prices of premix fuel are also problems (FL3: Moree).

In addition, a fishing group leader revealed that:

Outboard motors and premix fuel are expensive, with new Yamaha or Suzuki motors costing between GHS 17,000 and 225,000. We mostly get it at cheaper prices from politicians during election years as a form of campaigning to win votes (FL4: Biriwa).

Furthermore, a fishing group leader indicated that:

The price of premix fuel is high, which limits our activities. We now use normal gasoline, which is expensive, but we have no option. We do not make any profit, but since this is what we do for a living, we cannot stop (FL5: Apam).

Moreover, a fishing group leader indicated that:

We do not get premix fuel these days, and we cannot go far on the sea to catch more fish. Stopping the saiko's activities is also necessary, as they are disturbing (FL6: Gomoa Fetteh).

Moreover, a fishing group leader shared regret that:

The activities of the saiko are a big problem. They possess powerful vessels that can travel great distances on the sea, but we still use canoes and do not have access to premix fuel to power them these days. Most fishermen now use normal gasoline, but it is expensive, and not all of us can afford it (FL7: Nyanyano).

Another fishing group leader again reported that:

The fishing business faces greater financial challenges, including costly repairs and the purchase of premix fuel, which was initially affordable but is now unaffordable (FL8: Bortianor).

A fishing group leader noted:

We have issues with the high cost of premix fuel and the lack of purchase options. The government should store fuel near the community and stop saiko activities (FL9: James Town).

A fishing group leader also stated that:

The premix fuel is not coming these days, and this is our biggest challenge. The saiko is yet another challenge, but their activities have been reduced by the government. The price of outboard motors is too high (FL10: Teshie).

A fishing group leader expressed:

The price of the premix is too high. We are unable to purchase any premix these days. Therefore, we rely on regular gasoline, which is also quite costly. The fishing net is also expensive. The saiko's activities have significantly decreased, and people are no longer able to purchase their fish (FL11: Azizanya).

On the same issue, the leader of a fishing group reported that:

The government should reduce the high price of premix fuel. It should be available as well, because sometimes it becomes difficult to find some to buy (FL12: Dzita).

A fishing group leader lamented that:

The premix fuel price is a big concern for us. So, can there be a stable price for it? The price keeps increasing, which is not good for our work. Stopping the middlemen involved in the sale is crucial. The government should help us because, for some of us, fishing is our only means of survival (FL13: Vodza).

A fishing group leader, sharing his concern, stated that:

We face numerous challenges, but the most significant is premix fuel, which is secretly sold to non-fishermen and later sold at higher prices to us (FL14: Agavedzi).

A fishing group leader also made a comment that:

The main challenge is finance, as the business requires a strong capital base for equipment purchases, repairs, and fuel costs. The rising premix prices consume income, but with the right equipment, the business can become profitable (FL15: Adina).

3.4. Livelihood Opportunities of Respondents

Figure 5a–j and Table 4 depict the respondents' livelihood opportunities across the entire zone and the individual communities, respectively. According to Figure 5a, the majority (77% or 4040) of the respondents across the zone do not own the houses in which they live. Again, a greater proportion (84% or 4410) do not own the canoe or boat used for fishing (Figure 5b), and a large proportion (92% or 4840) indicate that their household's income is insufficient to cover their living expenses (Figure 5c). In support of this, it appears that the majority (79% or 3813) of respondents supplement their household's living expenses by borrowing money from fish sellers, followed by relatives (20% or 986), and

the least (1% or 45) from friends (Figure 5d). A large number (87% or 4585) of respondents reported that it is difficult to obtain loans from banks (both public and private), while few (13% or 665) respondents stated the contrary (Figure 5e).

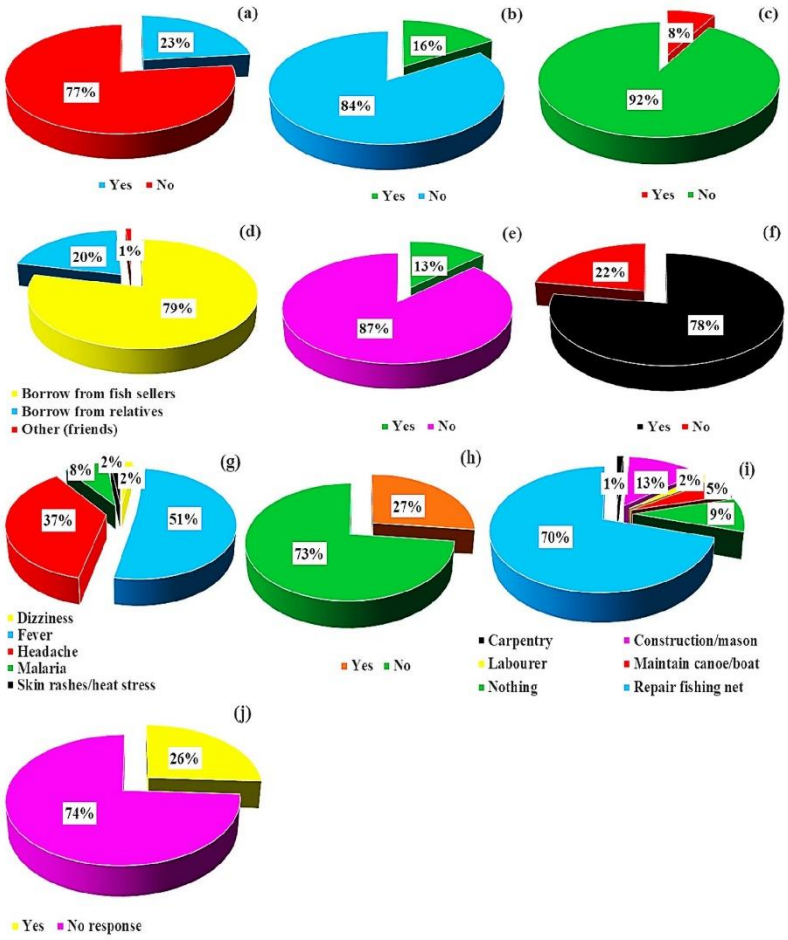


Figure 5. Livelihood opportunities of respondents: (**a**) house ownership; (**b**) canoe or boat ownership; (**c**) income sufficiency to cater for a household's living expenses; (**d**) where to find income to supplement a household's living expenses; (**e**) ease of securing loans from banks for fishing activities; (**f**) impact of climate change on health; (**g**) sickness resulting from climate change; (**h**) all-year fishing; (**i**) activities engaged in when not fishing; and (**j**) activities engaged in help improve livelihoods across the zone.

Table 4. Livelihood opportunities of fishermen.

Variables	Elmina	Cape Coast	Moree	Biriwa	Apam	Gomoa Fetteh	Nyanyano	Bortianor	James Town	Teshie	Azizanya	Dzita	Vodza	Agavedzi	Adina
Ownership of a dwelling place															
Yes	53	83	95	65	139	111	101	122	11	96	70	93	42	64	65
No	297	267	255	285	211	239	249	228	339	254	280	257	308	286	285
Ownership of canoe/boat used for fishing															
Yes	57	95	29	82	60	29	18	44	54	97	41	44	47	53	90
No	293	255	321	268	290	321	332	306	296	253	309	306	303	297	260
Sufficiency of income from fishing to cater for household's living expenses															
Yes	50	66	14	52	104	19	4	20	37	30	0	0	0	0	14
No	300	284	336	298	246	331	346	330	313	320	350	350	350	350	336
Where to find income to supplement a household's living expenses															
Borrow from fish sellers															
	265	261	234	244	212	231	275	266	220	227	324	264	273	220	297
Borrow from relatives															
	35	23	102	52	4	100	75	64	88	93	26	86	77	130	31
Others (friends)															
	0	0	0	2	30	0	0	0	5	0	0	0	0	0	8
Ease of securing loans from banks for fishing activities															
Yes	62	49	33	67	54	62	4	17	101	71	32	7	26	19	61
No	288	301	317	283	296	288	346	333	249	279	318	343	324	331	289
Impact of climate change on health															
Yes	342	312	181	148	200	229	291	324	224	237	302	330	307	322	333
No	8	38	169	202	150	121	59	26	126	113	48	20	43	28	17
Sickness resulting from climate change															
Dizziness															
	0	14	116	67	38	58	3	2	31	3	39	0	31	0	35
Fever															
	261	143	0	71	7	82	242	271	113	194	148	158	118	152	129
Headache															
	30	155	0	0	17	29	46	51	45	32	115	172	135	170	147
Malaria															
	51	0	52	10	87	50	0	0	27	8	0	0	23	0	22
Skin rashes/heat stress															
	0	0	13	0	51	10	0	0	8	0	0	0	0	0	0
Fishing throughout the year															
Yes	59	77	246	284	174	0	0	0	276	223	63	0	0	3	4
No	291	273	104	66	176	350	350	350	74	127	287	350	350	347	346
Activities engaged in when not fishing															
Carpentry															
	18	0	2	1	18	0	0	6	0	0	0	0	0	0	0
Construction/mason															
	89	131	33	47	92	0	16	53	24	4	0	0	0	0	0
Laborer															
	0	66	0	0	0	0	0	6	0	0	0	0	0	0	0
Maintain canoe/boat															
	0	0	0	0	0	0	0	0	44	123	0	0	0	0	27
Nothing															
	5	0	0	0	44	71	0	0	6	0	0	18	61	66	69
Repair fishing net															
	179	76	69	18	22	279	334	285	0	0	287	332	289	281	254
Activities engaged in help improve livelihoods															
Yes															
	155	243	72	66	120	0	16	65	56	121	0	44	0	40	0
No response															
	136	30	32	0	56	350	334	285	18	6	287	306	350	307	350

Furthermore, the majority (78% or 4082) of respondents acknowledged that climate variability has an impact on their health, compared to the few (22% or 1168) who opposed it (Figure 5f). According to Figure 5g, the majority (51% or 2089) of respondents across the zone had a fever, followed by headache (37% or 1497), and the fewest (2% or 77) had skin rashes or heat stress. A significant proportion (73% or 3841) of respondents across the zone do not fish all year (Figure 5h). When asked what they did when they were not fishing, it appears that a large proportion (70% or 2705) of respondents had no alternative livelihood opportunities because they only repair their fishing nets, followed by those who work in construction or masonry (13% or 489), and the fewest (1% or 45) as carpenters (Figure 5i). With no relevant alternative livelihood opportunities, most respondents (74% or 2861) did not react when asked whether the activities they engage in help enhance their livelihoods, with just a few (26% or 998) able to respond (Figure 5j).

The Table 4 responses show a greater level of variation. A significant number of respondents do not own houses in the study communities, with James Town having the highest (97% or 339) answer rate. Again, most of them do not own fishing canoes or boats, with Nyanyano having the largest (95% or 332) number. The respondents' income-insufficient situations differ throughout the study communities. However, in the communities of Azizanya, Dzita, Vodza, and Agavedzi, all (100% or 350) respondents stated that their incomes are insufficient to cover their household's living expenses. While a greater number of respondents in the study communities borrow from fish sellers to supplement their household budgets, the network is stronger in Azizanya, which had the highest (93% or 324) compared to the other communities. Furthermore, most respondents in the communities do not find it easy to obtain bank loans, with Nyanyano having the highest (99% or 346) response.

When asked to share their livelihood conditions during the interview, most of the fishing groups' leaders mentioned varied issues, including "income insufficiency", "financial support from fish sellers", and "difficulties in securing bank loans", among others. In sharing their worries on the issue, one fishing group leader reported as follows:

> *It is not easy. I borrow from a savings and loan [microfinance] company and not from the bigger banks. There is less pressure from them. I also borrow from my customers, those that I sell fish to. This helps me keep up with my household and business expenses* (FL1: Elmina).

Another leader of a fishing group stated that:

> *The fish business does not generate sufficient income. The fishing business relies heavily on trial and error. When we are in a serious financial situation, we cry for help from the fish sellers, not the banks. The banks should have been the best place, but it is not easy to get a loan. The bureaucracy is too much* (FL2: Cape Coast).

In addition, a fishing group leader reported that:

> *I do not deal with the banks. My wife and I have joined a susu [savings] group, and we contribute some amount every month. I borrow from there to support my activities and repay with a low interest rate, unlike the traditional bank. There is no penalty for late payment of the debt* (FL3: Moree).

A fishing group leader further stated that:

> *We can borrow from fish sellers but remember that they also face challenges as they do not get enough fish from us to sell. It is not easy to get money from the bank as a man. The banks primarily provide loans to women, and we, as men, borrow from them. I think the banks trust women more than men* (FL4: Biriwa).

A fishing group leader sharing his experience with bank loans indicated that:

> *Yes, you can get a loan from the banks, but the process is not that simple. I tried one, and I was able to secure it, but the interest I paid was too much, so I advised myself. I now borrow from the fish sellers with no interest rate* (FL5: Apam).

Furthermore, a fishing group leader expressed that:

> *The government does not support us, so we borrow from fish sellers and repay them with fish. Some people get loans from the bank, while others do not due to their inability to repay the loans in a timely manner* (FL6: Gomoa Fetteh).

Moreover, a fishing group leader expressed that:

> *The income used to be sufficient, but not at the present time. There are many banks that are willing to give loans, but their processes are so complex that most fishermen cannot afford them. Most of us prefer to borrow from fish sellers. Generally, women [fish sellers] do not struggle to get loans. I have some friends whose wives take the loan for them* (FL7: Nyanyano)

A fishing group leader also lamented that:

> *We have financial challenges. The banks can help, but it is not that simple. Most of my colleagues and I personally borrow from the fish sellers. They serve as the primary source of borrowing, even before one considers going to the bank* (FL8: Bortianor).

Similarly, a fishing group leader sharing difficulties in securing bank loans indicated that:

> *It is not easy to secure a loan from the bank. I will not lie to you. They demand that you present the details of your business. Most fishermen cannot afford the extensive detail work required. If you can go through it all, they will give you the loan* (FL9: James Town).

A fishing group leader noted:

> *The banks do not give loans to us; they would rather give money to our wives, and we borrow from them. I do not understand why, but that is what they do. The fish sellers are*

our only hope. They are the ones that give us money, but now the business is not good, so they also suffer (FL10: Teshie).

A fishing group leader established that:

The fish business is seasonal, with fluctuations in profits, but generally, earnings are not enough to support household and fishing activities. Most of us here do not borrow from the bank because of the bureaucracy. We either borrow from the susu [savings] group or from the fish sellers (FL11: Azizanya).

A fishing group leader shared his current livelihood conditions and the financial assistance he receives from fish sellers, indicating that:

There is a low catch. So, how is the income going to be sufficient? The premix fuel alone costs all the money, but I have family to care for. I rely on the fish sellers for help. I do not have any other preferred source of borrowing (FL12: Dzita).

Equally, a fishing group leader expressed that:

These days, my income is insufficient, and I spend it on premix fuel. I always must speak with the fish sellers for additional money, and I always have debt in front of me (FL13: Vodza).

Regarding the same issue, a fishing group leader reported that:

. . .It is not sufficient at all. No, I do not borrow from the bank. My son in Accra is a government employee [public sector worker], and it is easy for him to get a loan. So, I borrow from him to support my activities. I also borrow from the fish sellers for family upkeep (FL14: Agavedzi).

A fishing group leader also commented, stating that:

The income I earn is insufficient due to high expenses and insufficient fish. Yes, the banks are there, but it is not that easy to get a loan. The process is tedious. The best thing is to have a good relationship with the fish sellers, and you can rely on them for support (FL15: Adina).

Most of the respondents in the communities recognized the health impacts of climate variability, with Elmina having the highest proportion (98% or 342). Furthermore, while respondents acknowledged many sicknesses caused by climate variability, fever is prevalent, especially in Bortianor, which had the highest (84% or 271) responses. A considerable proportion (100% or 350) of respondents, particularly in Gomoa Fetteh, Nyanyano, Bortianor, Dzita, and Vodza, do not fish all year, while the remaining communities have few respondents who do (Table 4). Moreover, most respondents in the communities do not have alternative livelihood opportunities and only repair their nets when not fishing, particularly in Nyanyano, which had the greatest (95% or 334) number. However, a few of them engage in construction, carpentry, or as laborers, particularly in the communities of Elmina, Cape Coast, Moree, and Biriwa (Table 4). Most respondents, particularly those in Gomoa Fetteh, Vodza, and Adina, did not respond to whether the activities they engage in when not fishing help enhance their livelihoods. However, a high proportion of respondents in Elmina, Cape Coast, Moree, Biriwa, Apam, James Town, and Teshie were satisfied with their alternative livelihood activities other than fishing (Table 4).

3.4.1. Association between Independent Variables and the Livelihood Opportunities of Respondents

In the chi-square test of the association between the independent variables and the fishermen's livelihood opportunities (see Supplementary Materials Table S1), there is a significant ($p < 0.05$) association between all the independent variables considered in this study and the livelihood opportunities of the fishermen in the zone (see Supplementary Materials Table S1). Nevertheless, the strength of the associations shown by the Cramer's V statistic differed between variables. Except for age and house ownership, level of education and perceived health impact of climate variability, and household size and income sufficiency, which had a moderate strength of association (Cramer's V = 0.2), the

remaining variables had a weak strength of association (Cramer's V = 0.0 or 0.1), despite being significant (see Supplementary Materials Table S1).

Most of the independent variables examined revealed significant relationships among the individual communities. Except for variables like level of education and perceived impact of climate variability on health in Elmina, marital status and income sufficiency in Bortianor, James Town, and Teshie, years of fishing and income sufficiency in James Town again, marital status and house ownership in Azizanya, Vodza, and Adina, and years of fishing and canoe ownership in Azizanya and house ownership in Vodza, the remaining independent variables were significantly associated ($p < 0.05$). The Cramer's V statistics for the variables among the communities ranged from 0.1 (weak association) between the variables such as marital status and house ownership and income sufficiency and years of fishing and canoe ownership in Elmina, household size and income sufficiency and years of fishing and canoe ownership in James Town, marital status and house ownership in Teshie, and years of fishing and house ownership in Adina, to a high of 0.9 (strong association) between age and house ownership in Apam (see Supplementary Materials Table S1). It is important to note that certain statistical calculations were unable to be performed due to the presence of one or more cells with an expected count below 5, or due to the variable exhibiting constancy, particularly within the Dzita and Agavedzi communities (see Supplementary Materials Table S1).

3.4.2. Relationship between Independent Variables and the Livelihood Opportunities of Respondents

The binary logistic regression analysis shows the effect of the independent variables on fishermen's livelihood opportunities across zones and in individual communities (see Supplementary Materials Table S2). The omnibus test of the model coefficient demonstrated a better fit across the zone ($X^2 = 991.787$, df = 9, $p < 0.05$) than the null model. The independent variables in the model are significant predictors of the fishermen's livelihood opportunities (see Supplementary Materials Table S2). The Nagelkerke R^2 is 0.408, indicating that the model accounts for only 40.8% of the variations in the dependent variable (income sufficiency). It is worth emphasizing that, while the model is a significant predictor of the dependent variable, other significant predictors may exist.

Except for the married status and household sizes of 4 and >5, the Wald ratio and corresponding *p*-values of the independent variables differ significantly from those in the null model. Aside from the variables listed above, the remaining independent variables were significant predictors of the dependent variables across the zone (see Supplementary Materials Table S2). For instance, across the zone, the odds of the fishermen's income being insufficient reduce by 0.372 (with a 95% confidence interval of 0.290 to 0.477) the more they fish all year, by 0.343 (0.265 to 0.445) the more they own their houses, by 0.090 (0.068 to 0.119) the more they own a canoe, and by 0.064 (0.008 to 0.498), 0.122 (0.016 to 0.955), and 0.031 (0.004 to 0.252) the more they are aged 30–40, 41–50, and >50, respectively (see Supplementary Materials Table S2). According to the classification table, the total accuracy rate for the test was 92.7%. The model had a high sensitivity of 98.1% but a low specificity of 29.0%. The sensitivity was higher since the model accurately predicted that 98.1% of fishermen would report income insufficiency over sufficiency (see Supplementary Materials Table S2). In this case, the model's sensitivity reveals the fisherman whose income was insufficient as predicted by the model, while specificity indicates the opposite.

The analysis for each community differs considerably. In Elmina, Moree, Biriwa, Nyanyano, Bortianor, and Adina, no significant relationships were observed between the independent variables and the dependent variables, despite the model accounting for 92.6%, 84.4%, 82.6%, 75.8%, 79.5%, and 23.3% of the variations in the dependent variable, respectively. However, significant relationships were found in Cape Coast, Apam, Gomoa Fetteh, James Town, and Teshie. For example, the omnibus test of the model coefficient showed a better fit among the communities ($X^2 = 61.490$, df = 8, $p < 0.05$) than the null model with a Nagelkerke R^2 of 0.260 (26.0%) in Cape Coast; $X^2 = 351.838$, df = 9, $p < 0.05$,

and an R^2 of 0.901 (90.1%) in Apam; $X^2 = 105.458$, df = 8, $p < 0.05$, and an R^2 of 0.756 (75.6%) in Gomoa Fetteh; $X^2 = 74.091$, df = 9, $p < 0.05$, and an R^2 of 0.389 (38.9%) in James Town; and $X^2 = 126.512$, df = 9, $p < 0.05$, and R^2 of 0.685 (68.5%) in Teshie.

Except for marital status and age, the independent variables in Cape Coast were significant predictors of the dependent variables. Notably, the odds of a fishermen's income being insufficient reduce by 6.191 (with a 95% confidence interval of 2.304 to 16.630) if they fish all year, by 0.460 (0.217 to 0.997) if they own their houses, by 0.314 (0.151 to 0.652) if they own a canoe, and by 4.045 (1.210 to 13.518) if they have a household size of 4. When the fishermen in Apam fish all year, their odds of having insufficient income drop by 0.065 (0.013 to 0.331), or when they own a canoe, they reduce by 0.026 (0.004 to 0.147). Again, in Gomoa Fetteh, it reduces by 0.156 (0.031 to 0.758) when they own a canoe; in James Town, it reduces by 0.242 (0.051 to 1.145) when they fish all year, by 0.179 (0.034 to 0.935) when they own a house, or by 0.253 (0.105 to 0.606) when they own a canoe; and in Teshie, their income insufficiency reduces by 0.185 (0.048 to 0.708) when they own a house (see Supplementary Materials Table S2).

The test's total accuracy rate was 84.0% in Cape Coast, 95.7% in Apam, 97.7% in Gomoa Fetteh, 92.6% in James Town, and 95.1% in Teshie. Cape Coast has better (97.5%) and poorer (25.8%) sensitivity and specificity, respectively. In James Town, the situation is similar, with 99.4% sensitivity and 35.1% specificity. Apam has a high sensitivity and specificity of 97.6% and 91.3%, respectively. Gomoa Fetteh had good sensitivity and specificity, with 98.8% and 78.9%, respectively, and Teshie had 98.1% and 63.35, in that order. Due to the constant nature of the dependent variables, no statistics were generated for the communities of Azizanya, Dzita, Vodza, and Agavedzi (see Supplementary Materials Table S2).

3.5. Influence of SST and SSS on Total Annual Fish Catch

The variations in SST, SSS, and total annual fish capture in the oceanic portion of the zone were examined, as shown in Figure 6a,b, in response to the respondents' diverse viewpoints on oceanic parameters. Here, we computed the mean monthly and annual SST in °C and SSS in ‰ from the three coastal stations (i.e., Winneba, Tema, and Keta) as well as the total annual fish capture (in metric tons) from 2000 to 2020 for the Coastal Savannah zone.

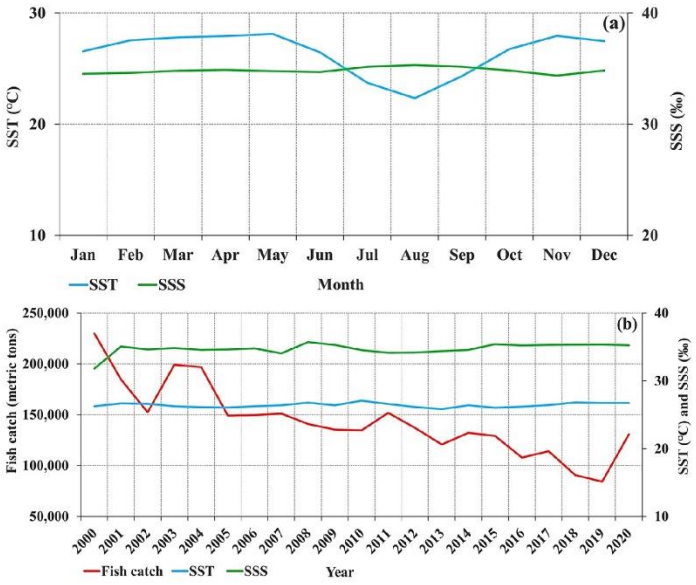


Figure 6. Variations in mean monthly (**a**) and annual (**b**) SST, SSS, and total annual fish catch from 2000 to 2020.

Figure 6a shows the mean monthly SST, which reveals substantial variations. The maximum mean monthly SST of 28.1 °C occurred in May, and the lowest of 22.3 °C was observed in August (Figure 6a). The mean monthly SSS demonstrates minimal variation (Figure 6a). The highest salinity levels, measured at 35.3‰, occurred in August, while the lowest levels, recorded at 34.4‰, were observed in November (Figure 6a).

According to Figure 6b, the mean annual SST does not vary greatly. Nonetheless, the maximum (27.1 °C) SST recorded in the last two decades was in 2010, and the lowest (25.8 °C) in 2013. The SSS shows a similar pattern (Figure 6b). The highest salinity levels of 35.7‰ occurred in 2008, and the lowest levels of 31.8‰ were observed in 2000 (Figure 6b). Between 2000 and 2020, the mean annual SST and SSS increased by 0.5 °C and 3.5‰, respectively. There has been a higher annual variation in total fish catch over the last two decades in the zone. The highest total annual fish catch (230,127.8 metric tons) happened in 2000, while the lowest (84,266.0 metric tons) occurred in 2019. A clear decreasing trend is observed in the total annual fish catch over the last two decades in the zone, supporting respondents' position on a substantial decrease in the total annual fish catch in the zone.

The multiple linear regression method was used to determine if changes in SST and SSS predicted the decreased total annual fish catch in the zone. Total annual fish catch = 1,248,666.687 − 7324.753 × (SST) − 26,241.781 × (SSS) was the fitted regression model. Overall, the regression analysis revealed a significant result (R^2 = 0.390, F (2, 18) = 5.763, p = 0.012). The analysis revealed that changes in SST did not predict the zone's decrease in total annual fish catch (β = −7324.753, p = 0.729). Changes in SSS, on the other hand, significantly predicted the decreased total annual fish catch (β = −26,241.781, p = 0.005).

4. Discussion

This study analyzed climate variability, coastal livelihoods, and the influence of ocean change on the total annual fish catch in Ghana's Coastal Savannah zone. Considering the ongoing global warming and its adverse impacts on different sectors, including coastal zones, it is critical to consistently assess social perceptions towards this phenomenon and its impact on people's livelihoods. This evaluation should encompass not only physical climate and oceanic variables but also the alignment or contrast of these factors with social perspectives.

It was established that a significant proportion of the fishermen in the zone are aware of the global climate variability crises and related impacts, with the mass media sector, particularly the broadcasting media (television and radio), playing a substantial role in that regard. This finding supports the broader consensus of the substantial contribution of the mass media space to the propagation of information regarding the global climate crises as well as the reduction in negative anthropogenic actions [80,81]. For instance, Sampei and Aoyagi-Usui [80] found a positive correlation between an increase in newspaper coverage of global warming and improved public concerns on the issue in Japan. Similarly, Junsheng et al. [81] found that mass media influences awareness, attitude, and knowledge of climate change among the people in the state of Selangor, Malaysia. While the newspaper is doing well in some regions, particularly Japan, its utilization is low, particularly by the fishermen in the Coastal Savannah zone of Ghana. They prefer television and the radio to the newspaper (see Figure 3b). The low utilization of the newspaper could be due to language constraints, as it is written in English. Most of the fishermen in the zone have either primary education or no formal education. Most broadcast media, on the other hand, communicate in the local dialect. Again, the fishermen across the zone are familiar with the causes of climate variability, with the majority attributing it to negative human actions, a response that conforms to the general scientific literature [82]. The fishermen mentioned deforestation as the major factor causing climate variability. This finding supports earlier research studies, including those in Ghana [83] and elsewhere [84]. The fishermen in the zone require more information on the contributions of urbanization and vehicular emissions, as they failed to recognize them as one of the factors responsible for climate

variability impacts. Urbanization, for instance, is considered an important driver of climate variability [85].

It has been revealed again that increasing temperatures and sea level rise were the two most common impacts of climate variability across the zone and individual communities, with rising CO_2 concentrations in the atmosphere being the most significant contributor. This finding agrees with Ankrah's [23] earlier study, which showed rising temperatures as the most evident impact of climate change in coastal Winneba, Ghana. The impacts resulting from combined climate variability, evidenced through rising temperatures, sea level rise, and related extreme events, have been highlighted in the scientific literature. For example, Nicholls et al. [8] and Wong et al. [9] warned that the combined effects of warming temperatures and sea level rise could endanger both the biophysical and socioeconomic systems of coastal areas. Church et al. [10] and Nicholls et al. [11] went on to state that the mean sea level could rise by a meter or more by 2100 and between 0.38 and 0.77 for the same period [12], which would be disastrous for coastal zones and their surroundings. The occurrence might inflict significant damage to the world's coastal regions, particularly those with minimal adaptation capacities in Ghana's Coastal Savannah zone. Furthermore, the fishermen recognized and took clear positions on the impact of climate variability, as well as changes in SST, on fish and fish stocks. Their position on this is consistent with greater scientific understanding. Several research studies, including those by Ankrah [23], Belhabib et al. [24], Brander [25], Lam et al. [26], and Pankhurst and Munday [27], have found that climate variability has a negative influence on fish and fisheries. SST changes are considered to have significant effects on fish habitats [29].

While fishermen acknowledged the impacts of SST changes on fish and fish stocks, they did not recognize the impacts of SSS changes. However, increases in SSS had a bigger influence than changes in SST on the decreased total annual fish catch in the zone (see Section 3.5). SSS changes are a major oceanographic component for fish growth [86]. In most fish species, SSS changes determine egg fertilization, incubation, yolk sac resorption, early embryogenesis, and larval growth, according to Bœuf and Payan [86]. Nian et al. [87] found that increasing SSS and warming SST directly led to a decline in Atlantic cod abundance from 1919 to 2016. As a result, the fishermen in the zone demand greater information and explanation about SSS changes and their implications. Furthermore, the study's findings revealed that the total annual fish catch has decreased substantially over the last two decades. The multiple regression model accounted for 39% of the variability in the zone's decrease in total annual fish catch. However, the other factors causing low fish catch, as stated by respondents (see Figure 4h), also play a substantial role. The fishermen were therefore accurate in this case, as physical fish catch data corroborated their claims. The finding is consistent with previous research studies conducted in various places, including the tropical regions [32], the Gulf of Guinea in West Africa [33], and the Canary Current large marine ecosystem [34]. Aside from climate variability, the fishermen identified other negative factors responsible for the decreased fish catch in the zone, with the involvement of many people in fishing and light fishing scoring highest. This finding supports previous studies conducted elsewhere by Sumaila et al. [31] and in various parts of Ghana by Atta-Mills et al. [38] and Owusu and Adjei [55]. It was also shown that high premix fuel prices or shortages, as well as saiko activities, were the main obstacles that hindered the fishermen's activities, which is comparable with previous research studies conducted by Alder and Sumaila [37], Atta-Mills et al. [38], and Owusu and Adjei [55]. For example, Alder and Sumaila [37] and Atta-Mills et al. [38] informed us about the increasing pressure on West African marine ecosystems from foreign vessels.

It was further shown that most of the fishermen in the zone do not have satisfactory livelihood opportunities. For instance, most of them do not own houses, and the same was true for canoes. Once again, their fishing income was insufficient to cover their household's living needs. Previous research studies, such as those of Ankrah [23], Apine et al. [40], and Tikadar et al. [70], have reported on fishermen's limited livelihood options. Even though Ghana has numerous financial institutions, it was discovered that loans for fishermen

are difficult to obtain. They, on the other hand, choose to borrow from fish sellers or family. This could be due to high interest rates, increased bureaucracy, and the fear of missing payment deadlines, which could result in incarceration. According to Owusu and Adjei [55], in the Western region of Ghana, fishermen find it difficult to access loans; yet those who can obtain loans from banks face pressure to fulfil payment deadlines and interest rates, leading to illegal fishing. Furthermore, it emerged that most fishermen have no viable alternative sources of livelihood other than fishing. This could play a larger role in the fishermen's income shortfall, especially since they do not fish all year. They would profit greatly by engaging in alternative sources of livelihood, particularly during the closed fishing season, when they are not permitted to fish. According to the findings, most of them simply repair their nets, with a few, particularly in metropolitan areas, participating in occupations such as construction, masonry, and carpentry. The development of improved alternative livelihood possibilities in coastal areas is said to have benefited fishermen's and small-scale fisheries' livelihoods. For example, Matera [88] reports on the Colombian islands of Providencia and Santa Catalina, and Katikiro reports on Tanzania as well [89]. It was additionally found that the socio-demographic factors, which were employed as independent variables in this study, had a strong relationship with the livelihood of fishermen. Regardless, the binary logistic regression test demonstrated that the income insufficiency status of fishermen across the zone could be substantially reduced when they have their own houses, canoes, fish all year, or as they age. As a result, government or relevant stakeholder support could be beneficial to the fishermen. At least the development of more improved livelihood activities in addition to fishing across the zone can help fishermen earn income to build their own houses or buy canoes to sustain their fishing activities.

In addition, most of the fishermen reported poor health effects owing to climate variability, with fever and headache being the two most common ailments. Most fishermen at their place of work (shore) repair their nets in the scorching sun as there are no proper shade structures where they can rest. This is congruent with the findings of Tikadar et al. [70], who found an incidence of illnesses among fishermen in Bangladesh's northeastern floodplains. According to Cissé et al. [90], climate variability, as well as related extreme events, have increased illnesses, which have a negative impact on the well-being and health of people.

5. Conclusions

This study examined climate variability, coastal livelihoods, and the influence of ocean change on the total annual fish catch in Ghana's Coastal Savannah zone. The main findings from this study are that over the years, climate variability awareness has increased substantially among fishermen across Ghana's Coastal Savannah zone, with a significant contribution in this regard coming from the broadcast media. Their positions on the major cause of climate variability are in line with the general scientific consensus on a warming world highly attributed to negative anthropogenic activities [82].

Fishermen across the zone have a strong position on rising temperatures and sea level rise as the most prevalent impacts of climate variability over the past two decades. They have a greater understanding of the impact of climate variability, as well as changes in SST, on fish and fish stocks, which agrees with the existing scientific information. Additionally, the fishermen reported a significant decline in the zone's annual total fish catch over the previous 20 years, which the physical fish catch data accurately supported and was consistent with the scientific literature (e.g., [32–34]). The involvement of many people and the use of light in fishing emerged as the other factors causing a decreasing fish catch in the zone. Moreover, high premix fuel prices or shortages and saiko activities were the main obstacles that hindered the fishermen's activities.

In addition, fishermen across the zone do not have satisfactory livelihood opportunities; the majority do not own houses or canoes and have insufficient income to meet their families' basic needs. Due to the difficulty and bureaucracy involved in obtaining loans from banks, fish sellers and relatives are the main means through which fishermen borrow

money. Apart from fishing, they have no sustainable alternative sources of livelihood, which may explain their income insufficiency. Policymakers and other important stakeholders need to assist the fishermen in this regard. Banks need to lower interest rates and provide more flexible payment options to fishermen to boost their confidence in borrowing to support their activities. For them to be able to fish all year, government-subsidized premix fuel prices should be more stable and reliable.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16091201/s1, Table S1: Chi-square test of association between independent variables and livelihood opportunities of fishermen; Table S2: Binary logistic regression showing the relationship between independent variables and livelihood opportunities.

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Informed Consent Statement: The research ethics commission of the Faculty of Arts and Humanities at the University of Porto reviewed and provided approval for the data collection instruments used in the study. Prior to the start of the interview, the participant was provided with a consent form that outlined their rights as a participant, such as the voluntary nature of the interview and their prerogative to withdraw from the study or request the removal or deletion of their previously recorded responses. Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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5.2. Using qualitative research methods to understand how climate variability impacts the livelihoods of fishermen in coastal Ghana

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RESEARCH

Using qualitative research methods to understand how climate variability impacts the livelihoods of fishermen in coastal Ghana

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Abstract
Though climate variability research has largely focused on natural science and quantitative measures, there has been a notable shift towards using social science, including qualitative methods, to understand the impact of climate variability on coastal livelihoods. While these methods have been widely used in many coastal regions, their application in coastal Ghana remains limited. This study used qualitative methods to examine fishermen's knowledge of climate variability and oceanic impacts on their livelihood opportunities on the central and eastern coasts of Ghana. Semi-structured interviews were used to gather data from 5,250 fishermen and 15 in-depth interviews were conducted with fishing group leaders. The results indicate that, while fishermen are aware of climate variability and oceanic impacts, their knowledge of city and urbanisation processes and their effects as urban climate drivers is limited. They perceived a decrease in the total annual fish catch over the last two decades as a result of overfishing and the practise of light fishing, along with climate variability. Several obstacles hinder the fishermen's activities, including high prices and shortages of premix fuel and saiko (trade in fish at sea between industrial trawlers and Ghanaian canoes). They are dissatisfied with their prevailing livelihood opportunities due to a lack of viable alternative options. The study revealed coastal livelihood initiatives to improve livelihood conditions, sustain fishermen's activities, and improve their general well-being. There is a need for a policy initiative that prioritises providing practical training and support for fishermen to participate in additional livelihood activities such as agriculture (crops, livestock, and poultry), small business, occasional wage labour, and handicrafts. Additionally, it is important to implement a strategy that ensures an uninterrupted and direct channel of communication and distribution for premix fuel between the fishermen and the Ministry of Fisheries and Aquaculture Development. Thus, qualitative methods continue to be a beneficial technique for achieving coastal livelihood goals in the face of climate variability.

Keywords Climate variability · Small-scale fisheries · Coastal livelihood · Qualitative methods · Coastal Ghana

Introduction

This study demonstrates the utilisation of qualitative research methods to enhance policy-making and decision-making processes among stakeholders in relation to the impact of climate variability on the livelihoods of small-scale fishermen in coastal Ghana. Specifically, it focuses on those dwelling on the central and eastern coasts who heavily depend on fisheries and fishing as their primary means of livelihood. Despite their significant economic contributions to sustainable development on a global scale (Hoang et al. 2020), coastal zones persistently experience adverse effects resulting from climate variability (Wong et al. 2014). Climate variability represents variations in the mean climate over time and space (IPCC 2018). Climate variability, reflects variations in the mean climate that exceed the

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observed changes in a specific weather system, whereas climate change reflects changes over a longer period (IPCC 2018). According to the IPCC (2018), both natural internal processes and external forcing can contribute to climate change and variability. The aforementioned circumstances have led to constrained livelihood prospects for numerous individuals, specifically those engaged in small-scale fishing activities within developing countries that possess limited capabilities for adaptation (March and Failler 2022). The small-scale fishermen operating within the fishing communities on the central and eastern coasts of Ghana are also constrained by a lack of alternative livelihood opportunities.

The use of qualitative research methods to investigate the impacts of climate variability on the coastal livelihoods of small-scale fisheries has become more prevalent in recent years. However, coastal Ghana has limited application of these methods to advance knowledge, inform policy, and facilitate decision-making. Research studies such as those of Ayilu et al. (2023), Atindana et al. (2020), Freduah et al. (2019), and Freduah et al. (2017) have employed qualitative research methods to study fishermen's livelihoods on the western coast of Ghana but made no attempt to underscore how the method can be effectively used to influence policy decisions. Moreover, there has been little research conducted on how climate variability impacts the livelihoods of small-scale fishermen located on the central and eastern coasts of Ghana. To address these knowledge gaps, the present study utilised qualitative methods to examine the impacts of climate variability on the livelihoods of fishermen located on the central and eastern coasts of Ghana. It demonstrates that qualitative research methods can support analysis of the following objectives: to understand fishermen's perceptions of causes of and knowledge about climate variability; to understand their perceptions of climate-related and oceanic impacts; as well as to examine the fishermen's alternative livelihood opportunities (i.e., additional opportunities within fishing). The objectives of the study are primarily descriptive in nature, seeking to understand the perspectives of and knowledge held by fishermen. Consequently, qualitative research methods are highly suitable for investigating these issues, as they are commonly employed to study such phenomena (Bernard 2017; Yin 1984). This study posits that while the causes of climate variability require natural science assessments, the impacts of climate vulnerability and their effects on different groups of fishermen (small vs. large scale, with differing worldviews and cultures, etc.) often require qualitative methods from social sciences. This study utilises empirical evidence on climate variability, coastal livelihoods, and the impact of ocean change on fish catch on the central and eastern coasts of Ghana. Qualitative research methods and analysis were employed to enhance understanding and inform policy-making and stakeholder decisions aimed at protecting the livelihood opportunities of small-scale fishermen in coastal areas.

The study includes various sections, including a description of the central and eastern coasts of Ghana, an exploration of the conceptual and theoretical focus on qualitative research methods, a detailed description of the methodology employed, an analysis of the obtained results, a discussion of the findings, an examination of the policy implications, and a concluding statement.

The central and eastern coasts of Ghana

The coastal areas of the Central, Greater Accra, and Volta regions, collectively form the central and eastern coasts of Ghana. They encompass a total of 20 out of the 26 coastal Metropolitan, Municipal, and District Assemblies (MMDAs) and three out of the four coastal regions within the country (Dovlo et al. 2016). This coastal zone, covering three distinct regions, constitutes approximately 70% of the country's coastline, spanning 560 km^2. Within this zone, there are a total of 203 landing sites, representing 69% of all fish landing sites in the country (Dovlo et al. 2016). The Central region exhibits the highest number of fish landing sites, accounting for 97 (33%) of the total sites across the three regions. The Greater Accra region follows closely with 59 (20%) landing sites, while the Volta region possesses 47 (16%) sites. Fishing is widely recognised as a significant occupation and a primary means of livelihood for about 2.6 million individuals, constituting approximately 10% of the total population (Dovlo et al. 2016; Seidu et al. 2022). The primary fish species captured within the region include Atlantic little tuna (*Euthynnus alleratus*), Scad Mackerel (*Caranz rhoncus*), Chub Mackerel (*Scomber colias*), Frigate mackerel (*Auxis thazard*), Sardinella (*Ssardinella spp*), Threadfin (*Galeoides decadactylus*), Burrito (*Brachydeuterus auritus*), Anchovy (*Engraulis encrasicolus*), Cassava fish (*Pseudotolithus senegalensis*), and Bumper (*Chloroscombrus chyrsurus*) (Dovlo et al. 2016). According to Dovlo et al. (2016), the fishing zone comprises 114 fishing communities, accounting for 61% of the total 186 communities in the country. Additionally, the zone is home to 73,916 fishermen, representing 69% of the total of 107,518 fishermen nationwide (Dovlo et al. 2016).

This study was conducted in 15 communities across the zone (Table 1). These communities were selected based on their significant levels of landings, number of fishermen, and their level of reliance on fishing for livelihood (Dovlo et al. 2016). Several other communities, such as Winneba, Senya Beraku, Tema, and Prampram, among others (Fig. 1), satisfied the selection criteria and possessed comparable importance for the study. However, the accessibility of these communities was limited due to resource constraints and the time limitations of the study.

Table 1 Characteristics of the selected fishing communities used in the study. Source: Dovlo et al. (2016)

S/N	Community	MMDAs	Region	Number of fishermen	Landing beach(es)
1	Elmina	Komenda-Edina-Eguafo-Abrem District	Central	1,512	Elimina Main
2	Cape Coast	Cape Coast Metropolitan Assembly	Central	556	Abrofo Mpoano and Duakor
3	Moree	Abura-Asebu-Kwamankese District	Central	997	Etuei
4	Biriwa	Mfantsiman Municipal Assembly	Central	836	Abaka Ekyir
5	Apam	Gomoa West District	Central	741	Apam Main
6	Gomoa Fetteh	Gomoa West District	Central	643	Mbanyin and Mbaa Mpoano
7	Nyanyano	Gomoa East District	Central	1,920	Nyanyano
8	Bortianor	Ga South Municipal Assembly	G/Accra	1,240	Bortianor
9	James Town	Ashidu Keteke Sub-Metropolitan Area	G/Accra	1,515	Ga Mashie
10	Teshie	Ledzokuku-Krowor Municipal Assembly	G/Accra	1,044	Sangonaa
11	Azizanya	Ada East District	G/Accra	800	Mataheko
12	Dzita	Keta Municipal Assembly	Volta	756	Agledome
13	Vodza	Keta Municipal Assembly	Volta	800	Vodza
14	Agavedzi	Ketu South Municipal Assembly	Volta	744	Agavedzi
15	Adina	Ketu South Municipal Assembly	Volta	1,493	Adina

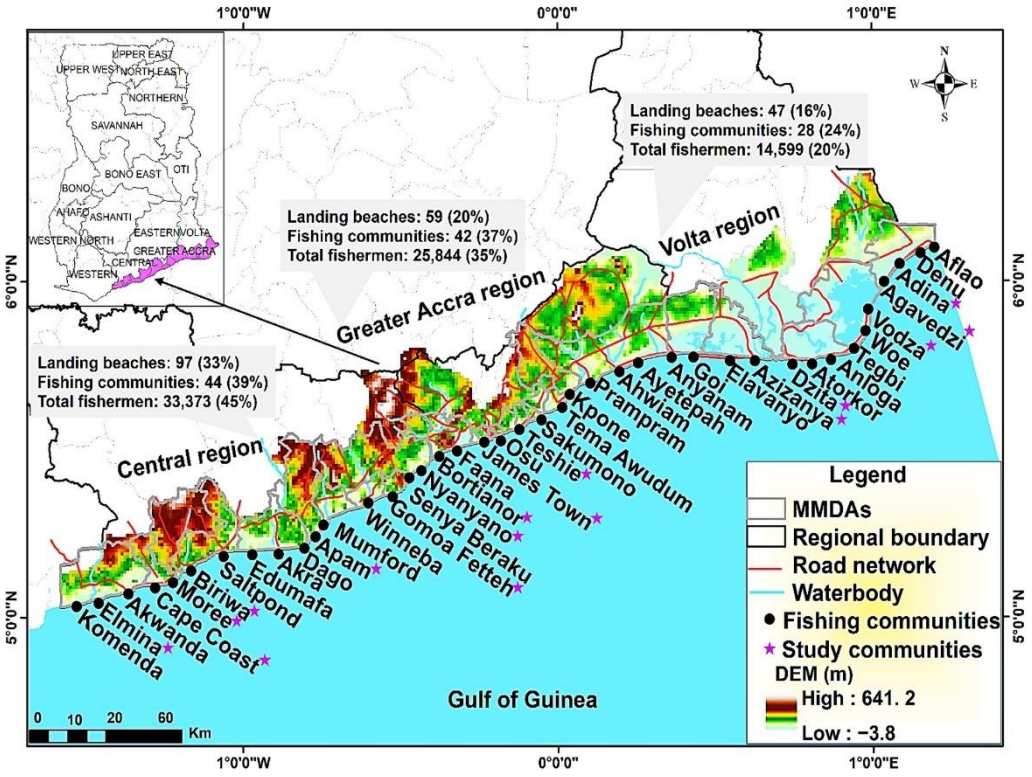


Fig. 1 Map showing the study communities in the Central, Greater Accra, and Volta regions of Ghana. Note: The statistics relating to landing beaches, fishing communities, and the number of fishermen were sourced from Dovlo et al. (2016)

Conceptual and theoretical focus and justification for qualitative research methods

Qualitative research methods have primarily emerged from the disciplines of anthropology, sociology, and the humanities. The existence of multiple perspectives regarding qualitative research poses a challenge in establishing a singular, universally accepted definition (Long and Godfrey 2004; Denzin and Lincoln 2003; Jovanović 2011). However, it is defined by Aspers and Corte (2019) as "an iterative process in which improved understanding for the scientific community is achieved by making new significant distinctions resulting from getting closer to the phenomenon studied". The initial step in the qualitative data analysis process involves the systematic arrangement of data pertaining to a particular subject matter. The identification and interpretation of underlying meanings within the data come next with the intention of improving understanding of the subject at hand (Shin et al. 2009). Creswell (2009) reiterates that qualitative research entails the exploration and comprehension of the interpretations people attribute to a social or human issue. Alasuutari (2010) highlighted the significance of qualitative methods in providing alternative perspectives on social reality, in contrast to the approaches employed in randomised controlled trials and quasi-experimental methods, which primarily focus on examining the relationships between independent and dependent variables. Alasuutari (2010) argues that qualitative research serves a dual purpose: it not only provides contextual information to complement quantitative research designs but also offers diverse perspectives on social reality in order to enhance our understanding of society and its events. Similarly, Tong et al. (2012) assert that the aim of qualitative research is to offer an in-depth understanding of human behaviour, emotions, attitudes, and experiences. As stated by Morse and Field (1996), qualitative research is emphasised as the primary approach for constructing the theoretical underpinnings of the social sciences. Equally, Alasuutari (2010) posits that the advent of qualitative research has led to significant progress in methodological frameworks within the realm of social sciences.

The use of qualitative research methods proves advantageous when investigating inquiries pertaining to the "how" and "why" aspects of social or human phenomena (Kuper et al. 2008; O'Brien et al. 2014). Qualitative research methods encompass various approaches, such as ethnography, phenomenology, case studies, discourse analysis, oral histories, and grounded theory, and employ methodologies such as interviews, focus group discussions, observation (including participant-observation), and document analysis (Harris 2002; O'Brien et al. 2014). As noted by Harris (2002) and O'Brien et al. (2014), each of these approaches and methodologies has its own set of theories and traditions. One of the key advantages of qualitative research and methodologies lies in their ability to offer adaptability and versatility throughout the various stages of data collection and analysis (O'Brien et al. 2014).

Methodology

Data sources and study design

This study exclusively focused on fishermen and did not include related groups such as fish sellers, fish mongers, etc. The choice was made due to the specific elements related to oceanic changes that were incorporated into the semi-structured interview form. The study utilises in-depth interviews and semi-structured interviews to examine the impacts of climate variability on the livelihoods of fishermen in fifteen fishing communities across the central and eastern coasts of Ghana (see Table 1). The data collection methodology employed in this research was informed by the climate-related risk framework established by the Intergovernmental Panel on Climate Change (IPCC 2014) and the sustainable livelihood framework proposed by Chambers and Conway (1992). The data collection period spanned from February to April 2023.

Sampling technique and data collection procedure

There were two separate data gathering processes: one for fishermen in general and one for fishing group leaders. A semi-structured interview was administered to 350 fishermen in each of the 15 communities, for a total of 5,250 participants, using a simple sample selection technique. Yamane's (1967) sample size formula was applied to determine the minimal sample size for the communities. Using Yamane's (1967) formula and assuming a 5% margin of error and a 95% confidence interval, the minimum sample size required for the communities based on the number of fishermen (see Table 1) ranged from 232.64 in Cape Coast to 331.03 in Nyanyano, making the sample of 350 utilised in this study representative.

The participants in the semi-structured interview were randomly selected based on a set of criteria. These criteria included residing in the community and having a minimum fishing experience of 10–20 years. Additionally, participants were required to possess knowledge regarding the impacts of climate variability on coastal environments and fishermen, as well as an awareness of the primary challenges that hindered their fishing activities. The rationale for the selection process was to prioritise fishermen who have demonstrated an established presence within their respective communities over individuals who have recently migrated solely to engage in fishing activities. The participants selected for the semi-structured interview were distinguished from those

selected for the in-depth interview based on two factors: the number of years they had lived in the community and whether they were native to the community. This implies that the fishing leaders for the in-depth interviews needed to be indigenous, but those in the semi-structured interviews did not. The semi-structured interview form consisted of four sections: socio-demographic characteristics, perceived causes of climate variability, perceived climate-related impacts, and alternative livelihood engagement opportunities apart from fishing. The semi-structured interview instrument consisted of a series of open-ended and closed-ended questions, allowing the participants to control the content of their responses and, to some degree, the flow of the interview (Bernard 2017). The completion of a semi-structured interview required a time commitment ranging from 20 to 30 min on average from the participant. Six field assistants were provided with instructions regarding the semi-structured interview form and the use of the KoboToolbox software (https://www.kobotoolbox.org/). The selection of field assistants was characterised by diversity based on the distinct languages such as Fante, Ga-Dangme, and Ewe spoken in the 15 selected communities. The participants were interviewed using mobile phones through KoboToolbox during the period from February to April 2023.

A purposive sampling technique (Campbell et al. 2020) was used to conduct an in-depth interview with 15 fishing group leaders, one from each of the 15 communities. To be considered a fishing leader, one has to be a native (born and raised in the community), have a minimum stay of 40 years within the specific fishing community, operate their own canoe, employ other fishermen, and rely solely on fishing as their primary source of livelihood. The fishing group leaders were identified as key informants due to their significant participation in fishing activities and their extended duration of stay within the community. The interview with fishing leaders encompassed a range of questions, including but not limited to the following: the trend in the annual fish catch; the obstacles encountered; the sufficiency of fishing-related income; the ease of securing bank loans; and alternative sources of livelihoods (Online Resource 1). Prior to commencing the interview, the participant was provided with a consent form that outlined their rights, such as the voluntary nature of the interview and their right to withdraw from the study or request the removal of their previously recorded responses. Anonymity and confidentiality were ensured for the participant through the omission of personal identifying information. The identities of the participants, such as their names, were substituted with the acronyms L1, L2, L3, L4, L5, L6, L7, L8, L9, L10, L11, L12, L13, L14, and L15, followed by the respective communities to which they belonged. For instance, L1: Elimina, L2: Cape Coast, L3: Moree, L4: Biriwa, L5: Apam, L6: Gomoa Fetteh, L7: Nyanyano, L8: Bortianor, L9: James Town, L10: Teshie, L11: Azizanya, L12: Dzita, L13: Vodza, L14: Agavedzi, and L15: Adina, represent the fishing leaders in Elimina, Cape Coast, Moree, Biriwa, Apam, Gomoa Fetteh, Nyanyano, Bortianor, James Town, Teshie, Azizanya, Dzita, Vodza, Agavedzi, and Adina communities, accordingly. The interviews took place in a setting where the participant was encountered, most commonly at home. In cases where the participant was at the shore, the interview was conducted in a location where they had privacy and were not accompanied by any additional individuals. The interview was carried out using the languages that were familiar to the leaders, such as Fante, Ga-Dangme, Ewe, and Twi. The interviews were taped solely upon the agreement of both the interviewer and the participant. Additionally, comprehensive notes were taken, resulting in a cumulative duration of 375 h, with each of the 15 leaders of the fishing groups being interviewed for 25 min. Thus, a total of 5,265 participants were sampled for the study.

Before beginning the interview, we conducted an extensive reflection on positionality and social relations in light of their possible effects on qualitative data collection and interpretation (Holmes 2020). Subsequently, we took an insider (emic ontological perspective) approach since the first author is a native of the study area and was personally involved in the interviews with the participants. The participants regarded the first author as harmless and thus trustworthy (Holmes 2020; Richa and Geiger 2007). This trust meant that the participants were open and honest with the first author about their in-depth experiences. This position also allowed the first author to ask more insightful questions of the participants. Although this positionality has limitations (Holmes 2020; Naaeke et al. 2011), it had no negative impact on the qualitative findings of this study. Instead, it aided in the acquisition of more detailed shared knowledge and experiences among the participants. When transcribing the interviews, we applied an objective, culturally neutral, and impartial approach to the participants' views.

Data analysis

The semi-structured interview data was exported in Excel format and subsequently imported into the Statistical Package for the Social Sciences (SPSS) software (version 26.0) for the purpose of conducting descriptive statistical analysis. At this point, an in-depth comparison of the outcomes was conducted for the 15 communities. The combination of results from the interview data drawn from each of the 15 communities was used to establish a case for the central and eastern coasts, considering the representativeness of the sample.

We followed the qualitative analysis procedure outlined in previous studies conducted by Arku et al. (2012) and Toivonen (2022). The procedure included the creation of themes and constructs, as well as the presentation of qualitative findings

(Arku et al. 2012; Toivonen 2022). Our study specifically examined key factors, including the trend in the annual fish catch, the obstacles encountered, the sufficiency of fishing-related income, the ease of securing bank loans, and alternative sources of livelihoods. Subsequently, an interactive and inductive qualitative approach was used for the purpose of data analysis, with the aim of generating themes and constructs (Arku et al. 2012; Toivonen 2022). The interviews conducted between February and April of 2023 were transcribed verbatim from the local languages into English, ensuring the accurate representation of the participants' words and audio recordings (Braun and Clarke 2012). The first author, a native of the study area, translated the local languages into English verbatim, understanding and recognising the nuances of the language, such as metaphors and words with distinct meanings in a fisheries context. This was confirmed by all the authors. In order to undertake thematic analysis, the interview transcripts were imported into the NVivo 14 software and subsequently coded. Prior to starting the coding process, the first author developed a set of key topics based on the interview transcripts, which were subsequently reviewed and approved by all authors. The first author imported the interview transcripts into the NVivo 14 software and coded all interview responses based on the developed topics. All authors discussed and reviewed this step of the coding process. When there was a discrepancy in a code, the first author recoded interview responses after receiving approval from all authors for a developed topic. The utilisation of thematic analysis offered an organised process for the recognition of common patterns of meaning within the transcripts of the interviews (Braun and Clarke 2012; Toivonen 2022). The themes identified in the codebook (Online Resource 2) were substantiated by direct quotations, which were employed to augment the findings obtained from the semi-structured interview responses.

Ethical considerations

Prior to the start of the study, the research ethics protocol was followed and approval was obtained from the ethics commission of the Faculty of Arts and Humanities at the University of Porto. The research, including the data collection instruments, was reviewed for ethical conformity and to ensure that it did not involve any risk or disadvantage to the participants. This was approved with resolution No. 31/CEFLUP/.

Results

Socio-demographic characteristics of participants

Table 2 shows the socio-demographic characteristics of the 5,250 participants who took part in the study. According to Table 2, a substantial number (41.3%, or 2,170) of the participants are within the age range of 30 to 40 years. Individuals aged over 50 years have the smallest number (7.5%, or 393). Married participants make up the majority (91.3%, or 4,791), while a minority (8.7%, or 459) are identified as single. Once more, the majority of participants (54.8%, or 2,875) have completed primary education, but none of them have completed senior secondary school or higher education. Furthermore, a large number (52.3%, or 2,744) of the participants reveal a household size exceeding 5, while the lowest number (11.6%, or 610) consists of individuals with a household size of 3. Moreover, a plurality number (44.5%, or 2,335) of the participants have been living in their communities for a period of 41–50 years, while a small number (7.5%, or 393) of them have lived in their community for over 51 years. Of the participants, 47.0% (2,469) have engaged in fishing activities for 21–30 years, while only 0.1% (3) have been fishing for 41–50 years.

Perceived causes and knowledge about climate variability

Table 3 depicts the perceived causes and knowledge about climate variability. From Table 3, a significant number of participants (100%, or 5,250) are aware of climate variability. Television is identified as the most common (80.5%, or 4,228) source of climate variability information and the least common (0.3%, or 14) for newspapers. Again, a high number of participants (44.7%, or 2,347) indicates negative human actions as the main driver of climate variability and the lowest 5.4% (282) as God's punishment. Deforestation (71.9%, or 3,776) and the cycles of nature (27.9%, or 1,467) appear as the two most significant contributors to climate variability, against others such as bush burning (0.0%, or 2), urbanisation (0.0%, or 0), and vehicular fumes or carbon monoxide (0.1%, or 5). Table 3 also reveals that negative human actions rank as the second highest cause, after deforestation.

Perceived climate-related and oceanic impacts

Table 4 shows the participants' perceived climate-related and oceanic impacts. According to Table 4, a substantial number (33.5%, or 1,759) of the participants recognise rising temperatures as the most common effect of climate variability over the past 20 years, while storms and waves are recognised as the least common impacts (0.1%, or 3). A large number (52.8%, or 2,774) of the participants once again identify increased levels of CO_2 in the atmosphere as the main factor responsible for the predominant impact of climate variability and the least factor (0.1%, or 3) as sand mining. Furthermore, a substantial number (96.0%, or 5,040) of participants demonstrate awareness regarding

Table 2 Socio-demographic characteristics of participants

Variable	Category	Frequency	Percentage (%)
Age	< 30	637	12.1
	30 – 40	2,170	41.3
	41 – 50	2,050	39.0
	> 50	393	7.5
Gender	Male	5,250	100.0
Marital status	Married	4,791	91.3
	Single	459	8.7
Education	Junior secondary/high school	278	5.3
	Senior secondary/high school	0	0.0
	No formal education	2,097	39.9
	Primary	2,875	54.8
	Tertiary	0	0.0
Household size	2	0	0.0
	3	610	11.6
	4	1,896	36.1
	> 5	2,744	52.3
Length of stay in community	10 – 20	0	0.0
	21 – 30	568	10.8
	31 – 40	1,954	37.2
	41 – 50	2,335	44.5
	51 and above	393	7.5
Years of fishing	10 – 20	694	13.2
	21 – 30	2,469	47.0
	31 – 40	2,084	39.7
	41 – 50	3	0.1

Table 3 Perceived knowledge and causes of climate variability

Variable	Category	Frequency	Percentage (%)
Awareness about climate variability	Yes	5,250	100.0
	No	0	0.0
Sources of information about climate variability	News paper	14	0.3
	Radio	1,008	19.2
	Television	4,228	80.5
Causes of climate variability	Both negative human actions and the cycles of nature	1,416	27.0
	The cycles of nature	1,205	22.9
	Negative human actions	2,347	44.7
	Punishment from God	282	5.4
Factors contributing to climate variability	The cycles of nature	1,467	27.9
	Bush burning	2	0.0
	Deforestation	3,776	71.9
	Urbanisation	0	0.0
	Vehicular fumes/carbon monoxide	5	0.1

the impact of climate variability on fish populations, while a minority (4.0%, or 210) express opposition towards this notion. Additionally, a significant majority (81.4%, or 4,273) of the participants indicate an understanding of the impact of sea surface temperature (SST) changes on fish and fish stocks. However, it is noteworthy that all the participants (100.0%, or 5,250) lack recognition of the

Table 4 Perceived climate-related and oceanic impacts

Variable	Category	Frequency	Percentage (%)
Most common impact of climate variability over the past two decade	Coastal erosion	852	16.2
	Rising temperatures	1,759	33.5
	Sea level rise	1,700	32.4
	Storms and waves	3	0.1
	Unpredictable rainfall	936	17.8
Factors contributing to the most common impacts	High wave energy	6	0.1
	Increased CO_2 concentration in the atmosphere	2,774	52.8
	Sand mining	3	0.1
	Shoreline change	849	16.2
	Warming of the sea	1,618	30.8
Impact of climate change on fish population	Yes	5,040	96.0
	No	210	4.0
Impact of SST on fish and fish stocks	Yes	4,273	81.4
	No	977	18.6
Impact of SSS on fish and fish stocks	Yes	2	0.0
	No	5,248	100.0
Total number of fish caught over the last two decades	Decreased	5,250	100.0
	Increased	0	0.0
Climate variability as the only cause of decreased fish catch	Yes	3	0.1
	No	5,247	99.9
Other factors causing low fish catch	Catching of fingerlings	22	0.4
	Poor fishing equipment	404	7.7
	Many people are fishing	2,523	48.1
	Illegal fishing activities	245	4.7
	More canoes/nets on the sea	770	14.7
	The use of light in fishing	1,196	22.8
	The use of wrong materials/chemicals	87	1.6
Major problems that limit fishing activities	High prices/shortage of premix fuel	3,134	59.7
	High prices of outboard motors	14	0.3
	Insufficient income/financial challenges	773	14.7
	Inadequate government support	33	0.6
	Poor fishing equipment	3	0.1
	The activities of saiko	1,293	24.6

impacts associated with changes in sea surface salinity (SSS) on fish and fish stocks.

All of the participants (100.0%, or 5,250) indicate that there has been a substantial decrease in the total number of fish caught in the area over the past two decades. Participants (99.9%, or 5,247) overwhelmingly agree that factors beyond climate variability are responsible for the decrease in fish catch in the area. Overall, 48.1% (2,523) of participants believe that the decrease in fish catch in the area is due to the high number of individuals engaged in fishing activities, while only 0.4% (22) perceive the catching of fingerlings as having the least impact on the decreased fish catch. A greater number (59.7%, or 3,134) of the participants indicate the high prices or shortages of premix fuel[1] as the major obstacle to fishing activities. A total of 24.6% (1,293) of the participants report engaging in saiko[2] activities, while poor fishing equipment is indicated as the least obstacle with 0.1% (3).

A thematic analysis was conducted from the interview data to understand the fishing leaders' perspectives on climate-related and oceanic impacts. The major themes that emerged encompassed the state of fish caught in the zone, the factors affecting fish catch in the zone, and the major

[1] The term premix fuel refers to a particular blend of oil and gasoline used by fishermen to power their canoes or boats, which is heavily subsidised by the Ghanaian government.

[2] The term saiko refers to trade in fish at sea between industrial trawlers and Ghanaian canoes.

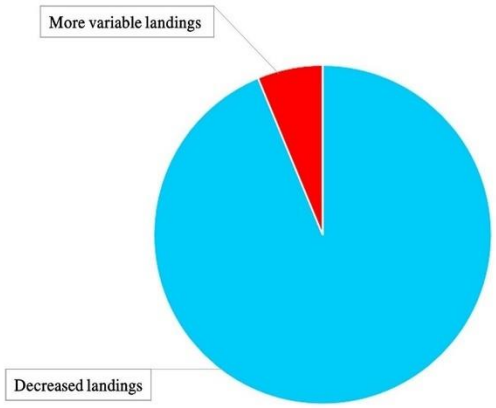


Fig. 2 Hierarchy chart showing the thematic analysis of the state of the fish caught in the zone over the past two decades

The fishing leaders perceive a substantial decrease in the total annual fish catch over the past two decades. This observation complements the responses provided by the participants in the semi-structured interview. On sharing their perspectives on the decreasing fish catch, fishing leaders responses are exemplified in these quotes:

- The annual catch? Oh, it has decreased. We struggle these days to get fish. Sometimes we go to the sea and return with little or no fish, and it is not helping the business (L1: Elmina).
- The amount of fish caught has decreased greatly. The amount and different types of fish we used to catch in the past are not available again (L5: Apam).
- The total annual fish catch has decreased, which should not be blamed on climate change alone but also on the bad attitude of some fishermen (L9: James Town).

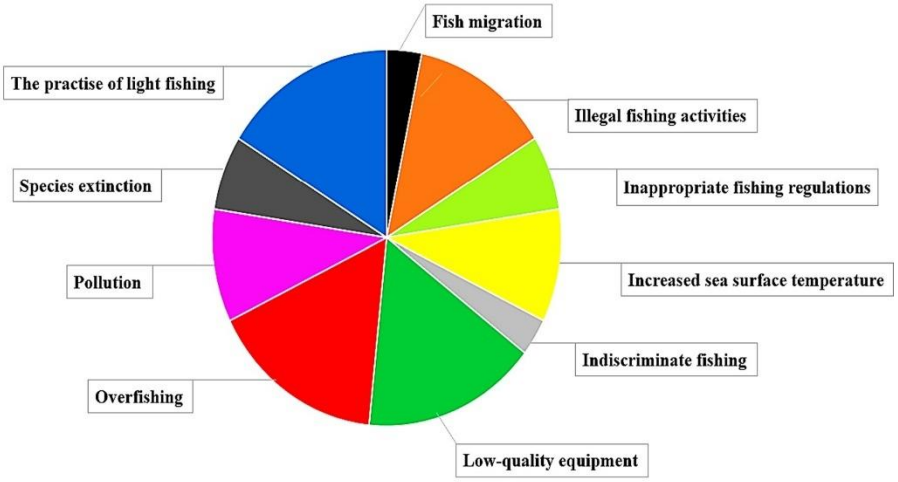


Fig. 3 Hierarchy chart showing the thematic analysis of the factors affecting the fish catch in the zone over the past two decades, along with climate variability

obstacles hindering fishing activities in the zone. The state of fish caught in the zone reflects the trends perceived by the fishing leaders regarding the total annual fish catch over the past two decades. Fishing leaders reported a decrease in the total annual fish catch, along with increased variability. The major obstacles that fishermen encounter in the zone also serve to highlight the challenges that hinder their fishing activities.

One of the main themes that emerged from our in-depth interviews with fishing leaders was a decrease in the total number of fish caught, as presented in the hierarchy chart in Fig. 2.

The main sub-themes that emerged from the analysis of the factors affecting fish catch in the zone were light fishing, overfishing, low-quality equipment, illegal fishing activities, increasing SST, and pollution, as depicted in the hierarchy chart in Fig. 3.

The fishing leaders noted that the aforementioned factors, along with climate variability, have contributed to a decrease in the total annual fish catch over the last two decades, which is again in line with the responses of the semi-structured interview participants.

On the issue of light fishing, fishing leaders stated that:

- One other major thing that is causing the low fish catch is the use of light in fishing. Some fishermen fish with light, which is bad. The light kills the fish. There is a divide among the fishermen on this issue. Some are against the use of light in fishing, like us, while others are in support. For example, if you go to Saltpond, Gomoa Fete, Winneba, or Nyanyano, they will say the use of light in fishing is bad, but it is the opposite in Elmina, Apam, and the Western part of the country. This is complicated. You can go to these communities and find out. We have complained about this, but they will not listen (L3: Moree).
- They fish with light and do not discriminate between fingerlings and mature fish. They catch all of them. The fish like light, and when they see the light in the water, both the fingerlings and mature fish are attracted (L9: James Town).
- We, the fishermen in this area, do not support the use of light in fishing. The light draws both the fingerlings and the mature fish, but they catch them all (L7: Nyanyano).

On the issue of overfishing, fishing leaders shared various experiences, as exemplified in the following quotes:

- Many people are involved in fishing nowadays in many parts of the country, which I think is also a factor (L1: Elmina)
- I would say it is because we have more canoes nowadays, with many people fishing (L11:Azizanya).
- The number of fishermen has increased, and the same is true for the canoes (L15: Adina).

On the issue of low-quality equipment, fishing leaders noted that:

- We do not have trawlers, just these canoes, which cannot operate at deep depths (L1: Elmina).
- We cannot catch them because we use low-powered machines (L6: Gomoa Fetteh).
- It is difficult to catch them, especially with the low-quality fishing equipment we use (L13: Vodza).

The fishing leaders raised several concerns about illegal fishing activities. The following quotes exemplify some of the fishing leaders' major concerns.

- Everything is changing now. Of course, there are some things that we, the fishermen, do that are wrong and may also cause a decreased fish catch. People use chemicals to fish, and what do you expect? (L5: Apam).
- This, I believe, is not only the result of climate change but also of our harmful activities (L14: Agavedzi).
- This does not disregard the harmful activities of some fishermen, particularly those that use chemicals for fishing (L15: Adina).

Some of the fishing leaders raised concerns about the increased SST, which they believe has caused a decrease in fish catch. The following quotes demonstrate some of the fishing leaders' concerns.

- There are several factors contributing to this. One is that when the sea becomes hot [increased sea surface temperature], the fish go deep down and we cannot catch them (L1: Elmina).
- The sea temperature plays a role. Fish neither like too much heat nor too much cold. They like it when the sea is warm. Based on these changes, they either come to the surface or to the bottom of the sea, and this situation affects the total catch (L3: Moree).
- Inform the government that in April or May, when the sea is hot on the surface [increased sea surface temperature] and the fish move to deeper depths, that is when they should close the sea [fishery close season, a Ghanaian government and regional fisheries regulation that prohibits fishermen from going to the sea to protect the environment, preserve aquatic life, and ensure sustainability of oceans and livelihoods]. They should not close it in June or July, when the sea becomes hot beneath and the fish come to the surface, and we can catch them and get more money (L4: Biriwa).

Other fishing leaders also expressed concerns about sea pollution as a factor contributing to the decline in catch, as shown in the following quotes:

- Those involve in the saiko (trade in fish at sea between industrial trawlers and Ghanaian canoes) catch the fish, select the fish type they want, and throw the rest, which are dead, back into the sea. This drives others far away, and we cannot get enough (L7: Nyanyano).
- on the high seas, people catch fish, select what they want, and throw the little dead ones away. They rot and smell bad, and this drives other fish away. They run so far away that we cannot catch them (L11: Azizanya).
- In the past, there was less pollution, and the fish were near and easily caught. They have moved deeper because of sea pollution (L13: Vodza).

As shown in the hierarchy chart in Fig. 4, the main subthemes discovered from the analysis of the major obstacles hindering the fishing leaders' activities in the area were premix fuel price instability and shortages or saiko activities.

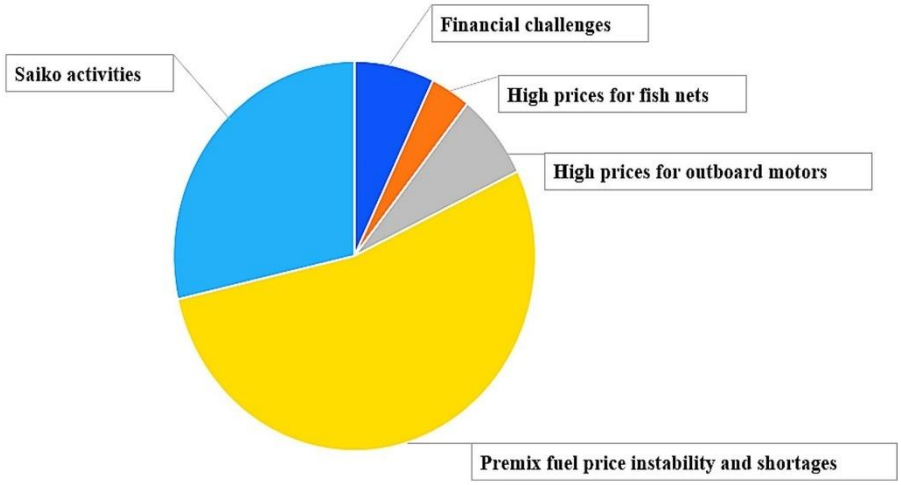


Fig. 4 Hierarchy chart showing the major obstacles that hinder the fishing leaders' activities

Most of the fishing leaders expressed serious concern and worry regarding the instability and shortages of premix fuel prices, which they identified as the main obstacle to their activities. The following quotes demonstrate some of fishing leaders' concerns.

- The premix fuel does not come these days. The small amount that comes is also sold to small people, who keep it and resell it to us at a higher price. A full gallon is 30 GH¢ [Ghanaian cedis], but the controllers sell them at 400 GH¢. We now use the petrol [gasoline] from the car at the station (L2: Cape Coast).
- The premix fuel is a problem. The price is high, and it is not easy to find some to buy. We complain every day, but nobody listens. This limits our activities. It is the fuel that we use to fill the outboard motor attached to the canoe so we can go far on the sea. So, if you do not get some, how can you work? We now use normal petrol, which is expensive, but we have no option. We do not make any profit, but since this is what we do for a living, we cannot stop. In fact, we need help. It seems like no one cares about us, but it is through this activity that we used to cater for the education of our children and the welfare of our families (L5: Apam).
- The premix fuel price is a big concern for me and most of my colleagues here. So, can there be a stable price for it? It keeps increasing, which is not good for our work. Seriously, something better must be done about it. We buy it at a higher price, and when we go to the sea, we do not get enough fish. Those middlemen who are involved in the sale should be stopped. How can there be a middleman in something that is subsidised by the government? What pains me most is that those doing this are not fishermen. The government should help us because, for some of us, fishing is our only means of survival (L13: Vodza).

The issue of saiko activities appeared to be one of the major obstacles that hindered the activities of the fishing leaders, which they raised several concerns about. The following quotes show some of the fishing leaders' concerns.

- The activities of the saiko (trade in fish at sea between industrial trawlers and Ghanaian canoes) are disturbing. It needs to be stopped. Even though our grandparents did not have sophisticated machines, they caught more fish. Some fishermen are from a country that I do not want to mention, but I guess you already know. They operate in our sea, catch the fish and sell them, and throw the dead fingerlings into the sea. This is our biggest challenge, and we would be grateful if this were stopped (L2: Cape Coast).
- We have serious issues with saiko (trade in fish at sea between industrial trawlers and Ghanaian canoes) activities. Last week, they seized the nets of my friends on the sea. These are foreigners who do this to us, which is very bad (L3: Moree).
- The activities of the saiko pose a significant challenge. Those involved are foreigners. They catch the fish, select the type they want, and either sell what they do not want to some of our local fishermen or throw it back into the sea. Those fish thrown back into the sea are always dead, and this drives others far away. They have powerful vessels to go far on the sea, but we use these canoes (L7: Nyanyano).

Table 5 Livelihood opportunities

Variable	Category	Frequency	Percentage (%)
Owns a dwelling place	Yes	1,210	23.0
	No	4,040	77.0
Owns the canoe/boat used for fishing	Yes	840	16.0
	No	4,410	84.0
Has sufficient income from fishing to cater for household's living expenses	Yes	410	7.8
	No	4,840	92.2
Where to find income to supplement a household's living expenses	Borrow from fish sellers	3,813	78.7
	Borrow from relatives	986	20.4
	Others (friends)	45	0.9
An easy process to secure banks loans for fishing activities	Yes	665	12.7
	No	4,585	87.3
Impact of climate change on health	Yes	4,082	77.8
	No	1,168	22.2
Sickness resulting from climate change	Dizziness	437	10.7
	Fever	2,089	51.2
	Headache	1,144	28.0
	Malaria	330	8.1
	Skin rashes/heat stress	82	2.0
Fishing throughout the year	Yes	1,409	26.8
	No	3,841	73.2
Activities engaged in when not fishing	Carpentry	45	1.2
	Construction/mason	489	12.7
	Labourer	72	1.9
	Maintain canoe/boat	194	5.0
	Nothing	340	8.8
	Repair fishing net	2,705	70.4
Activities engaged in help improve livelihoods	Yes	998	26.0
	No response	2,847	74.0

Livelihood opportunities

Table 5 shows the livelihood opportunities of the participants. From Table 5, a substantial number of semi-structured participants (77.0%, or 4,040) do not own their houses, while an even larger number (84.0%, or 4,410) do not own the canoes used for fishing. In a similar manner, the majority (92.2%, or 4,840) of the participants have a household income that is insufficient to meet their needed expenses. Most participants (78.7%, or 3,813) depend on fish sellers as their primary means of borrowing to supplement their household income or maintain their canoes, compared to just 0.9% (45) who do so from friends. Moreover, a substantial majority (87.3%, or 4,585) of the participants encounter challenges when attempting to obtain loans from both public and private banks. A great number (77.8%, or 4,082) of the participants experience negative health impacts as a result of climate variability, with fever identified as the most prevalent illness (51.2%, or 2,089). Additionally, a large number of the participants (73.2%, or 3,841) do not fish throughout the year, and many participants (70.4%, or 2,705) lack alternative livelihood sources Also, a substantial number of the participants (74.0%, or 2,847) expressed dissatisfaction with their current livelihood conditions.

A thematic analysis was conducted from the interview data to understand the fishing leaders' views on their prevailing livelihood prospects. The major theme that emerged was livelihood opportunities of the fishing leaders. The main sub-themes identified include support from fish sellers, bank loan anxieties, insufficient income, and financial challenges, as presented in Fig. 5.

Fish sellers are an important source of financial aid for the fishing leaders, allowing them to satisfy their family expenses while also maintaining their fishing operations. The following quotes illustrate the responses of fishing leaders to this support network:

- I borrow from my customers, those that I sell fish to. I have a good relationship with them, but their money is not enough. I use the money from the fish sellers for

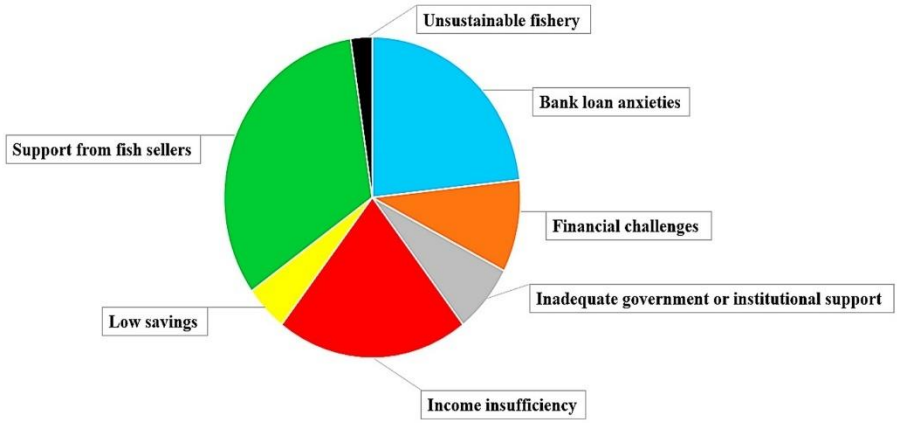


Fig. 5 Hierarchy chart showing the livelihood opportunities of the fishing leaders

household expenses, while that from the savings and loans goes to the fish business, like buying nets and maintenance (L1: Elmina).

- Most of us prefer to borrow from fish sellers. If you fish for a long time and gain the trust of the sellers, they will always be happy to help because they also need the fish. For them, they get the loan easily. I do not know why. Generally, women [fish sellers] do not struggle to get loans. I have some friends in Moree and Saltpond whose wives take the loan for them (L7: Nyanyano).
- Most of my colleagues and I personally borrow from the fish sellers. They are the primary source of borrowing before one could even think of going to borrow from the bank (L8: Bortinaor).
- We can borrow from fish sellers when we do not have money but remember that they also face challenges because they do not have enough money because the more we give them fish, the more they get to lend (L4: Biriwa).

Due to their fears of potential legal repercussions, such as imprisonment, from acquiring bank loans and their inability to meet repayment deadlines, the majority of fishing leaders refrain from obtaining loans. The following quotes exemplify some of the fishing leaders' issues.

- It is not easy. I borrow from a savings and loan [microfinance] company and not from the bigger banks. There is less pressure from them. I save money with them, and that is why they help me (L1: Elmina).
- I do not deal with the banks. My wife and I have joined a susu [savings] group, and we contribute some amount every month. It consists of people in different trade. Together with my wife, we borrow from there to support my activities. We repay with a low interest rate, unlike the traditional bank. They also understand when there is a delay in the payment of the amount borrowed. This has been so helpful to me (L3: Moree).
- It is not easy to get money from the bank as a man. They mostly give them to the women, and we also borrow from them. I do not know why they do not want to give loans to us, the men. I needed a loan to buy more nets, and I had to speak with my wife to go for it for me, but it is the same. I think they trust the women more than the men (L4: Biriwa).
- It is not easy. I will not lie to you, but it is possible to get. The banks demand that you present the details of your business. For example, whether you have a boat or a canoe, your catch numbers, etc. So, you need to take stock of all your activities on paper. Sometimes, they ask for collateral, which most fishermen do not get. There is a lot of detail work to be done, and most fishermen cannot afford it. If you are able to go through it all, they will give you the loan (L9: James Town).

The fishing leaders also experience insufficient income status as a result of the lack of viable alternative sources of livelihood, as shown in the following quotes:

- The income earned from the fish business is not enough. Look, we have worked for four months, but none of us has even 50 GH¢ on us as I speak (L2: Cape Coast).
- The fish business is seasonal. Sometimes you get more fish and make a profit; other times it is the opposite, but generally, I can say that the money you earn is not enough to cater for a household and fishing activities. You need to find additional money somewhere (L11: Azizanya).

- The income I earn these days is not sufficient. It was better in the past because now items are expensive. Also, I do not get enough fish. It is only when you get more fish that you get more money. Yes, if I do not get help elsewhere, how could I survive? I have five children, and two are at the university. I spend a lot on them (L15: Adina).
- There is a low catch. So, how is the income going to be sufficient? The premix fuel alone costs all the money, but I have family to care for (L12: Dzita).

Some of the fishing leaders raised concerns about the financial challenges they encounter as a result of their insufficient income, which limits their capacity to sustain their livelihoods. The following quotes represent some of the fishing leaders' concerns.

- The fishing business is just trial and error. We are in a serious financial situation (L2: Cape Coast).
- Look, there is a problem. Like I said earlier, we have financial challenges (L8: Bortianor).
- I always have debt in front of me (L13: Vodza).

Discussion

This research employed qualitative methods to gain insights into the impacts of climate variability on the coastal livelihoods of fishermen on the central and eastern coasts of Ghana. Given the prevailing climate crisis and its adverse effects on people's livelihoods and general well-being, it is crucial to emphasise the significance of conducting studies that utilise qualitative research methods. Such studies aim to comprehend societal viewpoints and experiences pertaining to this phenomenon. Qualitative research methods serve the purpose of not only supplementing quantitative research designs with contextual information but also providing a range of perspectives on social reality to enrich our comprehension of societal events (Alasuutari 2010). The qualitative method, through its bottom-up approach, has proven beneficial in facilitating the advancement of institutional policy and decision-making as it aids in comprehending societal experiences (Alasuutari 2010).

Using qualitative research methods, this study established that a substantial number of fishermen on the central and eastern coasts of Ghana are aware of the occurrence of climate variability. The findings indicate that broadcast media, specifically television and radio, play a significant role as the main sources of information for these individuals. This finding is consistent with the previous study conducted by Kleinberg and Toomey (2023), wherein a qualitative research approach was employed to comprehend the perspectives of the general public regarding climate variability within the United States. Kleinberg and Toomey (2023) argue that the use of qualitative research methods can facilitate a relational approach to communicating climate variability. This approach emphasises the significance of perceiving science communication as a means to establish connections rather than merely persuade. While previous research by Schmidt et al. (2013) showed that print media, particularly newspapers, have been effective in raising awareness about climate variability across many countries, their use among fishermen on the central and eastern coasts of Ghana has been relatively limited. The increased usage of broadcast media over print media may be attributed to language limitations, as print media predominantly employ the English language, making it challenging for fishermen with limited education to comprehend and read. In contrast, the majority of broadcast media predominantly employ the use of the local dialect for communication purposes. The fishermen's perception aligns with the prevailing scientific literature (IPCC 2014), attributing climate variability largely to negative human actions. The fishermen in the zone widely regarded deforestation as the primary driver of climate variability but were not aware that other factors, such as urbanisation, also played significant roles, as described by Grimm et al. (2008).

Again, the use of qualitative research method has facilitated the understanding of the perspectives and lived experiences of the fishermen in relation to the impacts of climate-related and oceanic events within the zone. The majority of the fishermen within the zone identified the rise in temperatures and sea level as the most common impacts of climate variability. They regarded the rise in atmospheric CO_2 concentrations as the primary factor responsible for the aforementioned impacts. The scientific literature has provided quantitative assessments of the impacts of rising global temperatures and sea levels (IPCC 2021; Nicholls et al. 2014). The fishermen's perspectives and experiences support the earlier study by Lam et al. (2016) that climate variability and SST changes have significant negative effects on fish populations and stocks. The insights and firsthand accounts provided by the fishermen have contributed to a deeper comprehension of their limited knowledge concerning SSS changes and their impact on fish and fish populations. Based on the interactions, it became evident that a substantial number of the fishermen hold the perception that changes in SSS do not have any impact on fish and fish stocks. However, it is important to note that this perception is in direct contradiction to the prevailing consensus within the broader scientific literature. The negative effects of changes in SSS on fish and fish stocks were emphasised by Boeuf and Payan (2001). The fishermen have observed a substantial decrease in the total annual fish catch during the past two decades. The social positions and experiences mentioned are in line with the conclusions of the quantitative study by Lam et al. (2012) that evaluated the potential effects of climate change on fisheries and their implications for economic, food, and

nutritional shortages in the Gulf of Guinea region of West Africa. This statement supports Alasuutari's (2010) assertion that qualitative research methods can be effectively employed to support or confirm a quantitative inquiry. Based on their lived experiences, the fishermen correctly recognised the involvement of many people (overfishing) and the practise of light fishing as the main factors, in addition to climate variability, that contribute to the decrease in the annual fish catch. This finding supports the earlier research conducted by Owusu and Adjei (2021). The fishermen's account of the main obstacles impeding their fishing activities, particularly the high prices of premix fuel or a shortage of it, agrees with previous research conducted by Atta-Mills et al. (2004) and Owusu and Adjei (2021), while providing additional detail for the area of this study.

Furthermore, the use of qualitative methods fostered an understanding of the livelihood realities experienced by the fishermen. The findings from the semi-structured and in-depth interviews indicate that a substantial number of the fishermen expressed dissatisfaction with their livelihood opportunities. The majority of them lack ownership of both their houses and the canoes used for fishing. Consequently, they express dissatisfaction with the level of the income earned from fishing activities to meet their household expenses. The aforementioned results are consistent with the previous study on the livelihoods of small-scale fishermen conducted by Tikadar et al. (2022) in the floodplains of northeastern Bangladesh. Given the challenges associated with obtaining loans from both public and private banks, fishermen often rely on fish sellers as their primary intermediaries for accessing borrowed funds. Ghanaian fish sellers have long been a primary source of funds for small-scale fishermen (Christensen 1977). The challenges faced by fishermen in securing loans from banks could arise from the bureaucratic procedures commonly associated with banks, higher interest rates, and nervousness regarding potential imprisonment resulting from failure to meet repayment obligations. Owusu and Adjei (2021) identified comparable challenges within the fishing communities located in the Western region of Ghana. Based on their shared experiences, it became evident that the fishermen lacked any viable alternative means of earning a livelihood apart from engaging in fishing activities. As evidenced, the majority of fishermen, particularly those located in the Volta region, primarily focus on repairing their fishing nets or engage in non-fishing-related activities during the closed fisheries season, which legally prohibits fishing. Only a limited number of them engage in activities such as carpentry, construction, masonry, and general labour during this period. According to Matera (2016), the implementation of alternative livelihood options has proven to be highly advantageous for fishermen, as observed in the case of Providencia and Santa Catalina islands in Colombia.

Coastal livelihood policy implications

This qualitative inquiry highlighted some coastal livelihood policy implications that should be taken into consideration in the management of coastal zones in Ghana, with the aim of safeguarding and protecting the livelihoods of fishermen and small-scale fisheries as a whole. Considering the findings of the study, policymakers have the opportunity to implement innovative plans by collaborating with fishermen, coastal zone managers, and planners.

To begin with, the study suggests the development of viable alternative livelihood opportunities for the fishermen operating on the central and eastern coasts of Ghana. Given the restrictions imposed by regulations that prohibit fishermen from engaging in fishing activities throughout the year, it is imperative that they possess alternative sources of income to sustain themselves, their households, and their fishing activities. The implementation of a diverse range of alternative livelihood options has the potential to mitigate the issues of overfishing, light fishing, and chemical usage in the coastal waters of Ghana. The development of alternative livelihood options in the central and eastern coasts of Ghana can serve as a pilot effort for assessing the behaviour and attitudes of fishermen, with the aim of determining their level of acceptance. This pilot study can subsequently be expanded to encompass other fishing zones within Ghana.

The study's findings suggest that the Ministry of Fisheries and Aquaculture Development in Ghana plays a crucial role in maintaining price stability and ensuring the reliability of premix fuel, thereby safeguarding the fishing sector. The fishermen expressed their dissatisfaction regarding the price changes and shortages of premix fuel, resulting in their adoption of normal gasoline as an alternative. The premix fuel subsidy initiative represents a commendable policy directive implemented by the government that warrants continued support and maintenance. Nevertheless, it is imperative to alleviate the intricacies and bureaucratic procedures associated with its implementation. It is recommended that the government establish direct communication channels with fishermen, specifically through the chief fishermen and other leaders within fishing groups. This approach would bypass intermediaries from outside the fisheries sector who engage in fuel hoarding and subsequently resell it to fishermen at inflated prices.

Moreover, the implications of the study's findings suggest that it is important for the government to implement effective measures aimed at curbing high-sea transhipment or saiko activities. This is one of the primary challenges that impedes the operations of fishermen on the central and eastern coasts of Ghana, and the regulation of these activities would have a direct benefit for local fishermen. The presence of foreign fishermen using advanced and sophisticated fishing vessels within the coastal waters of Ghana has a detrimental impact

on the small-scale fishermen operating in the zone, as their livelihoods are entirely dependent on fishing activities.

Conclusion

The study's findings indicate that the use of qualitative research methods in the context of climate variability and coastal livelihoods plays a significant role in the generation of knowledge and the enhancement of understanding regarding complex societal events. The use of qualitative research methods in this study has facilitated the acquisition of valuable insights into the lived experiences of the fishermen operating within the central and eastern coasts of Ghana. These insights reflect their knowledge and awareness of climate variability, the climate-related and oceanic impacts on their fishing activities, as well as the prevailing conditions of their livelihoods. The findings of the study support the broader literature consensus that qualitative research methods not only complement quantitative research designs by providing contextual information but also offer a range of perspectives on social reality that enrich our understanding of society and its events.

The predominant impacts of climate variability in the zone over the past two decades have been the rise of sea temperatures and sea levels. These impacts are primarily due to the increased levels of CO_2 in the atmosphere (IPCC 2014). The fishermen possess a better understanding of the impacts of climate variability and SST changes on fish and fish populations. However, their knowledge regarding the impacts of SSS changes in this context is insufficient. The lack of awareness among the fishermen about the impacts of SSS on fish and fish stocks surprised the authors. Their assertions regarding the decreasing annual fish catch over the past two decades were substantiated and consistent with previous quantitative studies conducted in the area. The decrease in annual fish catch in the area can be attributed primarily to overfishing and the practise of light fishing, along with climate variability. The fishermen encounter significant challenges in their activities due to the presence of high prices and shortages of premix fuel, as well as the prevalence of saiko activities. The fishermen express dissatisfaction with the current conditions of their livelihood, which are marked by many constraints.

The study's findings possess the capacity to contribute to the development and execution of appropriate policies aimed at enhancing the well-being of fishermen in the coastal zones of Ghana. There is a need for a policy initiative that prioritises providing practical training and support for fishermen to participate in additional livelihood activities such as agriculture (crops, livestock, and poultry), small business, occasional wage labour, and handicrafts. Fishermen in Port Antonio, Jamaica, Mtwara district, southern Tanzania, and the Providencia and Santa Catalina islands in Colombia have effectively utilised the above-mentioned alternative livelihood opportunities (Epstein et al. 2022; Katikiro 2016; Matera 2016), and Ghanaian policy decision-makers can prioritise these activities for fishermen. The study suggests that qualitative research methods should be regarded an effective approach for improving the livelihoods and general well-being of coastal communities. This study's limitations include its exclusive focus on only fishermen and no related groups such as fish sellers and fish mongers. Further research that examines the livelihood conditions of all fishing-related groups in the face of climate variability would be beneficial for the area.

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Author contributions Johnson Ankrah: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – Original draft preparation, Writing-Review and Editing. Ana Monteiro: Writing-Review and Editing, Supervision. Helena Madureira: Writing-Review and Editing, Supervision.

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Data availability Not applicable.

Declarations

Ethics approval The ethics commission of the Faculty of Arts and Humanities at the University of Porto provided approval for the conduct of the study with resolution No. 31/CEFLUP/.

Informed consent The research ethics commission of the Faculty of Arts and Humanities at the University of Porto reviewed and provided approval for the data collection instruments used in the study. Prior to the start of the interview, the participant was provided with a consent form that outlined their rights as a participant, such as the voluntary nature of the interview and their prerogative to withdraw from the study or request the removal or deletion of their previously recorded responses.

Competing interest The authors declare no competing of interest.

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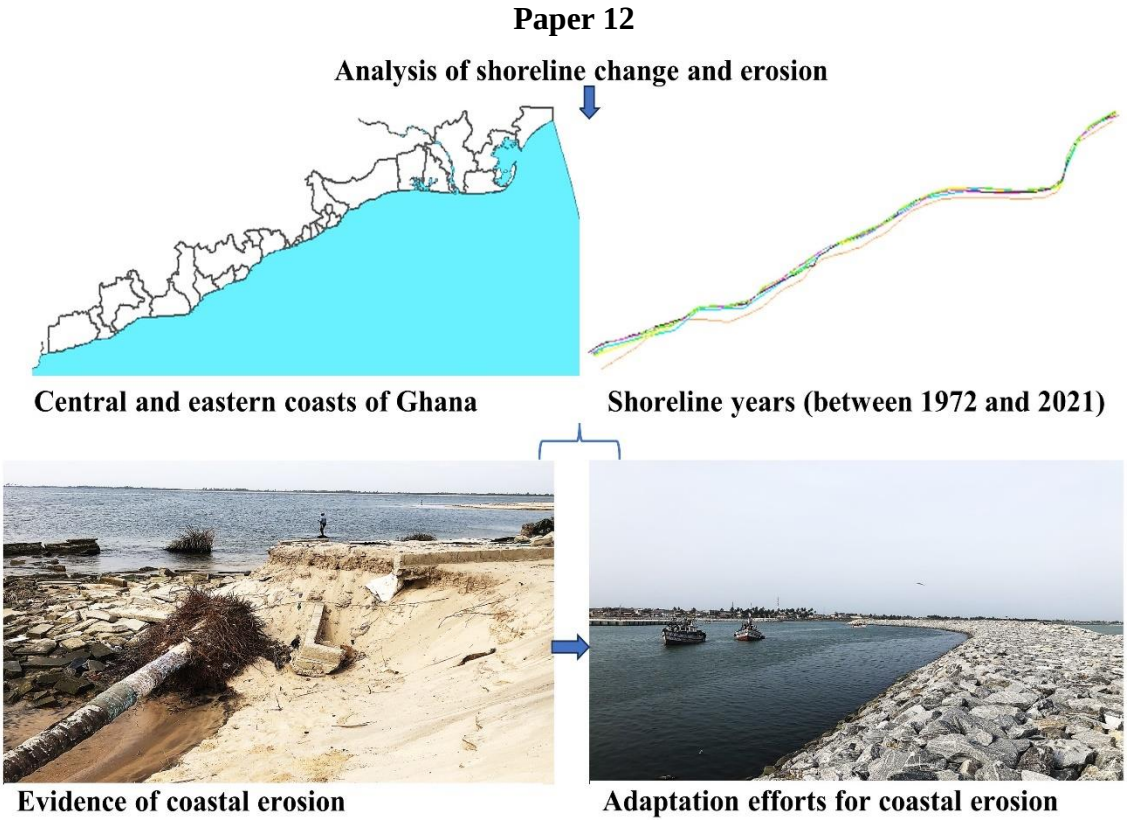
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CHAPTER 6: Analyses the influence of climate change on shoreline change and the impacts of erosion on the ecosystems and their implications on the communities in the coastal savannah agroecological zone of Ghana

6.1. Shoreline change and coastal erosion: an analysis of long-term change and adaptation strategies in coastal Ghana

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RESEARCH

Shoreline change and coastal erosion: an analysis of long-term change and adaptation strategies in coastal Ghana

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Abstract
This study analysed long-term shoreline change, the influence of erosion, and adaptation strategies in coastal Ghana. The change between 1972 and 2021 was analysed using Landsat satellite images and the Digital Shoreline Analysis System (DSAS v.5.0), and adaptation strategies were revealed through field observations. The End Point Rate (EPR), Linear Regression Rate (LRR), and Weighted Linear Regression (WLR) were used to estimate the rate of change, whereas the Net Shoreline Movement (NSM) and Shoreline Change Envelope (SCE) were used to calculate the distances of change. The coefficient of shoreline armouring (K) index was used to evaluate the grade of artificial or human interventions on the coast. The erosion rates for the EPR (– 107.6 m/year, or 95.0%) and LRR (– 75.7 m/year, or 99.3%) were higher than the accretion rates of (28.5 m/year, or 5.0%) and (33.6 m/year, or 0.7%), respectively. The NSM recorded maximum erosion (– 14,080 to – 10,840 m) and accretion (1107 to 2135 m) with an average distance of – 4943.1 m. The SCE estimated a maximum (14,080.5 m) and minimum (813.8 m) distances with an average distance change of 5557.9 m. The central coast experienced erosion at average rates of – 119.0 m/yr, – 89.6 m/yr, and – 94.0 m/yr, according to EPR, LRR, and WLR statistics. The eastern coast observed lower erosion rates than the central coast, with rates of – 75.3 m/yr, – 53.2 m/yr, and – 41.9 m/yr for the EPR, LRR, and WLR statistics, respectively. Since 1972, there has been a significant increase in artificial coastal structures on Ghana's central and eastern coasts. The central coast has reached a maximal level of shoreline armouring index, while the eastern coast has reached a minimal level. Although hard protective measures have been implemented on most parts of the coast for adaptation, improved policy initiatives on soft and nature-based protection measures are encouraged based on their favourable ecological impact and economic effectiveness.

Keywords Coastal erosion · Shoreline change · DSAS · Remote sensing · Coastal armouring · Coastal adaptation

Introduction

Coastal zones have always been the preferred locations for human settlement throughout history (Barragán and Andrés 2015; Ferreira et al. 2021; Nijamir et al. 2023). Coastal areas offer enhanced benefits, including tourism, recreational opportunities, fishing, employment prospects, industrial and commercial activities, and the provision of habitats for marine species, among other factors (Barragán and Andrés 2015; Bera and Maiti 2019; Ferreira et al. 2021; Kılar 2023). Small and Nicholls (2003) estimate that more than 30% of the world's population lives on or near the coast. The increased human concentration along the world's coastal regions has exerted substantial pressure on vital resources, particularly the shorelines (Ferreira et al. 2021; Jonah et al. 2016; Ülger and Tanrıvermiş 2023). As reiterated by Nijamir et al. (2023), the susceptibility of the world's shoreline increases as human concentration and related activities increase at the coast. The condition of shorelines worldwide is deteriorating due to the effects of global climate change and related sea level rises, which result in impacts including coastal flooding, wave activity, and storm surges (Saddam et al. 2023). According to Bamunawala et al. (2021), the cumulative effects of climate change, associated sea level

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rise, and human activities will cause 90% of the world's shoreline to retreat.

The greater threats posed by climate change and human activities to the world's coastal regions and related shorelines have resulted in the development of suitable methods, data resources, and tools for the analysis, detection, and quantification of shoreline change (Ankrah et al. 2022; Boak and Turner 2005). The techniques for detecting shoreline change have witnessed significant advancements, accompanied by a notable expansion in the range of available data sources (Ankrah et al. 2022; Boak and Turner 2005; Zanutta et al. 2020). The tools used for analysing shoreline change rates have experienced significant advancements, particularly with the advent of computer technology in the 1970s and the subsequent development of Geographic Information Systems (Ankrah et al. 2022; Burningham and Fernandez-Nunez 2020). There has been a substantial improvement in the availability of tools for analysing changes in shorelines. These include the different versions of the Digital Shoreline Analysis System (DSAS) (Danforth and Thieler 1992; Himmelstoss et al. 2018, 2021; Thieler et al. 2003, 2005, 2009), ArcGIS/ArcMap, and QGIS, etc.

The negative impacts of climate change and anthropogenic activities cause the position of shorelines to change, which either results in erosion or accretion of the coast (Siyal et al. 2022; Mageswaran et al. 2021; Munasinghe and Warnasuriya 2023). According to the findings of Luijendijk et al. (2018), 24% of the global sandy beaches have been eroded at rates beyond 0.5 m per year (m/yr), while 28% have been accreted, and 48% have been stable over the last three decades. There has been a substantial increase in research on shoreline change and erosion across many coastal regions (e.g., Bera and Mati 2019; Dawson 2021; Ferreira et al. 2021; Kılar 2023; Nijamir et al. 2023; Saddam et al. 2023; Siyal et al. 2022; Stanchev et al. 2018). The increased research efforts have contributed to an improved understanding of the dynamic nature of shorelines and their consequential impacts on coastal regions, hence facilitating the implementation of more effective strategies for coastal management and adaptation (Ankrah et al. 2023; Charuka et al. 2023a). Researchers widely acknowledge the importance of adapting to coastal risks, such as shoreline change and erosion (das Neves et al. 2023; Evadzi et al. 2017; Pais-Barbosa et al. 2023). Adaptation is thus considered a crucial process as it plays a significant role in reducing vulnerabilities and enhancing the resilience of both communities and ecosystems (Charuka et al. 2023a; Kirby et al. 2021).

The shoreline of Ghana, spanning approximately 550 km, is currently facing significant challenges due to the adverse effects of climate change and human activity (Evadzi et al. 2017). Ghana's shoreline is changing, causing coastal erosion that impacts communities, resources, and ecosystems. However, few research studies, including those by Abdul-Kareem et al. (2022), Angnuureng et al. (2022), Appeaning Addo et al. (2020), Appeaning Addo (2014), Appeaning Addo et al. (2011), Appeaning Addo et al. (2008), Boye et al. (2018), Jayson-Quashigah et al. (2013), Jonah et al. (2016), Lamptey et al. (2022), and Mann et al. (2023), have analysed the changing shoreline of Ghana's coast. These studies are relevant; however, they are limited to small portions of Ghana's shoreline. For example, Abdul-Kareem et al. (2022) examined only a small part of the Apam beach. Angnuureng et al. (2022) researched a limited area within Elmina Bay. Accordingly, Appeaning Addo et al. (2020) studied the shoreline changes in the Volta River estuary. Mann et al. (2023) studied shoreline change along Ghana's eastern coast, focusing specifically on the small area of Keta and not addressing the remaining parts of the shorelines along the eastern coast. Few studies, such as the ones conducted by Digital Earth Africa (2020), have investigated the changes in the shoreline along the central and eastern coasts of Ghana. Although Digital Earth Africa (2020) has made a significant effort, there is still a dearth of knowledge regarding the specific adaptation strategies being implemented on the central and eastern coasts of Ghana. This study aims to address the substantial lack of knowledge regarding shoreline change and erosion influence on Ghana's central and eastern coasts, which span around 465 km out of the total 550 km of shoreline. Again, there is a lack of understanding of coastal erosion and potential adaptation strategies along Ghana's central and eastern coasts. The present study is essential due to the limitations of previous studies on small portions of the shoreline, which could impede policy-making decisions. There is also a lack of comprehensive discussion on the specific adaptation strategies implemented either by the local coastal communities or by policy initiatives to address shoreline change and erosion along the coast (Gbedemah 2023). Ankrah et al. (2023) emphasised the limited integration of remote sensing and field observation methods in assessing shoreline change and erosion along the West African coast. Although remote sensing techniques play a crucial role, it is important to complement them with field observation for enhanced policy decisions (Ankrah et al. 2023).

Therefore, the aim of the present study is to analyse long-term shoreline change, the influence of erosion, and adaptation strategies on Ghana's central and eastern coasts using remote sensing and field observation techniques. The remote sensing techniques employed were multitemporal Landsat satellite images (Landsat MSS, TM, ETM+, and OLI_TIRS), and the field observation techniques used were photography surveys and site descriptions. The study specifically analysed the long-term shoreline change of the central and eastern coasts between 1972 and 2021 using the End Point Rate (EPR), Linear Regression Rate (LLR), Weighted Linear Regression (WLR), Net Shoreline Movement (NSM),

and Shoreline Change Envelope (SCE). This study first performed the long-term shoreline change analysis for the entire (both the central and eastern) coast, then for segments 1 (the central coast) and 2 (the eastern coast). The study focused on an extended temporal period of shoreline development (from 1972 to 2021) in order to provide valuable insights for policy-making decisions. These statistical parameters are essential and relevant to the study findings, as they aid in understanding the distances of change (i.e., NSM and SCE in m) and the rate of change (i.e., EPR, LRR, and WLR in m/yr) (Ayalke et al. 2023; Himmelstoss et al. 2021) in relation to the erosion or accretion of the coast. Also, the study computed a specific shoreline armouring index (Aybulatov and Artyukhin 1993) to analyse the human interventions on the coast during the period from 1972 to 2021. Field observation techniques, such as photography surveys and site descriptions, supplemented the aforementioned analysis, revealing the impact of erosion on coastal resources and offering evidence of coastal adaptation options.

Study area

Ghana is located in West Africa, with a shoreline that extends for approximately 550 km (Evadzi et al. 2017). The coast of Ghana is categorised into three distinct regions, namely western, central, and eastern, which are differentiated based on their geomorphological characteristics (Boateng et al. 2017). The coast is defined by the administrative regions of Western, Central, Greater Accra, and Volta (Charuka et al. 2023a). The primary focus of this study was on the central and eastern coasts, covering the entire Central, Greater Accra, and Volta regions (Fig. 1a). Most parts of Ghana are within the Precambrian (Fig. 1b). The metamorphosed and folded Birimian, Tarkwaian, the Togo series, the Dahomeyan formation, and the Buem formation are the major Precambrian rock units in Ghana (Abu and Sunkari 2020; Darko et al. 2019). On the central coast, rock units of the Precambrian, Mesozoic, and Paleozoic ages dominate (Bansah et al. 2014). The central coast has discontinued beaches as a result of the persistent activities of the adjacent highlands, consisting of igneous, metamorphic, and sedimentary rocks of crystalline and clastic nature (Abu and Sunkari 2020; Ly 1981). The Cape Coast basin largely covers the central coast with metamorphic and sedimentary rocks, influencing the sediment load on this coast (Abu and Sunkari 2020). The rocks on the central coast are resistant to the tidal wave action of the sea, except for a few shales and sandstones (Ly 1981).

The central coast of Ghana has the most extensive shoreline, measuring around 316 km (Charuka et al. 2023a). This coastal region stretches from the eastern portion of Sekondi-Takoradi to the western area of Prampram in the Greater Accra region (Boateng et al. 2017). The shoreline has a medium-energy environment and is characterised by embayed coasts, rocky headlands, rocky shores, littoral sand barriers, and enclosing coastal lagoons (Boateng et al. 2017; Charuka et al. 2023a). Ly (1980) observed that wave attacks along the central shoreline resulted in the exposure of igneous, sedimentary, and metamorphic rocks from the Precambrian, Paleozoic, and Mesozoic eras, in addition to unconsolidated Quaternary sediments. According to Boateng (2012), the geological and geomorphological features of the coast play a crucial role in determining its resistance to erosion and related processes. For instance, the presence

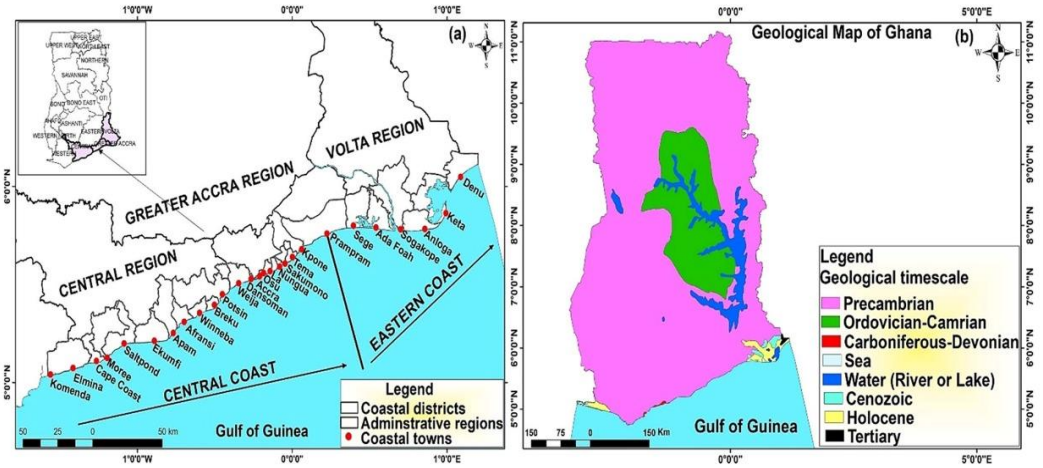


Fig. 1 Map showing the location of the central and eastern coasts **(a)** and the geological timescales **(b)** of Ghana. Note: To construct Ghana's geological timescales, the study obtained Africa's surficial geology from the United States Geological Survey (USGS 2002)

of metamorphic and sedimentary rocks resists tidal waves and minimises coastal erosion, as highlighted by Abu and Sunkari (2020) and Ly (1981).

The eastern coast covers a distance of about 149 km, extending from the east of Prampram to the border of Aflao with the Republic of Togo (Charuka et al. 2023a). This section of the shoreline is a high-energy coast, as indicated by the presence of wave heights often greater than 1 m in the surf zone (Boateng et al. 2017; Ly 1980). It has a sandy shoreline, which is characterised by the erosive impact of the Volta River estuary's deltaic influence (Charuka et al. 2023a; Ly 1980). Although Precambrian rock units are found on the eastern coast, they are covered by Cenozoic, Holocene, and Tertiary rock sediments as well as sediments from water (river or lake) (Fig. 1b). As highlighted by Benneh and Dickson (1988), there is a dominance of quaternary rock units consisting of fine sand, gravel, and clay on this coast.

Aside from the geology of the coast, other factors, including wave direction, currents, and land use, also play a considerable role in the shoreline change and erosion of the coast. As reiterated by Appeaning Addo (2011), coastal morphological dynamics basically result from climatic factors and physical processes that are aggravated by anthropogenic activities. Appeaning Addo (2011) asserts that geology aids these processes. The effects of wind action on shoreline geomorphology are direct and indirect (Appeaning Addo 2011; Gardner 2020; Pappalardo et al. 2017). Winds with strong intensity and direction reduce fine-grained sediments from beaches, which lower their surfaces, and direct rock particles onshore, alongshore, and offshore (Bird 2008). For instance, waves that advance to the coast of Accra have a south-southwest direction, as revealed by Appeaning Addo (2015) and Amoani et al. (2012). Appeaning Addo (2009) stressed strong wind-produced waves as a key cause of shoreline change. Tidal currents also pose a substantial influence on sediment size and patterns on most seafloors (Appeaning Addo 2011; Qin et al. 2018). Land use change and other human interventions also influence shoreline change and erosion of coasts (Dada et al. 2019; Islam et al. 2021; Misra and Balaji 2015; Prosser et al. 2018; Samanta and Paul 2016). Misra and Balaji (2015) reported a significant shoreline erosion due to an increase in agricultural activities, urban settlements, and bare lands and a decrease in mudflat coverage as a result of urbanisation in the coastal areas of southern Gujarat, India. On the Mahin mud portion of the Nigerian coast, Dada et al. (2019) found that marine and human influence are responsible for the erosion on the coast, despite the increased wave climate actions.

Shoreline change and erosion have been observed on the central and eastern coasts of Ghana. The issue of expanding human habitation around the mouth of the Volta River was acknowledged as a significant concern by Ly (1980). According to Ly (1980), the increased erosion observed in these portions of the coast can be traced to the construction of the Akosombo dam in 1961. This infrastructure development substantially reduced the supply of sand from the river, therefore exacerbating the erosion process. Ly (1980) further asserts that shoreline change in the central and eastern coasts of Ghana can be attributed to the removal of sand from the unconsolidated Quaternary sediments found along the shoreline. This sand is then relocated to the littoral zone in order to compensate for the loss of sand produced by longshore transport (Ly 1980).

Materials and methods

Data acquisition and processing

The shoreline change along the coast was analysed using multitemporal Landsat satellite images. The Landsat images used were obtained from the United States Geological Survey (USGS) Global Visualisation Viewer (GloVIS) website (https://glovis.usgs.gov/), which includes Landsat MSS (1972/11/11), TM (1984/09/11, 1990/12/25), ETM + (2000/12/04, 2010/12/16), and OLI_TIRS (2020/08/13, 2021/01/11). Figure 2a–c show the shoreline years of the entire (both the central and eastern coasts) and segments 1 and 2. The images used were a radiometrically and geometrically corrected Level-1 Terrain (L1T) product for the period 1972–2021. The shoreline along the central and eastern coasts spans about 465 km. For each shoreline year, two satellite image scenes were provided (Online Resource 1). ArcGIS 10.8 was thus used to mosaic and merge the satellite images (Görmüş et al. 2021; Ozturk and Sesli 2015). The study used the Normalised Difference Water Index (NDWI) (Gao 1996) to delineate the water-land boundary, as previously done by Siyal et al. (2022). The NDWI method was thus employed for band 6 Near-Infrared (NIR) and band 4 (Visible Green) on the 1972 image (Landsat 1–3, MSS), band 4 (NIR) and band 2 (Visible Green) on the 1984 and 1990 images (Landsat 4–5, TM) and that of the 2000 and 2010 (Landsat 7, ETM +), and band 5 (NIR) and band 3 (Green) on the 2020 and 2021 images (Landsat 8, OLI_TIRS). As highlighted in earlier studies such as those conducted by Feyisa et al. (2014), Fisher et al. (2016), Laksono et al. (2023), and Xu (2006), the NDWI index ensures stability in delineating the water-land boundary and minuses built-up land noises. In order to delineate the water-land boundary, a positive water pixel value with an ideal threshold of zero (0) was applied to all water-land boundary classes (Cao et al. 2020; Laksono et al. 2023; Xu and Gong 2018). Three classes of NDW were utilised, which included zero (0) for land, one (1) for water, and no data for areas that had cloud cover. The NDWI of all satellite images was estimated based on the parameters in Eq. (1) (Laksono et al.

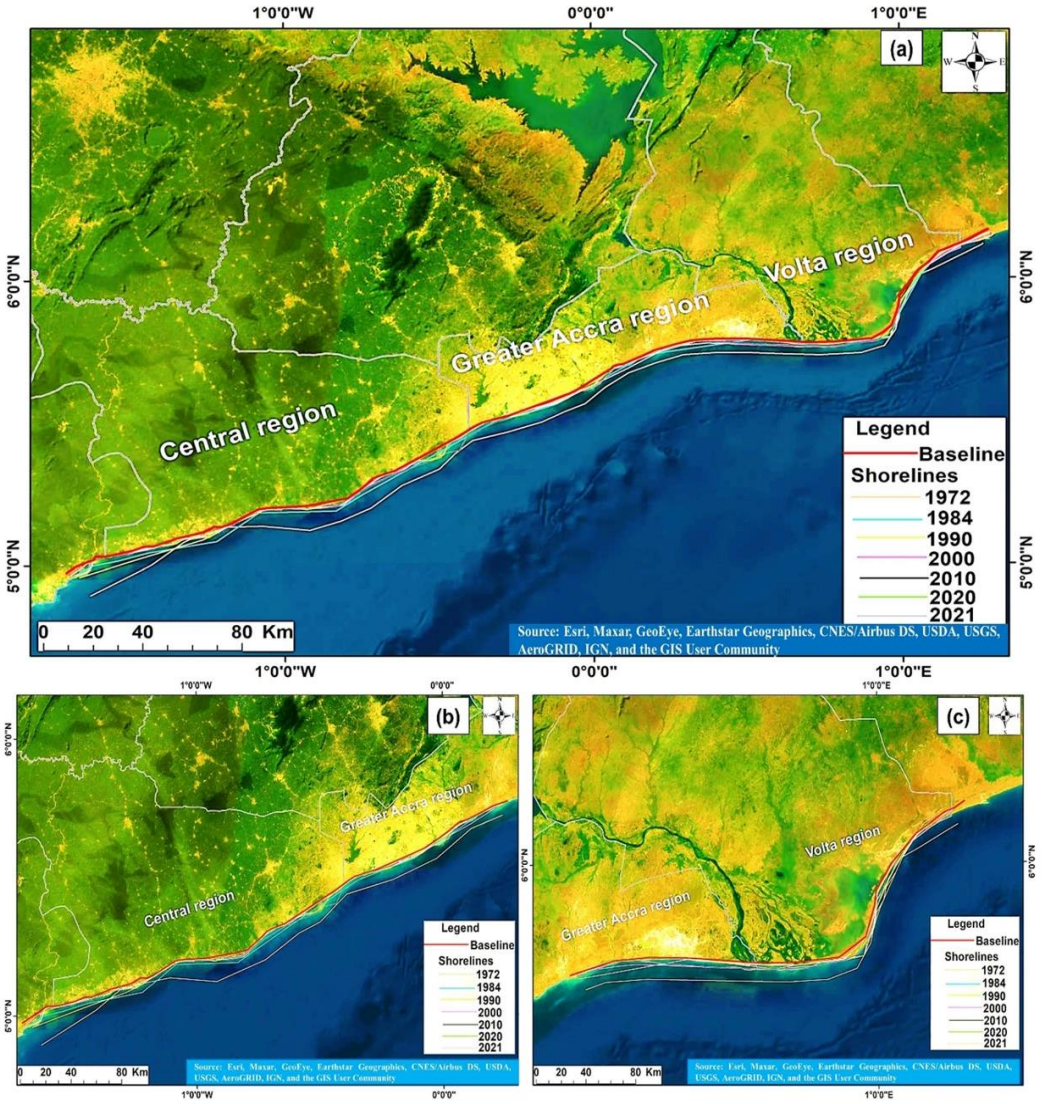


Fig. 2 Shorelines of the 1972, 1984, 1990, 2000, 2010, 2020, and 2021 of the entire coast **(a)** and segments 1 **(b)** and 2 **(c)**

2023; McFeeters 1996; Xu 2006), and all shoreline years were carefully digitalized in ArcGIS 10.8. The extracted shorelines were exported to the DSAS in vector (shapefile) format for shoreline change analysis.

$$NDWI = \frac{Green - NIR}{Green + NIR} \quad (1)$$

where

NDWI is the Normalised Difference Water Index; *Green* represents band 4 (Landsat 1–3, MSS), band 2 (Landsat 4–5, TM and Landsat 7, ETM+), and band 3 (Landsat 8, OLI_TIRS); and *NIR* shows band 6 (Landsat 1–3, MSS), band 4 (Landsat 4–5, TM and Landsat 7, ETM+), and band 5 (Landsat 8, OLI_TIRS).

Shoreline uncertainty analysis

The uncertainties related to each shoreline position were examined. The uncertainties associated with each shoreline year are summed together to yield a total value (Dawson 2021; Fletcher et al. 2003). Based on the satellite images used, several sources of uncertainty can be identified,

including digitalization of shoreline position (E_d), image rectification (E_r), image resolution (E_p), seasonal change (waves) (E_s), tidal fluctuations (E_t), and cloud (E_c) (Dawson 2021; Ferreira et al. 2021; Fletcher et al. 2003; Munasinghe and Warnasuriya 2023). However, there was no uncertainty about image rectification in this study because all satellite images were rectified and referenced by the UTM 30N projection and the WGS 84 as datum (Görmüş et al. 2021). To avoid uncertainty caused by seasonal changes, the study used only satellite images from low tide (dry season) seasons to improve visibility of the shoreline (Kılar 2023; Saddam et al. 2023; Siyal et al. 2022). According to the previous studies of Abdul-Kareem et al. (2022), Appeaning Addo (2013), and Evadzi et al. (2017), the tidal range for Ghana's coast is 1 m, which is small and is not considered when estimating the uncertainty of the shoreline. Although the tidal range is within 1 m, it can become significant at beaches with flat slopes (Athanasiou et al. 2019). Thus, such a tidal correction is not necessary. In addition, images downloaded during the dry season were cloud-free. The study used images with a cloud cover of less than 20% (Laksono et al. 2023; Quang et al. 2021). For instance, the images from 1972, 1984, 1990, 2000, 2010, 2020, and 2021 had cloud cover values of 16.00%, 5.00%, 7.00%, 18.00%, 14.00%, 0.01%, and 14.06%, respectively. As a result, three sources of uncertainty were identified in this study: digitalization of shoreline position (*Ed*), image resolution (*Ep*), and tidal fluctuations (E_t). Uncertainties regarding the *Ed*, *Ep*, and *Et* are points of concern (Fletcher et al. 2012; Görmüş et al. 2021; Islam and Crawford 2022). The uncertainties associated with the *Ed* emerged from the manual digitalization of shoreline positions from visual scrutiny (Islam and Crawford 2022). By digitalizing the shoreline positions manually and with possible errors, this study adopted an uncertainty value of ± 0.5 m for each shoreline. The uncertainty of the *Ep* is related to the spatial (pixel) resolution of the satellite imagery (Görmüş et al. 2021; Islam and Crawford 2022). All satellite imagery used in this study had a spatial resolution of 30 m, except for the 1972 imagery, which had a 60 m resolution. According to Fletcher et al. (2012), tide-related changes in shoreline positions contribute to the uncertainty of the E_t. Therefore, this study adopted an uncertainty value of ± 0.5 m for the E_t for each shoreline. The uncertainties (*U*) for each shoreline are determined as the square root of the sum of the squares of the identified uncertainties (Dawson 2021; Fletcher et al. 2003; Hapke et al. 2011). The total uncertainties (*TU*) for each shoreline position were thus calculated following the parameters in Eq. (2) (Ferreira et al. 2021; Hapke et al. 2011), with the results displayed in Online Resource 1. These uncertainties aided in the estimation of the shoreline change rate for the individual transects (*U*), which is based on the parameters in Eq. (3) (Baig et al. 2020; Hapke et al. 2011; Jonah et al. 2016).

$$TU = \sqrt{Ed^2 + Ep^2 + Et^2} \tag{2}$$

where

TU represents the total shoreline position uncertainty for each year, *Ed* shows the uncertainty of the digitalization of shoreline position, and *Ep* indicates the uncertainty of image resolution.

$$U = \frac{\sqrt{TU_1{}^2 + TU_2{}^2 + \ldots TU_n{}^2}}{Year_n - Year_1} \tag{3}$$

where

U is the shoreline change rate for the individual transects; TU_1 and TU_2 indicate the total uncertainties at each shoreline position; *n* shows the total number of shorelines, which is 7 in this study; $Year_n$ represents the last shoreline year, which is 2021; and $Year_1$ denotes the initial shoreline year, which is 1972. The uncertainty analysed for the individual transects is ± 5.04 m/yr (see Online Resource 1).

Shoreline change analysis

Shoreline change analysis was first performed on the entire (both the central and eastern) coast. The shoreline was further divided into segments 1 and 2 for the central and eastern coasts, respectively, for detailed analysis (Fig. 3a–c) To estimate shoreline change rates, DSAS (v. 5.0), a USGS ArcGIS extension, was applied to the shoreline (Himmelstoss et al. 2018). Three vector files—a shoreline, a baseline, and a transect perpendicular to the baseline and the shoreline—are utilised by the DSAS to estimate change over time (Ferreira et al. 2021; Kılar 2023; Siyal et al. 2022). The estimation of shoreline change rates is achieved through the intersection of cast transects with each shoreline vector, where the baseline transects start (Ferreira et al. 2021). A 2-km buffer was generated around the merged shorelines in ArcGIS 10.8. A 150-m-long baseline was delineated and positioned onshore. The DSAS generated a total of 720 transects along the shoreline and baseline for the entire coast (Fig. 3a), with the following parameters: a spacing of 520 m, a maximum search distance of 20,000 m, and a smoothing distance of 500 m. A total of 459 and 258 transects were also generated for segments 1 (Fig. 3b) and 2 (Fig. 3c), respectively, using the same parameters.. These parameter values were chosen to ensure complete coverage of the shoreline, considering the specified buffer and baseline values. The change statistics along the shoreline were examined with a 90.0% confidence interval. The

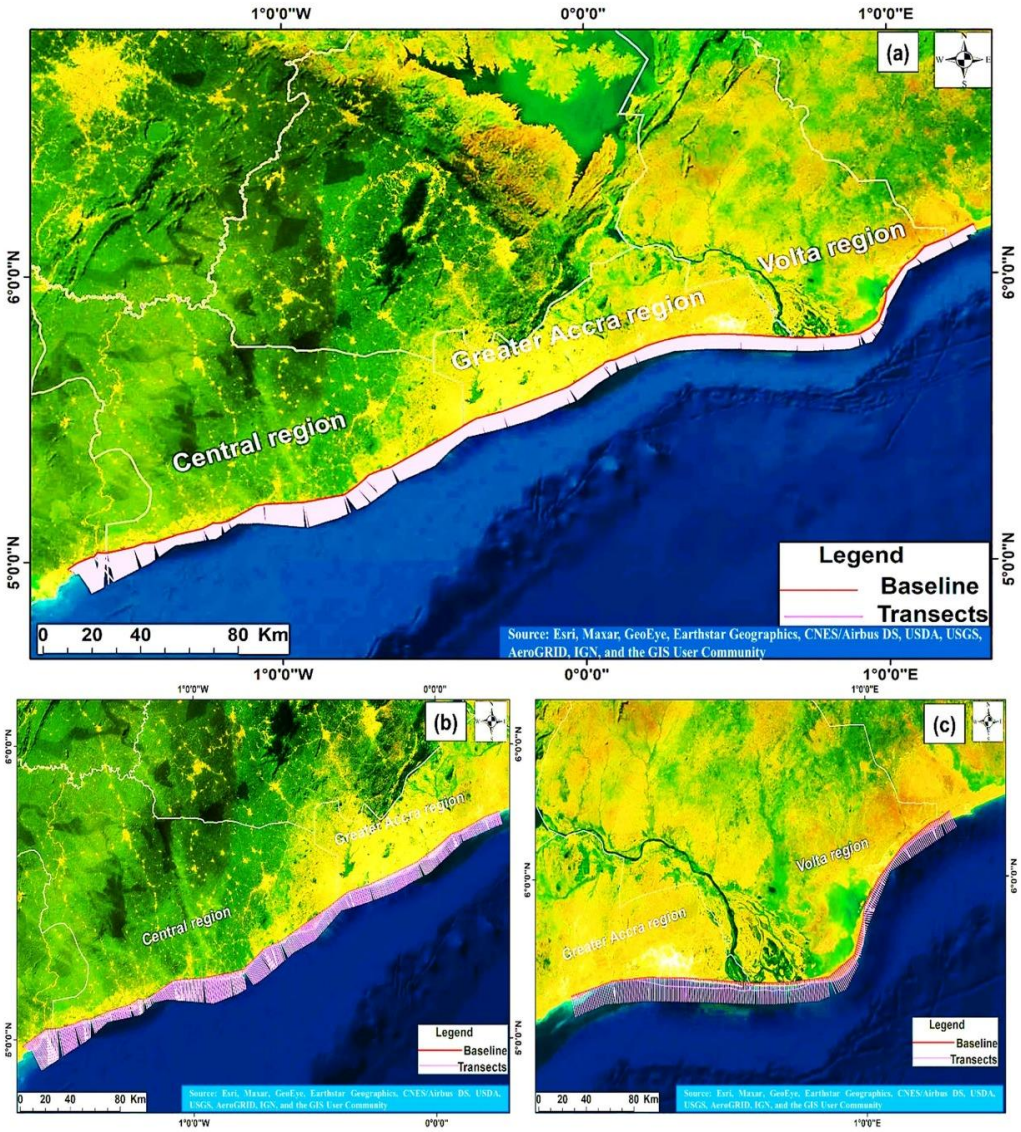


Fig. 3 Transects of the entire (both central and eastern) coast **(a)**, and the central **(b)** and the eastern **(c)** segments of Ghana

statistics used in this study to analyse the shoreline change rate were the EPR, LLR, WLR, NSM, and SCE. Previous studies have provided a detailed description of the change rate statistics mentioned above, including those conducted by Kılar (2023), Laksono et al. (2023), Siyal et al. (2022), and Thieler et al. (2009). The EPR and the LRR calculate the rate of change in m/yr, while the NSM and SCE report distance in m (Ozturk and Sesli 2015; Thieler et al. 2009).

Estimation of coefficient of shoreline armouring index

As reiterated by Jaramillo et al. (2021), most coastal environments and related infrastructure have been highly armoured for protection against shoreline erosion. Armoured coasts are thus recognised as a common approach globally for societal responses to the increasing impacts of shoreline change and coastal erosion (Jaramillo et al. 2021; Nordstrom 2014), regardless of their adverse

environmental impacts, as highlighted in the studies of Gittman et al. (2016) and Lee et al. (2018). According to Jaramillo et al. (2021), the amouring of coasts will increase as the global climate continues to change and human interventions on coasts, including population growth, rise.

For shoreline change and erosion analysis, the estimation of a specific shoreline armouring index that is distinct from natural shoreline changes unaffected by human intervention is required. A specific shoreline armouring index was thus applied to the shoreline segments.

The coefficient of shoreline (coastal) armouring, which is denoted as K, is an index that is used to evaluate the grade of artificial or human interventions on coasts (Laksono et al. 2023). The index is determined by dividing the sum of the lengths (*l*) of all coastal structures that are above and below the water surface by the entire length (L) of the coast or shoreline being assessed (Aybulatov and Artyukhin 1993; Laksono et al. 2023). These coastal structures include breakwaters, jetties, seawalls, and groynes, among others, as indicated by Aybulatov and Artyukhin (1993) and Laksono et al. (2023). The scale of the coastal armouring is determined qualitatively and categorised into four classes, namely 'Minimal' (when K = 0.0001–0.1), 'Average' (K = 0.11–0.5), 'Maximal' (K = 0.51–1.0), and 'Extreme' (> 1.0) (Laksono et al. 2023).

As stated by Munasinghe and Warnasuriya (2023), field observations provide a comprehensive depiction of the characteristics of a particular location, offering a more accurate representation of the actual occurrences within the natural environment. Consequently, a field observation was conducted between February and March 2023 on the central and eastern coasts to observe and document evidence of erosion along the shoreline, the effects on coastal resources and ecosystems, and the armouring types (adaptation strategies) being implemented. During this time, field photographs and detailed notes were taken. These field photographs and detailed notes supplemented the results of the physical shoreline change through remote sensing and coastal armouring types.

Results

Long-term shoreline change (1972–2021) for the entire (both the central and eastern) coast

The long-term shoreline change between 1972 and 2021 of the entire coast was estimated using the EPR, LLR, WLR, NSM, and SCE (Figs. 4, 5, 6, and 7). Online Resource 2 displays the statistical results of the shoreline change analysis, while Fig. 8a–b show the profiles of erosion (negative values) and accretion (positive values) of the 720 transects of the coast. Figure 9a – g depict the evidence of erosion occurring on the coast, which was documented through field observation.

In Fig. 4, the EPR recorded an erosion rate of – 212.9 m/yr to – 287.4 m/yr (lowest to highest) and an accretion rate of 10.5 m/yr to 84.8 m/yr (lowest to highest). The EPR recorded an average rate of change of – 100.8 ± 0.3 between 1972 and

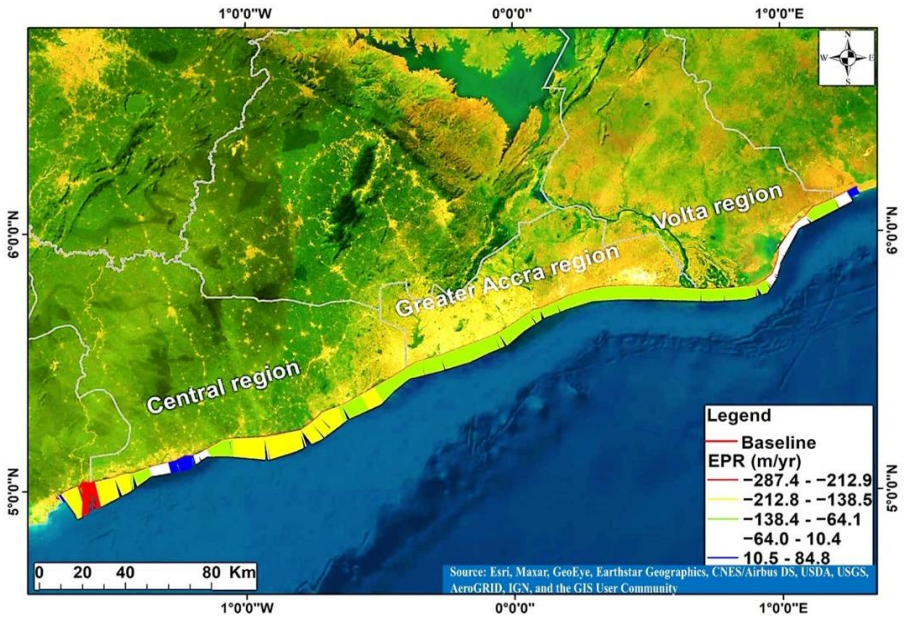


Fig. 4 EPR of the central and eastern coasts of Ghana

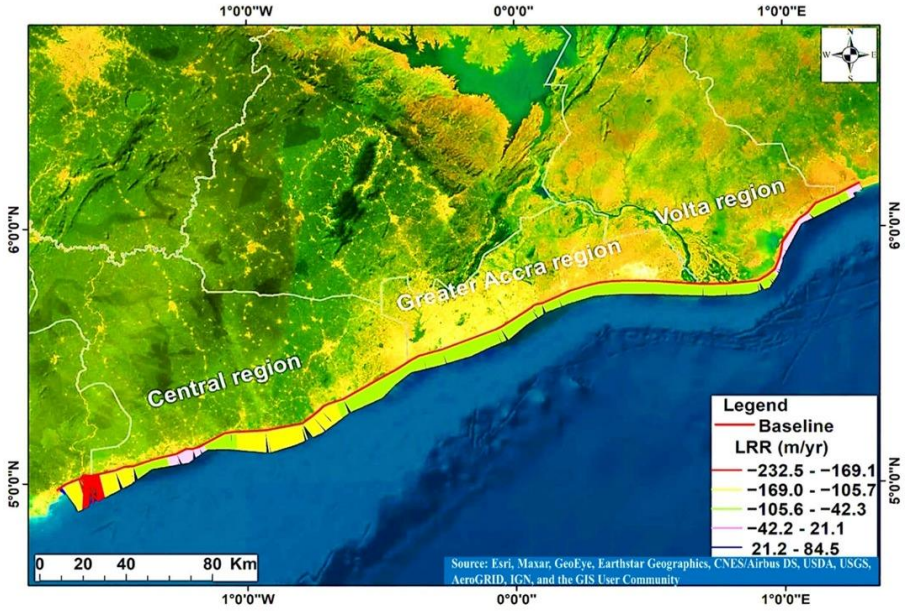


Fig. 5 LRR of the central and eastern coasts of Ghana

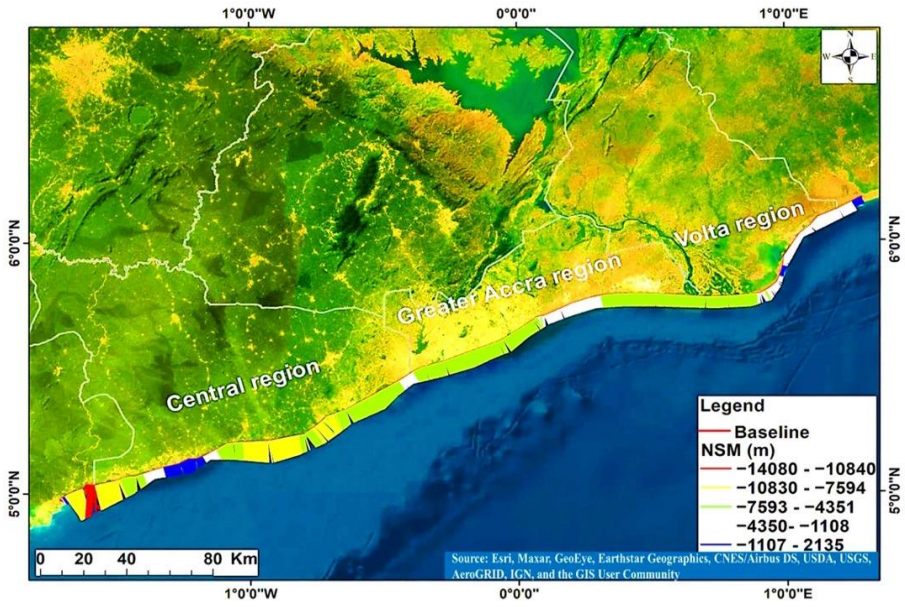


Fig. 6 NSM of the central and eastern coasts of Ghana

2021 (Online Resource 2). Again, the EPR recorded an average erosional rate of – 107.6 m/yr and an accretion rate of 28.5 m/yr (Online Resource 2). According to the EPR, 95% of the shoreline has eroded, with just a 5% accretion (Online Resource 2).

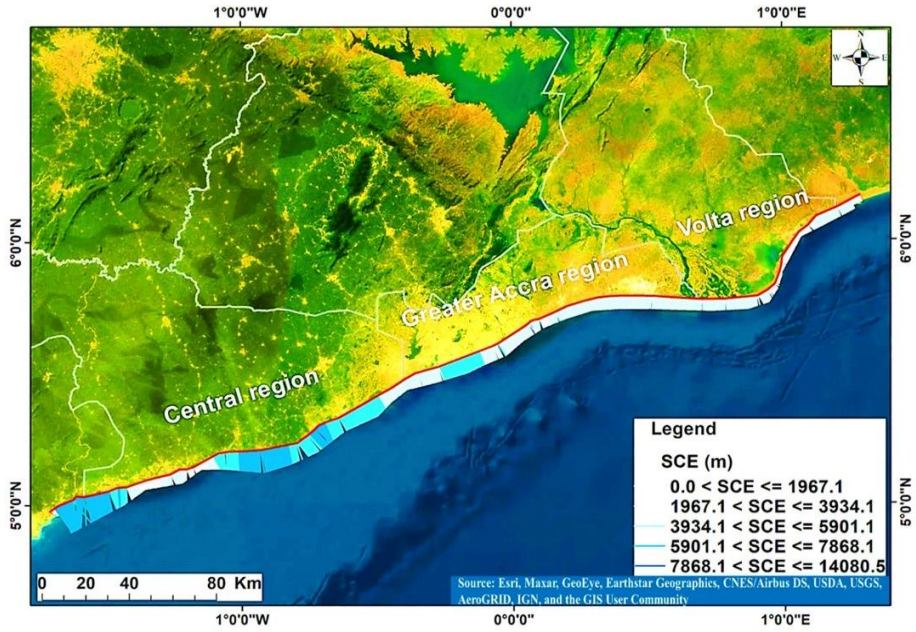


Fig. 7 SCE of the central and eastern coasts of Ghana

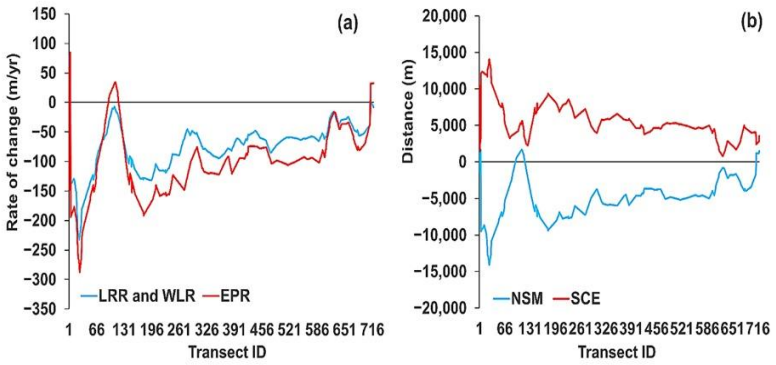


Fig. 8 Erosion and accretion profiles of the central and eastern coasts of Ghana **(a)** EPR and LRR, **(b)** NSM and SCE

Both the LRR and the WLR statistics showed the same results. Therefore, the LRR result in Fig. 5 matches the WLR result with no figure illustration. The estimated values of the LRR are almost similar to those of the EPR (Fig. 5). The LRR recorded the highest erosion rate (– 169.1 to – 232.5 m/yr) and the highest accretion rate (21.2 to 84.5 m/yr) (Fig. 5). Between 1972 and 2021, the LRR recorded an average rate of change with an uncertainty of – 75.0 ± 16.4 (Online Resource 2). The LRR estimated the average erosional rate of – 75.7 m/yr and the accretional rate of 33.6 m/yr (Online Resource 2). According to LRR statistics, 99.3% of the shoreline has eroded, with only a 0.7% accretion (Online Resource 2).

The NSM values show maximum erosion of – 10,840 to – 14,080 m (lowest to highest) and maximum accretion of 1107 to 2135 m (Fig. 6), with an average distance of – 4943.1 m (Online Resource 2). The NSM estimated an average of – 5263.6 m of all negative (erosion) distances and 1145.8 m of positive (accretion) distances (Online Resource 2). Based on NSM statistics, 95% of the shoreline has eroded with only 5% accretion between 1972 and 2021 (Online Resource 2). The SCE recorded a maximum of 14,080.5 m



Fig. 9 Field observations showing the effects of erosion on coastal resources and ecosystems **(a–g)**

and a minimum of 813.8 m (Fig. 7), with an average distance change of 5557.9 m (Online Resource 2).

Figures 4, 5, 6, and 7 show that the areas on the central coast had higher erosion and accretion rates (for EPR and LRR) as well as distances (NSM and SCE) of change compared to the eastern coast (see Fig. 1 to understand the coastal divisions).

Figure 9a shows erosion in the Elmina Bay area. Erosion has affected coastal infrastructure on the Saltpond coast (Fig. 9b), the James Town coast (Fig. 9c), and the Ada coast (Fig. 9d). Erosion has also threatened and destroyed coconut plantations along the Apam (Fig. 9e), Cape Coast (Fig. 9f), and Ada (Fig. 9g) coasts.

Long-term shoreline change (1972 –2021) for segments 1 and 2

The long-term shoreline change between 1972 and 2021 for segments 1 (Fig. 10a–e) and 2 (Fig. 10f–j) coast was estimated using the EPR, LLR, WLR, NSM, and SCE. Online Resource 3 displays the statistical results of the shoreline change analysis, while Fig. 11a–d show the profiles of erosion and accretion of the 459 and 258 transects of segments 1 and 2, respectively.

In segment 1, Fig. 10a shows that the EPR recorded an erosion rate of – 199.5 m/yr to – 270.5 m/yr (lowest to highest) and an accretion rate of 13.6 m/yr to 84.6 m/yr (lowest to highest). The EPR recorded an average rate of change

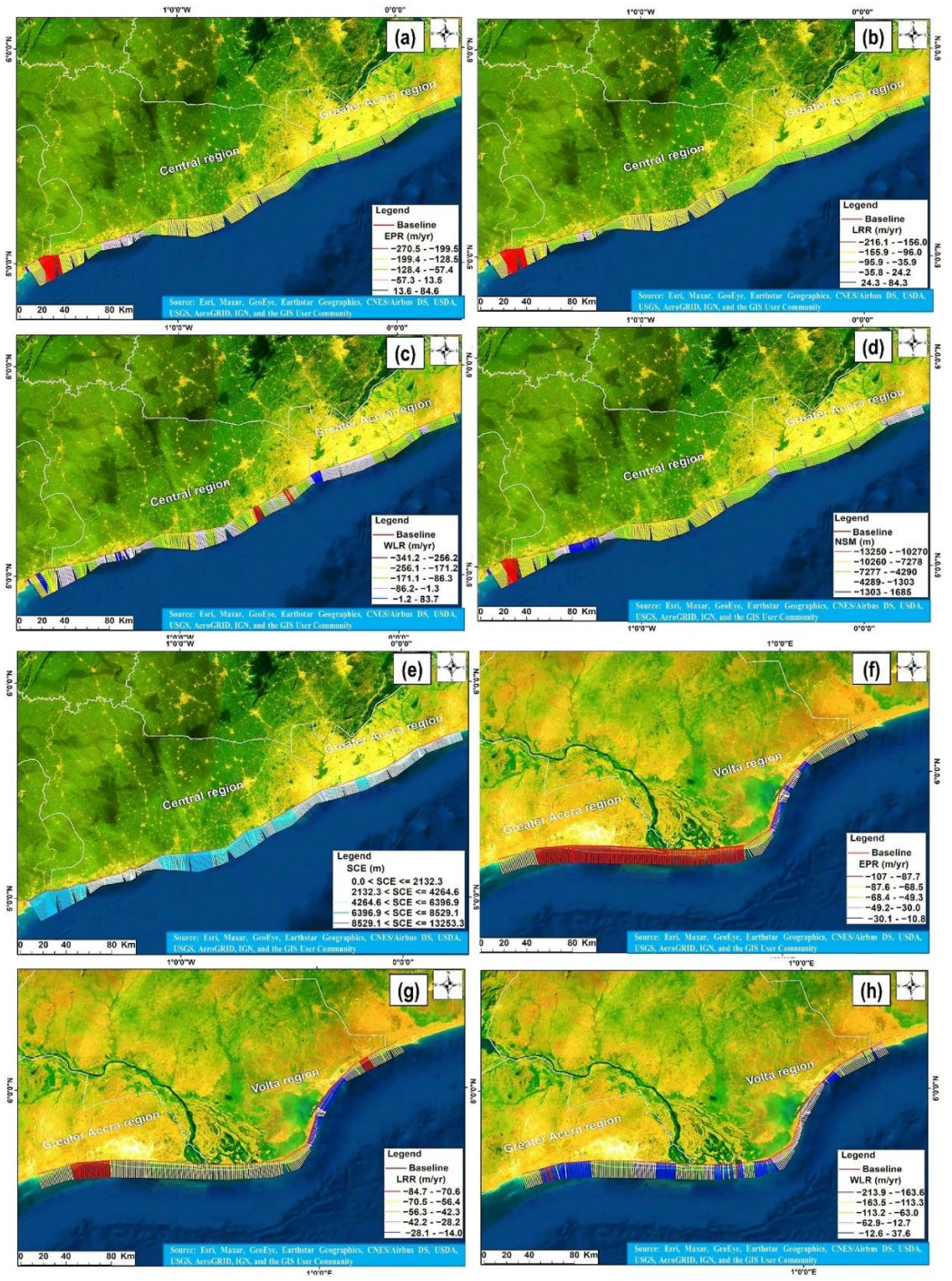


Fig. 10 EPR, LRR, WLR, NSM, and SCE of segment 1 (central) (**a**–**e**) and segment 2 (eastern) (**f**–**j**) coasts of Ghana

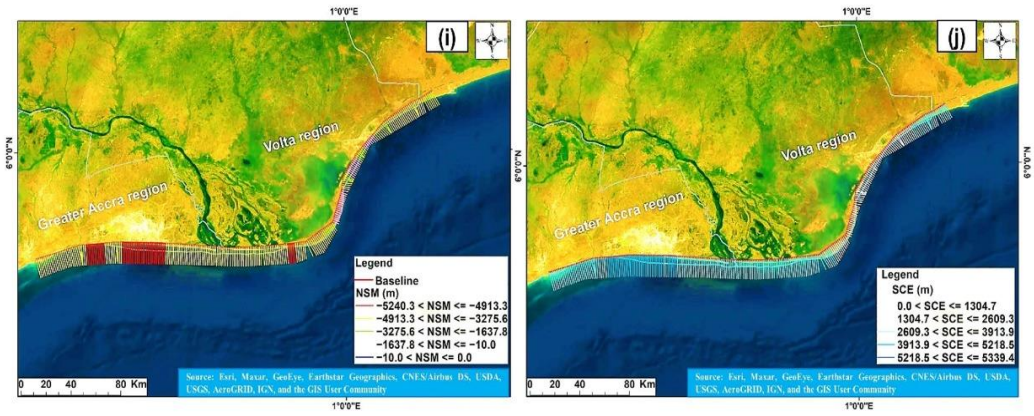


Fig. 10 (continued)

of – 119.0 ± 0.05 between 1972 and 2021 (Online Resource 3). Again, the EPR recorded an average erosional rate of – 123.0 m/yr and an accretion rate of 17.8 m/yr (Online Resource 3). According to the EPR, 97.2% of the shoreline of segment 1 has eroded, with just a 2.8% accretion (Online Resource 3).

According to Fig. 10b, the LRR recorded the highest erosion rate (– 35.8 to – 216.1 m/yr) and the highest accretion rate (24.3 to 84.3 m/yr). Between 1972 and 2021, the LRR recorded an average rate of change with an uncertainty of – 89.6 ± 19.7 (Online Resource 3). The LRR estimated the average erosional rate of – 90.6 m/yr and the accretional rate of 58.1 m/yr (Online Resource 3). According to LRR statistics, 99.3% of segment 1's shoreline has eroded, with only 0.7% accretion (Online Resource 3).

In Fig. 10c, the WLR statistics reveal a maximum erosion rate (– 1.2 to – 341.2 m/yr) and the highest accretion rate (0.0 to 83.7 m/yr). The WLR recorded an average rate of change with an uncertainty of – 94.0 ± 15.5 (Online Resource 3). The WLR revealed an average erosional rate of – 100.7 m/yr and an accretional rate of 17.3 m/yr (Online Resource 3). The WLR statistics showed that 94.3% of the shoreline of segment 1 has eroded, with only a 5.7% accretion (Online Resource 3).

In Fig. 10d, the NSM values show maximum erosion of – 10,270 to – 13,250 m and maximum accretion of 1303 to 1685 m, with an average distance of – 5830.1 m (Online Resource 3). The NSM estimated an average of – 6014.7 m of all negative (erosion) distances and 501.9 m of positive (accretion) distances (Online Resource 3). According to the NSM statistics, 97.2% of the shoreline of segment 1 has eroded, with only 2.8% accretion between 1972 and 2021 (Online Resource 3). In Fig. 10e, the SCE shows a maximum of 13,253.3 m and a minimum of 1399.7 m, with an average distance change of 6415.4 m (Online Resource 3).

In segment 2, Fig. 10f shows that the EPR recorded an erosion rate of –10.8 m/yr to –107.0 m/yr with a zero (0) accretion rate. The EPR recorded an average rate of change of – 75.3 ± 0.06 between 1972 and 2021 (Online Resource 3). Again, the EPR recorded an average erosional rate of – 75.3 m/yr with no (0) accretion (Online Resource 3). According to the EPR statistics, 100.0% of segment 2's shoreline has eroded, with no (0) accretion (Online Resource 3).

Figure 10g shows that the LRR recorded the highest erosion rate (– 14.0 to –84.7 m/yr) with a zero (0) accretion rate. The LRR estimated an average rate of change with an uncertainty of – 53.2 ± 19.2 between 1972 and 2021 (Online Resource 3). Again, the LRR recorded an average erosional rate of – 53.3 m/yr with a zero (0) accretional rate (Online Resource 3). Based on the LRR statistics, 100.0% of the shoreline of segment 2 has experienced erosion with no accretion (Online Resource 3).

The WLR statistics show a maximum erosion rate (– 12.6 to – 213.9 m/yr) and the highest accretion rate (0.0 to 37.6 m/yr) (Fig. 10h). The WLR revealed an average rate of change with an uncertainty of – 41.9 ± 21.0 (Online Resource 3). The WLR again recorded an average erosional rate of – 58.0 m/yr and an accretional rate of 19.2 m/yr (Online Resource 3). According to the WLR statistics, 79.1% of segment 2's shoreline has experienced erosion, with 20.9% accretion (Online Resource 3).

In segment 2, the NSM values in Fig. 10i reveal a maximum erosion of – 10.0 to – 5240.3 m and zero (0) accretion, with an average distance of – 3686.0 m (Online Resource 3). The NSM statistics show that 100.0% of the shoreline of segment 2 has eroded, with zero (0) accretion between 1972 and 2021 (Online Resource 3). The SCE in Fig. 10j also reveals a maximum of 5339.4 m, a minimum of 619.4 m, and an average distance change of 3916 m (Online Resource 3).

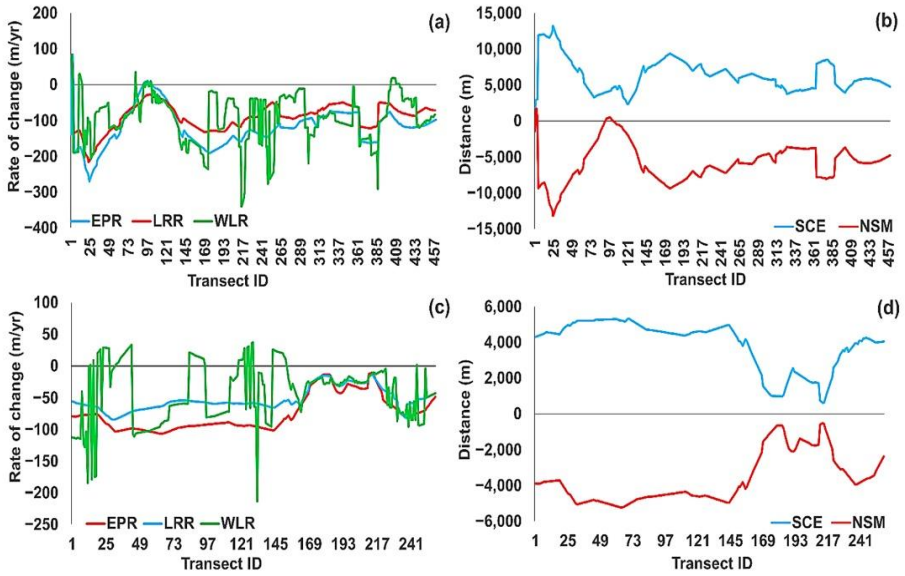


Fig. 11 Erosion and accretion profiles of EPR, LRR, WLR, NSM, and SCE of segment 1 (central) **(a–b)** and segment 2 (eastern) **(c–d)**

The erosion and accretion profiles in Fig. 11a–d show that segment 1 has higher erosion and accretion rates (for EPR, LRR, and WLR), as well as distances (NSM and SCE) of change compared to segment 2.

Artificial shoreline versus natural shoreline

Table 1 shows the K index of the central and eastern coasts, as well as the entire coast (i.e., a combination of both central and eastern coasts), between 1972 and 2021. The last decades have seen a significant implementation of artificial coastal structures along the entire coast. From 1972 to 2021, the K index for the entire coast increased by approximately 15%, ranging from 0.08 recorded in 1972 to 0.23 observed in 2021. Thus, the entire coast K index falls within the 'Minimal' class range for 1972 and within the 'Average' class range for 2021. In segment 1 (central coast), the K index ranged from 0.12 ('Average' class range) registered in 1972 to 0.72 ('Maximal' class range) recorded in 2021. In segment 2 (eastern coast), the K index ranged from 0.00 to 0.08 between 1972 and 2021, which fall under the 'Minimal' class range. Coastal structures have replaced about 60% and 8% of the natural coastline on the central and eastern coasts, respectively. Thus, the eastern coast has a lower grade of shoreline armouring compared to the central coast (Fig. 12). Figure 13a–d illustrate the shoreline evolution of the entire coast, as well as segments 1 and 2, along with the K index. Figure 14a–i also display some of the major coastal structures that have been constructed along the central and eastern coasts to prevent shoreline erosion.

Discussion

Shorelines across the world will continue to retreat as the detrimental effects of climate change, sea level rise, and anthropogenic activities worsen (Bamunawala et al. 2021). The situation will worsen as coastal zones continue to receive a substantial share of the world's population (Ferreira et al. 2021; Jonah et al. 2016; Small and Nicholls 2003; Ülger and Tanrıvermiş 2023), making the shorelines, coastal resident population, and related ecosystems vulnerable (Charuka et al.

Table 1 The coefficient of shoreline armouring estimated for the central and eastern segments and the entire coast for 1972 and 2021. Note: All the estimations are in metres

	Segment 1 Central coast			Segment 2 Eastern coast			Entire coast (both central and eastern)		
Year	L	l	K	L	l	K	L	l	K
1972	225,115	28,107	0.12	125,114	0	0.00	356,265.0	28,107	0.08
2021	225,115	162,323.6	0.72	125,114	10,152	0.08	356,265.0	80,629.9	0.23

2023a; Nijamir et al. 2023). Adapting to increasing coastal risks is critical for minimising coastal ecosystem vulnerability (IPCC 2022). As a result, this study analysed long-term shoreline change and the influence of erosion on the central and eastern coasts of Ghana using remote sensing and field observation techniques.

Ghana's central and eastern coasts under anthropogenic and physical forcings

Anthropogenic activities have increased on the central and eastern coasts over time. The coastal areas in Ghana are home to major economic, industrial, residential, historical, tourism, and conservation sites (Amlalo 2006; Boateng 2012). The Tema harbour, Accra, the capital city with a greater urban settlement, and several historic sites, including castles and forts (e.g., Elmina Castle, Cape Coast Castle, Osu Castle, among others), are located on the central coast (Boateng 2012; Wellens-Mensah et al. 2002). The eastern coast also boasts Fort Prinzenstein at Keta and Fort Kongenstein at Ada, despite their partial destruction by erosion (Boateng 2012). The results thus demonstrate that between 1972 and 2021, the coast experienced more erosion than accretion. The EPR and LRR statistics revealed that about 95.0% and 99.3% of the coast experienced erosion, compared to just 5.0% and 0.7% accretion. The NSM and SCE estimations also reflected this, showing more erosion of the coast than accretion. The findings are in line with the earlier studies conducted in Ghana by Angnuureng et al. (2022), Appeaning Addo et al. (2008), Evadzi et al. (2017), Jayson-Quashigah et al. (2013), Jonah et al. (2016), and Jonah (2015). Angnuureng et al. (2022) reported, for example, that although the front portion of the beach near Elimina Castle is adequately protected, the downdrift, more exposed portions have higher erosion rates. Jonah (2015) found that the Elmina, Cape Coast, and Moree sections of Ghana's shoreline eroded at a rate of 1.22 m/yr ± 0.16 m between 1974 and 2012. Elsewhere, research studies such as those of Ferreira et al. (2021), Laksono et al. (2023), Munasinghe and Warnasuriya (2023), Nijamir et al. (2023), and Siyal et al. (2022) reported greater erosion above accretion rates.

The results also show that the central coast has had greater erosion rates and change distances than the eastern coast. Higher erosion rates on the central coast may be caused by anthropogenic activities such as beach sand mining and rapid urbanisation, as well as sea level rise (Boateng 2012; Jonah et al. 2016, 2015; Jonah 2015). For example, Jonah et al. (2015) identified beach sand mining as a substantial contributor to erosion on the Elmina, Cape Coast, and Moree coasts. On the aforementioned coasts, Jonah et al. (2015) estimated an annual volume of 285,376 m3 of sand

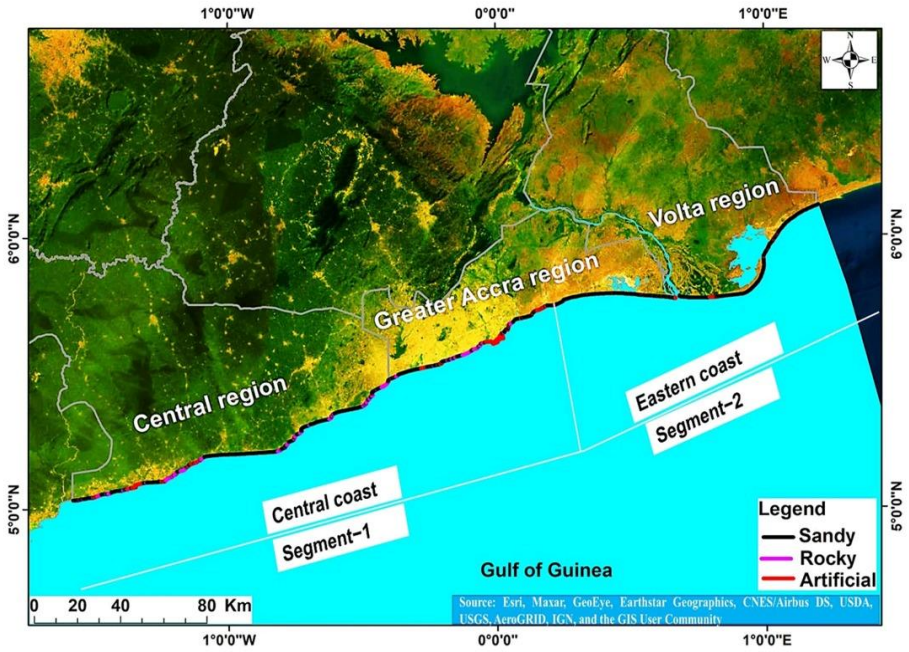


Fig. 12 The morphology types of the central and eastern coasts of Ghana in 2021

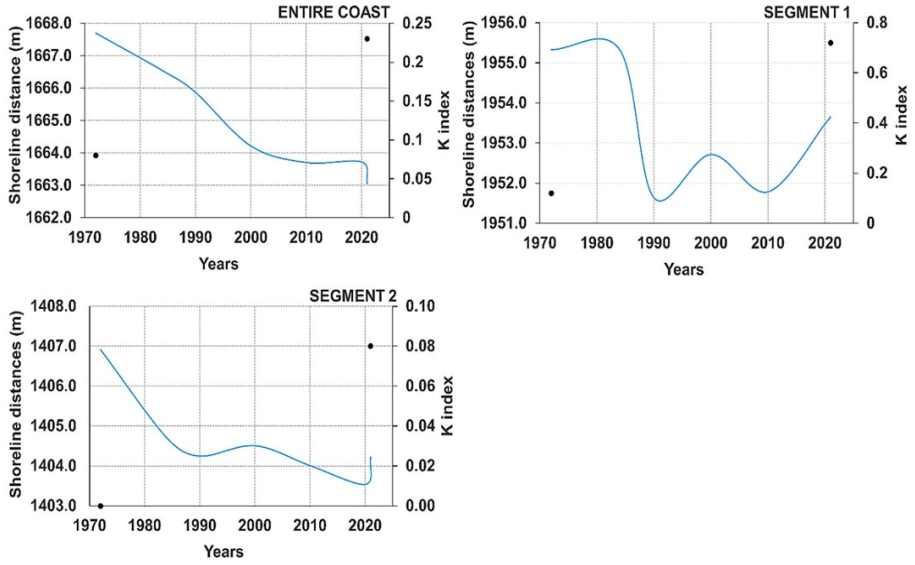


Fig. 13 Shoreline evolution and the K index of the entire coast as well as segments 1 and 2. Note: The blue line indicates the average transect distance from the baseline recorded for each shoreline year. The black dot shows the K index observed between 1972 and 2021

transported by tipper trucks. According to Boateng (2012), construction and unplanned artificial coastal structures block littoral sediment, resulting in coast erosion. The construction of the Akosomba dam on the Volta River has been recognised for the erosion on the eastern coast, particularly at Ada, the Volta River estuary, and Keta (Appeaning Addo et al. 2011; Boateng 2012; Jayson-Quashigah et al. 2013; Ly 1980).

The findings from the shoreline change analysis indicate that there was more erosion than accretion on both segments 1 and 2. Not only can we attribute this to increased human interventions, but also to the impact of hydrodynamic processes like wave direction, frequency, and intensity. However, the hydrodynamic processes do not exert a consistent impact on the coast. Segment 1 of the shoreline exhibits medium-energy conditions, characterised by embayed coasts, rocky headlands, rocky shores, littoral sand barriers, and enclosing coastal lagoons (Boateng et al. 2017; Charuka et al. 2023a). The geological and geomorphological characteristics of the coast are essential factors in determining its ability to withstand waves and erosion. Previous research conducted by Abu and Sunkari (2020) and Ly (1981) demonstrated that the existence of metamorphic and sedimentary rocks effectively withstands wave action and reduces coastal erosion. According to Abdul-Kareem et al. (2022), the geological characteristics of the Apam beach on the central coast cause incoming waves to change direction and distribute their energy along the shoreline. The deflection mechanism reduces the movement of sediments caused by waves on the beach (Abdul-Kareem et al. 2022). Therefore, a greater number of erosional events took place on the exposed sandy beaches, littoral sand barriers, and surrounding coastal lagoons in segment 1, while fewer occurred on the embayed coasts, rocky headlands, and rocky shores (see Fig. 15). The impact of waves on segment 2 (the eastern coast) is more significant because of its soft geology and geomorphology, which are defined by sandy shorelines (Charuka et al. 2023a; Ly 1980). The sandy shorelines on segment 2, especially at Keta beach, exhibit low resistance to wave conditions, resulting in easy erosion of sand through drift (Appeaning Addo et al. 2011).

The coastal area experiences high-energy conditions, characterised by wave heights above 1 m in the surf zone (Boateng et al. 2017; Boateng 2012; Ly 1980). Thus, the high energy wave conditions from the Gulf of Guinea exert greater impacts on segment 2 compared to segment 1 (Appeaning Addo et al. 2011; Boateng 2009). The The findings of Boateng (2012) revealed an average wave period of 6 s and frequent near-storm events on segment 2, particularly along the Keta and Ada coasts. Research studies conducted by Abessolo Ondoa et al. (2017), Almar et al. (2015), and Anthony et al. (2019) have revealed the impact of ocean wave conditions on the Gulf of Guinea. Campos et al. (2019) and Silva et al. (2020) have recently conducted research that indicates an increase in ocean wave conditions in the South Atlantic Ocean.

It is imperative not to overlook the impacts of sea level rise on Ghana's shoreline and the accompanying erosion (Appeaning Addo et al. 2011). According to Evadzi et al.

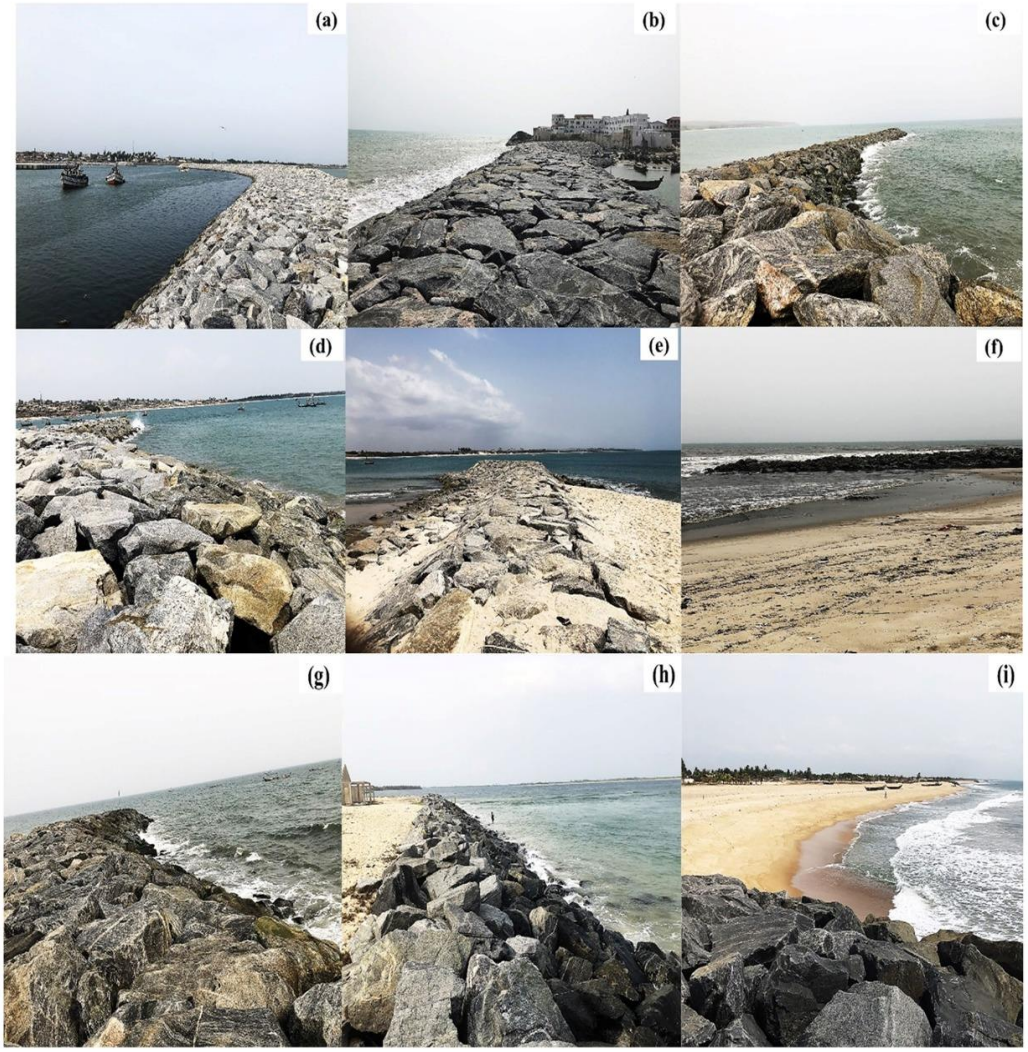


Fig. 14 Coastal structures implemented along the coast **(a)** Elmina Castle area; **(b)** Cape Coast Castle area; **(c)** Moree; **(d)** Winneba; **(e)** Gomoa Fetteh; **(f)** James Town; **(g)** Teshie; **(h)** Volta River estuary at Ada Foah; and **(i)** Keta

(2017), the average sea level has risen by about 5.3 cm and accounts for 31% of Ghana's annual coastal erosion rate. Given that sea level rise accounts for 31% of Ghana's annual erosion, the negative anthropogenic activities identified by Boateng (2012) and Jonah et al. (2015) may have a substantial impact on shoreline change and related erosion.

Coastal armouring impact and shoreline response

The increased grades of shoreline armouring are recognised as one of the key factors that increase the vulnerability of coasts to natural risks (Jana and Bhattacharya 2013; Laksono et al. 2023). The estimation of the shoreline armouring index (K) on the central and eastern coasts revealed a high grade of artificial coast between 1972 and 2021. Regardless, the construction of coastal structures was not continuous across the entire shoreline. The central coast, which stretches from Komenda in the Central region to the western portion of Prampram in the Greater Accra region, has a higher grade of shoreline armouring with a K index from 0.12 ('Average' class range) in 1972 to 0.72 ('Maximal' class range). The

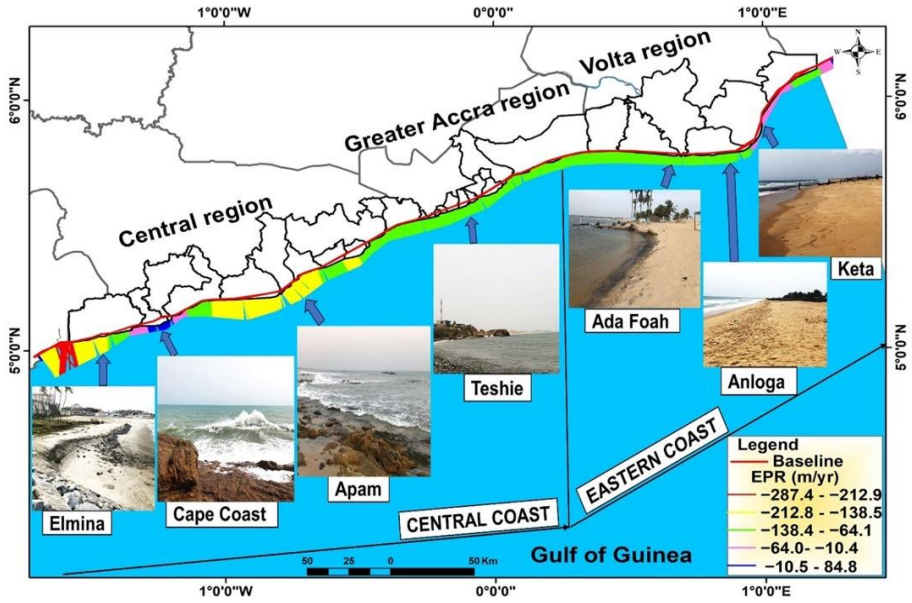


Fig. 15 Distribution of coastal lithologies and erosion rates on the central and eastern coasts

eastern coast, which stretches from east of Prampram to the border of Aflao with the Republic of Togo, has a lower grade of shoreline armouring ('Minimal' class range), with a K index from 0.00 in 1972 to 0.08 in 2021. The central coast has a more extensive shoreline compared to the eastern coast (Charuka et al. 2023a), and this could account for the difference in the coefficient of the K index. Although shoreline armouring has increased over time, erosion is still prevalent on the coast. For instance, segment 1, with about 60% of shoreline armouring, still experienced erosional events of 97.2%. The situation is worse on segment 2, with less (8%) shoreline armouring, where about 100.0% of the coast has experienced erosion, as revealed by the NSM statistics. The depositional events on segment 1 occurred on the areas that have been armoured with breakwaters. Breakwaters are reported to be more efficient in retaining sediments than shore-normal structures such as jetties (Miles et al. 2001; Molina et al. 2019). The downdrift, more exposed areas with no shoreline armouring, including the open sandy beaches and the sandy areas covered with coconut plantations, experience higher erosion. This trend is largely recognised on the Ghanaian coast (Angnuureng et al. 2022; Jonah 2015) and along the Gulf of Guinea coast (Aman et al. 2019). A similar trend has been recognised in the Mediterranean coast regions such as Sicily of South Italy (Anfuso et al. 2013; Laksono et al. 2023) and Andalusia, Spain (Molina et al. 2019). Most of the shoreline armouring on segment 2 is built with groynes and jetties, which are permeable (Charuka et al. 2023b; Gbedemah 2023) and generate accretion and erosion updrift and downdrift, respectively (Anfuso et al. 2012; Bray et al. 1995). Also, the Volta delta, the existence of many lagoons, and the construction of the Akosombo dam all have a significant impact on erosion on the eastern coast (Appeaning Addo et al. 2011; Boateng 2012; Jayson-Quashigah et al. 2013; Ly 1980). The driving nature of river deltas and streams, along with the gradual construction of dams, negatively affects the sediment inputs to the shoreline (Molina et al. 2019). The increase in shoreline armouring thus influences the sediment longshore drift and shoreline sediment dynamics on both segments 1 and 2.

Field observations demonstrated increased armouring (adaptation efforts) on most of Ghana's central and eastern shorelines. This policy initiative supports advocacy efforts to increase coastal cities and settlements adaptation to increasing risks (IPCC 2022). On most of the central and eastern coasts, policymakers have built breakwaters and jetties from large granite rocks to prevent erosion (see Fig. 14a – i). Most landing beaches and historical sites along the coast have breakwaters and jetties running parallel or perpendicular to ensure safe landings for fishing canoes and prevent erosion. Field observations indicate that no measures have been taken to prevent erosion in areas with vegetation, such as the coconut plantation areas on the coast. Although vegetation areas are a source of

adaptive strategy in and of themselves, the pace at which they are eroding demands attention. On the coast, the adaptation strategies used are those of hard engineering protection measures (see Fig. 14a – i), with no soft engineering or nature-based measures. Although commonly used in many coastal areas, hard protection measures, such as those implemented on Ghana's central and eastern coasts (see Fig. 14a – i), are only effective in the short-to-medium term and are costly (IPCC 2022). As the IPCC (2022) emphasises, the residual risk that arises from the adoption of hard protective measures continues since the protection can fail. Das Neves et al. (2023) highlighted that even if they guarantee the lowest residual risk to 2100, the avoided damages are uncertain to cover the coastal protection investment costs. The IPCC (2022) suggests combining hard engineering with soft engineering (e.g., beach nourishment) and nature-based measures (e.g., retaining mangroves and marshes) in coastal areas. Pais-Barbosa et al. (2023), for example, demonstrated the effectiveness of soft engineering measures such as artificial sand nourishment in minimising coastal erosion along the Ovar (Aveiro, Portugal) shoreline using a cost–benefit analysis. Bera and Maiti (2019), as well as Saddam et al. (2023), have advocated for the increased plantation of mangroves as a nature-based measure to reduce coastal erosion. The involvement of coastal communities in coastal erosion policy initiatives is critical for coastal management plans and practices. Community involvement in coastal erosion issues, as noted by Pais-Barbosa et al. (2023), leads to improved decisions, increased trust, and broad acceptance of coastal management policies.

Conclusions

The use of remote sensing, GIS, and field observation techniques in the continuous monitoring of shoreline changes is considered to be effective (Ankrah et al. 2023; Munasinghe and Warnasuriya 2023). The combination of these techniques helps in understanding and obtaining an accurate picture of shoreline change and erosion issues for improved policy decisions (Ankrah et al. 2023; Munasinghe and Warnasuriya 2023). The objective of this study was to long-term analyse shoreline change and the influence of erosion on the central and eastern coasts of Ghana using remote sensing and field observation techniques.

The findings demonstrate that Ghana's central and eastern coasts have eroded at rates faster than they are accreting. For the entire (both central and eastern) coast, shoreline changes are characterised by erosion, as revealed by the EPR and LRR statistics, with an average rate of – 100.8 m/yr and – 75.0 m/yr, respectively. Shoreline change showed a dominance of erosion in segment 1 (central coast), with average rates of – 119.0 m/yr, – 89.6 m/yr, and – 94.0 m/yr for the EPR, LRR, and WLR statistics, respectively. Segment 2 (eastern coast) has lower erosion rates compared to segment 1, with rates of – 75.3 m/yr, – 53.2 m/yr, and – 41.9 m/yr, for the EPR, LRR, and WLR statistics, in that order. Both segments 1 and 2 were highly armoured between 1972 and 2021. The shoreline armouring index of segment 1 increased from 0.12 ('Average' class range) in 1972 to 0.72 ('Maximal' class range) in 2021, a 60% increase. The shoreline armouring index in segment 2 increased from 0.00 in 1972 to 0.08 in 2021, which shows a 'Minimal' class with an 8% increase. The high grades of shoreline armouring on segment 1 affect sediment deposition downdrift and affect the dynamics of the coast. The reduced sediment deposition from the Volta River and the Akosombo dam, as well as longshore drift, influence erosion on segment 2 (the eastern coast). Field observations show that policy initiatives have enhanced adaptation efforts in most sections of the coast. However, the implemented adaptation efforts consist of hard engineering protective measures that are effective in the short-to-medium term but expensive. No soft engineering or nature-based protective measures were observed on the coast.

This study, therefore, recommends improved policy initiatives on soft engineering and nature-based coastal protection measures based on their favourable ecological impact and economic effectiveness. The increased erosion occurring in coastal vegetation areas requires attention. These areas would greatly benefit from sand nourishment and coconut reforestation. Implementing proper monitoring systems and effective coastal zone management plans can help prevent continuous erosion of the coast.

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Author contributions J.A. conceptualized the study, conducted the field observation, performed the formal analysis and investigation, wrote the original draft preparation, and reviewed and edited the manuscript. All authors read and approved the final manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interest The authors declare no competing interests.

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CHAPTER 7: Conclusions, summary, and final considerations

7.1. Introduction

The principal goal of this thesis was to assess the impacts of climate change and variability in the coastal savannah agroecological zone of Ghana, where there is a dearth of knowledge about climate change and variability. The multimethod employed in this thesis and the interdisciplinary approach to establish specific research objectives were absolutely decisive at achieving this primary goal, as follows:

1) To evaluate climate change and climate variability in the coastal savannah agroecological zone of Ghana.
2) To project possible future climate change scenarios for the coastal savannah agroecological zone of Ghana.
3) To analyse the influence of El Niño-Southern Oscillation on rainfall variability in the coastal savannah agroecological zone of Ghana.
4) To analyse the impacts of climate change and climate variability on marine and freshwater fish harvest and their effects on the socio-economic livelihoods of the communities in the coastal savannah agroecological zone of Ghana.
5) To analyse the influence of climate change on shoreline change and the impacts of erosion on the ecosystems and their implications on the communities in the coastal savannah agroecological zone of Ghana.

The concluding chapter of this thesis, therefore, provides a summary and analysis of the main findings. The chapter again examines the policy implications for climate change and climate variability impacts in the coastal savannah agroecological zone of Ghana. The chapter also suggests areas for future research based on the specific research objectives discussed in the preceding chapters.

7.2. Evaluation of climate change and climate variability in the coastal savannah agroecological zone of Ghana

Chapter 2 of this thesis presented the evaluation of climate change and climate variability in the coastal savannah agroecological zone of Ghana. This was achieved by analysing the spatiotemporal characteristics of drought and wetness events (Paper 5), assessing temperature variability through a day-to-day temperature variability framework (Paper 6),

and examining the perceptions of climate risks and adaptation strategies among smallholder farmers (Paper 7).

Using the Standardized Precipitation Evapotranspiration Index (SPEI) and the ordinary Kriging interpolation method, this thesis has established which locations in the coastal savannah agroecological zone of Ghana experience more drought and wetness events and the years where these events were at extreme levels. The empirical data (from 1981 to 2021) presented in Chapter 2 (Paper 5) for the changepoint analysis revealed the homogeneous nature of rainfall and temperature in the coastal savannah agroecological zone. However, there were significant temperature changes between the mid-1990s and 2012. The changepoints in the climate variables, particularly temperature, could be linked to the growing industrial and commercial activities (i.e., urbanisation) in the zone, especially in Accra, the capital city, and Tema. Evidence of these effects on temperature change has been established in the cities in southeast Australia (Yildirim and Rahman, 2022), in Raipur, the capital city of Chhattisgarh state, India (Jaiswal et al., 2015), and in the Umbria region, central Italy (García-Marín et al., 2020).

The data also revealed that the drought and wetness event incidences in the coastal savannah agroecological zone of Ghana have distinct spatial and temporal patterns. On the temporal scale, the results showed more moderate-to-extreme drought events in the 1980s and 1990s than in the 2000s, while wetness event incidences were higher in the 2000s than the earlier decades. On a spatial scale, the results revealed more extreme drought and wetness event incidences in the Central and Greater Accra areas, as well as severe conditions in the Volta areas of the coastal savannah agroecological zone. The findings from Paper 5 support scientific evidence on the increased frequency and intensity of drought and wetness events (Alsafadi et al., 2020; An et al., 2020; Ge et al., 2016; IPCC, 2014a; Polong et al., 2019; Spinoni et al., 2014; Wang et al., 2018). The findings of An et al. (2020) revealed a significant increase in the frequency and intensity of droughts in Inner Mongolia, China. Similarly, the findings of Polong et al. (2019) revealed increased dry and wet events in the Tana River Basin in Kenya. The findings of Ge et al. (2016) demonstrated the increased drought frequency, intensity, and duration in the northern and eastern Indian plains. The drought and wetness event incidence in the coastal savannah agroecological zone poses a threat to the livelihood opportunities of people, especially smallholder farmers, as established in Paper 7. Even though the results in Paper 5 demonstrated increased wetness events in the zone, which could support smallholder farming activities in the zone, there is evidence of significant losses to the livelihoods of these farmers due

to floods (Yaro, 2013). Therefore, Paper 5 recommended regular monitoring of drought and wetness events to protect and sustain the farming activities of smallholder farmers in the zone.

This thesis has improved our understanding of how temperature changes from one day to the next in the coastal savannah agroecological zone of Ghana by applying Gough's (2008) and Tam et al.'s (2015) day-to-day variability (DTD) frameworks. The results presented in Chapter 2 (Paper 6) showed that there exists an orderly climate ($G < 1$) in the coastal savannah agroecological zone of Ghana. Again, the monthly averages in G (the ratio of DTD to standard deviation (SD)) revealed higher levels of variability in the day-to-day maximum temperature (DTD T_{max}) than the day-to-day minimum temperature (DTD T_{min}). These averages were greater in March, especially for the Ada Foah and Apam areas. Furthermore, it was revealed that the highest monthly average change in DTD (ΔDTD) was observed in the areas of Ada Foah, Apam, and Elmina, while the lowest occurred in Denu, Keta, and Saltpond. Although in a different climatic location, the result is consistent with those of Gough (2008), who first applied the framework to the cities of Toronto and Calgary, Canada, and Tam and Gough (2012) in their study on past temperature variability in three locations in Canada. Ada Foah experienced the greatest DTD throughout the year, except in January, when Keta surpassed it, at threshold exceedances of 2 °C and 4 °C in both DTD T_{max} and DTD T_{min}. The 4 °C threshold exceedances in DTD T_{min} presented a dissimilar case, with no records observed for any location except Cape Coast. Furthermore, the thesis found that the seasonal pattern in DTD T_{max}, DTD T_{min}, and ΔDTD was higher in the dry season (November−March) than in the wet season (May−July), which could be linked to the high solar radiation and greater insolation observed during the dry season in Ghana (Tanu et al., 2021). The higher dry season variation could also be due to seasonal wind development. The north-east trade winds, or harmattan winds, from the Sahara Desert outperform the south-westerly winds from the Atlantic Ocean, resulting in higher temperatures. The thesis also established that from 1981 to 2021, the annual averages of DTD $T_{max\ and}$ DTD T_{min} increased, especially for the Ada Foah and Apam areas. However, the improvements in DTD T_{min} were weak. The results indicate that, with a similar climate, it is obvious that local variations exist in the coastal savannah agroecological zone. Aside from the large seasonal wind development, the dynamics in local topography could account for this. The studies conducted in Canadian territory by Gough (2008), Mohsin and Gough (2010), and Tam and Gough (2012) have revealed how local topography can cause dramatic temperature changes.

The analysis of how temperature changes from one day to the next is crucial for understanding the earth's climate variability. The evidence of DTD in the coastal savannah agroecological zone could pose threats to the inhabitants' health and daily activities. Studies such as those conducted elsewhere by Bi et al. (2022), Noelke et al. (2016), Zhang et al. (2018), and Zhou et al. (2020) have reported evidence on the negative effects of DTD on human health and related mortalities, especially for the elderly. This may not differ from the coastal savannah agroecological zone or Ghana as a whole. Studies such as those of Klutse et al. (2014) and Song and Yan (2022) have highlighted the negative impacts of temperature variability on malaria transmission in Ghana. The DTD in the zone could also affect agricultural activities, which could constrain smallholder farmers' livelihood opportunities. According to the IPCC (2018), DTD can increase evapotranspiration through evaporation from the soil and water surface, as well as transpiration from plants, which could affect crop productivity and yield.

Using a mixed-methods approach, the data presented in Chapter 2 (Paper 7) examined smallholder farmers' perceptions of climate risks and adaptation strategies in the coastal savannah agroecological zone of Ghana. By employing a mixed-methods approach, this thesis has improved our understanding of how smallholder farmers perceive climate risks and the strategies they employ to adapt to these risks. An analysis of this nature is essential, as it not only contributes to the current literature on farmers' perceptions of climate risks but also has the potential to enhance our understanding in the formulation of appropriate adaptation strategies that can safeguard the livelihoods of smallholder farmers in the coastal savannah agroecological zone and Ghana as a whole. An analysis of this nature also highlights the added benefits of improving farmers' climatological literacy, as well as the importance of informal knowledge in the field of science.

The results presented in Paper 7 revealed that there has been a notable increase in smallholder farmers' awareness and understanding of climate change and variability, which can be attributed to the enhanced dissemination of information through broadcast media platforms such as television and radio. The farmers' increased knowledge of climate change and variability is consistent with those in the northern region of Benin (Obossou et al., 2023) and in the Rupandehi district of Nepal (Manandhar et al., 2011), where the broadcast media plays an important role in creating awareness of climate change and variability. The farmers attributed climate change and variability primarily to increased anthropogenic activities, which supports the prevailing scientific consensus (IPCC, 2014c). The results from the analysis of the physical climatological data revealed greater variability

in rainfall and wind speed patterns over the past two decades across the coastal savannah agroecological zone. The physical analysis corroborated the farmers' perspectives. Smallholder farmers in the northern Ethiopian highlands (Hubertus et al., 2023) and in northeastern Burundi (Batungwanayo et al., 2023) have observed similar variation in rainfall. The IPCC's AR5 predicts more erratic rainfall in the SSA region, potentially causing adverse effects on crop productivity, threatening food security, and negatively impacting farmers' livelihoods (IPCC, 2014c, 2022). Again, the farmers perceive extreme temperatures, droughts, pests, and diseases as the major climate risks that have an impact on their agricultural practices. These farmers' assertions are accurate, as the results in Papers 5 and 6 showed an increased frequency, duration, and intensity of drought and temperature variability in the zone. The farmers believe that the increased risks posed by climate change and variability in their agricultural methods have led to poverty, thereby impacting their means of livelihood and contributing to food insecurity in the country. The claims are accurate, as the literature shows that the agricultural sector of many countries faces substantial risks from climate change and variability, which threaten global food security and livelihoods (Aryal et al., 2020; Brink et al., 2023; IPCC, 2014c). The IPCC (2014c) stressed that farmers in developing countries encounter critical difficulties due to their rain-fed agricultural practices and low adaptation capacities. Despite the increased climate risks, the data in Paper 7 established that the smallholder farmers in the coastal savannah agroecological zone have employed various adaptation strategies such as crop diversification, cultivating improved seed varieties, using fertilisers, rearing livestock, and using irrigation. This is consistent with the previous studies of Batungwanayo et al. (2023), Shah et al. (2023), and Yaro (2013). The farmers identified a number of obstacles that hinder their activities, with financial constraints and high costs of farm inputs being the main obstacles, corroborating the previous studies of Batungwanayo et al. (2023), Shah et al. (2023), and Yaro (2013). Building on previous studies such as those conducted by Batungwanayo et al. (2023), Fosu-Mensah et al. (2012), and Shah et al. (2023), the result of the binary logistic regression analysis showed that farmers' socioeconomic characteristics, such as age, gender, education, and farming experience, are significant predictors of their adaptation decisions.

Climate risk perceptions and awareness among farmers are crucial for developing appropriate adaptation strategies (Yaro, 2013). Ado et al. (2019) contended that in the early phases of adapting to climate change and variability, having more knowledge is important. This is because the amount of awareness in a community indicates their level of exposure

to climate-related risks and affects their vulnerability to such impacts. Local knowledge and perceptions of climate risks should thus form the basis of agricultural policies in a bottom-up manner, as perceptions define adaptation outcomes (Yaro, 2013). The findings from Paper 7 have a major impact on smallholder farmers' agricultural practices in the coastal savannah agroecological zone. As the global climate continues to change with more risks emanating from changes in temperature, rainfall, and related extreme events, the development of an early warning system, continued awareness creation by the mass media, and improved academic engagement in addressing the present and potential climate risks could be beneficial for farmers. The patriarchal society of Ghana necessitates the implementation of targeted policies by the government and financial institutions, specifically designed to support women smallholder farmers. These policies should address the domination faced by women, as well as their limited access to resources such as land and capital and the unequal power dynamics they encounter. The Ministry of Food and Agriculture should implement subsidies for farm inputs, as this would safeguard farmers' agricultural practices, enhance their economic status, and improve their livelihoods.

7.3. Projection of possible future climate change scenarios for the coastal savannah agroecological zone of Ghana

The empirical data presented in Chapter 3 (Paper 8) revealed that the coastal savannah agroecological zone of Ghana has warmed substantially in the past four decades and rainfall has become more variable, supporting the literature consensus of a warming world (Alexander et al., 2006; Easterling et al., 2000). Based on the extreme temperature indices, the results established that the SU25, TXn, and TN90p significantly increased in the zone, which is consistent with the previous studies of Barry et al. (2018), Iyakaremye et al. (2022), and Moberg et al. (2006). Additionally, the results revealed a significant decrease in the TN10p and the DTR across the zone, supporting the earlier studies of Barry et al. (2018) and Easterling et al. (1997). The recent increase in land-use changes through urbanisation, population growth, and economic and industrial activities could be the cause of the decrease in the DTR in the zone. The coastal cities in Ghana, especially Accra (the capital), Tema, and Cape Coast, are known for their improved economic and industrial activities (GSS, 2013). Mohan and Kandya (2015) found that urban heat island effects, caused by urbanisation and population growth, lead to a decrease in DTR. The results revealed spatially varied warming trends for the TXx, TNx, TX10p, TX90p, and the CSDI across the zone, which supports previous studies by Ji et al. (2014) and Tong et al. (2019).

The results from the extreme rainfall indices revealed variations across the zone. For example, the locations of Cape Coast, Elmina, Moree, and Saltpond recorded a significant decrease in the RX1day, RX5day, SDII, and R10, whereas the other locations showed no significant change. The results showed a similar situation for the R95p and R99p, with Accra, Prampram, Ada Foah, Anloga, Keta, and Denu showing a significant decrease in the CDD, while the other locations showed no significant change. The R20, CWD, and PRCPTOT revealed no significant increase or decrease across the zone. The results support the evidence of a spatially variable nature of rainfall, as demonstrated in the previous studies conducted elsewhere by Abdullah et al. (2022), Santos et al. (2019), and Vondou et al. (2021). The findings further support the previous studies of Nicholson (2000) and Sanogo et al. (2015), which reported on the variable nature of rainfall in the West African region and the entire African continent, respectively.

The results of the possible future climate change projection showed that the CanESM2 (RCP 2.6, 4.5, and 8.5) and HadCM3 (A2 and B2) scenarios predict an increase in mean monthly maximum and minimum temperatures and rainfall for the coastal savannah agroecological zone in the 2030s, 2050s, and 2080s, despite the increase in variations. Based on the results, the mean maximum temperature is projected to reach the highest of 1.5 °C and the lowest of −1.6 °C across the zone. The results projected the mean minimum temperature to peak at 1.4 °C and the lowest at −2.3 °C. Under RCP 8.5, the results showed a projected mean annual change in maximum and minimum temperatures of 1.6 °C in the 2080s and 3.2 °C in the 2050s. The finding is consistent with the earlier studies of Birara et al. (2020) and Iwadra et al. (2019). Under all scenarios, the results expected the average monthly rainfall to vary between approximately 29.0% and 148% across the zone. The mean annual rainfall is expected to vary between −0.8% and 79% under all scenarios, supporting the previous study of Iwadra et al. (2019).

The results presented in Paper 7 have significant implications for water supply, agriculture, livelihoods, and the health of the inhabitants in the coastal savannah agroecological zone, as well as Ghana as a whole. The variations in temperature and rainfall could result in extreme events such as drought and floods in the zone, as established in Chapter 2 (Paper 5). Drought and flood incidence in the zone could have significant negative impacts on agricultural activities. For example, drought can cause crop failures, losses, and the general drying of crops, while floods can also damage seeds and seedlings and remove fertile soil, as established in Chapter 2 (Paper 7) and confirmed in the previous studies of Armah et al. (2010) and Ding et al. (2011). With the expected increase in rainfall,

there is also a possibility of a high incidence of diarrheal and intestinal diseases, as well as cholera. The projected increase in future rainfall in the zone will be beneficial for water resources, which will increase the annual river runoff.

7.4. Analysis of the influence of ENSO on rainfall variability in the coastal savannah agroecological zone of Ghana

The empirical data in Chapter 4 (Paper 9) provides useful insights on the variable nature of rainfall and how the different ENSO phases influence rainfall variability in the coastal savannah agroecological zone of Ghana between 1981 and 2021. Using a range of methods such as the cumulative departure index and the rainfall anomaly index, the results from Paper 9 revealed more above-average rainfall across the coastal savannah agroecological zone for the major season than the minor season and annual rainfall from 1981 to 2021. The 1980s and early 1990s experienced near- and above-average rainfall in the minor season, while the 2000s had below-average rainfall across the zone. The annual rainfall showed a similar pattern to that of the minor season, except for the Cape Coast location, which experienced above-average annual rainfall for most years. The above-average major-season rainfall was higher in the Denu area compared to the other areas, indicating local variations in the zone. The finding supports the previous studies conducted elsewhere by Ayanlade et al. (2017), Hein et al. (2019), and Nathan et al. (2020) that employed the cumulative departure index to analyse seasonal and annual rainfall variations.

The results of the rainfall anomaly index revealed that across the zone, the year 2020 experienced the highest positive anomaly for the major season rainfall, which occurred in the Denu area, and that of the minor season in 2021 in the Accra area. The highest negative anomaly for the major season also occurred in 1987 in the Accra area, as did the minor season in 1996. The highest positive and negative anomalies in both the major and minor seasons rainfall across the zone support the evidence in Chapter 2 (Paper 5), which established the increased drought and wetness event incidences, especially in the 1980s and 1990s. The finding further supports smallholder farmers' observation of drought as a major climate risk in the zone, as evidenced in Chapter 2 (Paper 7). The finding also agrees with the previous study by Nicholson et al. (2018), which highlighted the numerous drought periods in the West African region.

The coefficient of variation for the major season rainfall ranged from 17% to 22% compared to the minor season, which ranged from 36% to 46%. The coefficient of variation for the rainy days also varied between 95% and 114% for the major season, while that of

the minor season ranged from 102% to 106%. As a result, the coefficient of variation analysis revealed clear seasonal rainfall variability across the zone. For example, the major season rainfall variations were higher in the Denu area and lower in the Accra area. Minor seasonal variations also reached their highest and lowest in the Accra and Prampram areas, respectively. Several factors, including local convective activities caused by vegetation types and topographic dynamics (Braimah et al., 2022; Owusu, 2018), could be responsible for the local rainfall variations in the coastal savannah agroecological zone, as evidenced elsewhere by Li et al. (2022) and Shetty et al. (2022).

It was also revealed that the onset of rains for the major season was similar across the zone, which corresponded to day 92, while the cessation varied between days 183 and 212. The corresponding onset for the minor season rains ranged from days 245 to 249, and a similar cessation occurred on day 306 across the zone. The length of the minor and major seasons ranged from days 57 to 61 and 91 to 120, respectively. This analysis is essential for the smallholder farmers in the zone considering the variable nature of rainfall in the zone, which reflects the differential incidences of drought and wetness events as evidenced in Chapter 2 (Paper 5). The result of the onset and cessation of rains in both the major and minor seasons will benefit the smallholder farmers in the zone, especially as they have adopted the adaptation decisions of planting improved seed varieties and where irrigation systems are insufficient, as established in Chapter 2 (Paper 7).

The results from the ENSO influences on rainfall found no significant difference in total annual rainfall for the different ENSO phases. The results indicated that the different ENSO phases explained only a small variation in total annual rainfall, ranging from 1% to 12%. The La Niña phase was associated with greater mean annual rainfall and had greater influence on major season rainfall than the El Niño and Neutral phases. As the ENSO presents a small influence on total annual rainfall variability in the zone, it is conceivable that the ITCZ seasonal oscillation and other localised conditions serve as the dominant factors for rainfall variability in the zone. The seasonal movement of the ITCZ and the African Easterly Jet greatly influences rainfall in West Africa (Le Barbé et al., 2002; Nicholson, 2008). The north and south movements of the ITCZ cause more and no rainfall, respectively, in Ghana. The other localised effects could include the orographic effects of mountains, lakes, and large waterbodies.

The results presented in Paper 9 have several implications for the coastal savannah agroecological zone. The variations in rainfall amount, rainy days, onset, and cessation across the zone could affect several livelihood opportunities, especially those of the

smallholder farmers in the zone. Therefore, policy initiatives can address the variability by enhancing irrigation systems in the zone. For example, the Ayensu, Densu, and Volta Rivers can serve as a source of irrigation systems for smallholder farmers. For smallholder farmers, a timely climate forecast and information from the Ghana meteorological agency could also be helpful.

7.5. Analysis of the impacts of climate change and climate variability on marine and freshwater fish harvest and their effects on the socio-economic livelihoods of the communities in the coastal savannah agroecological zone of Ghana

Using a mixed-methods approach, the data presented in Chapter 5 (Paper 10) examined climate variability, coastal livelihoods, and the influence of ocean change on fish catch in the coastal savannah agroecological zone of Ghana. By using this approach, the thesis has enhanced our understanding of fishermen's perceptions of climate variability, its impacts on fish catch, and how it affects their livelihoods. The thesis established that a significant proportion of the fishermen in the zone are aware of the global climate variability crisis, with the broadcast media playing a substantial role. As established in Chapter 2 (Paper 7), the broadcast media's role in creating climate change and variability impact awareness has benefited not only the smallholder farmers in the zone, but also the fishermen. The fishermen attributed the causes of climate variability to negative anthropogenic actions, supporting the general scientific consensus (IPCC, 2014a, 2022). Although the fishermen have increased knowledge of climate variability, they require more information on the contribution of urbanisation as a major factor responsible for climate change as they were unable to recognise such impacts. Over the past two decades, the fishermen in the zone have observed a substantial decrease in the total annual fish catch. The physical fish catch data substantiated the fishermen's accurate observation of a declining fish catch in the zone. The fishermen attributed the decline in the total annual fish catch to several factors, including overfishing and light fishing, as well as climate variability. The finding is consistent with the previous studies of Sumaila et al. (2011) and Owusu and Adjei (2021). The results established that the oceanographic parameters accounted for 39% of the variability in the decrease in the total annual fish catch in the zone. This indicates that the additional factors causing decreased fish catch raised by the fishermen also play a substantial role. The fishermen face several obstacles that limit their activities, the most significant of which are high premix fuel prices and high-sea transhipment (saiko) activities. Other fishing communities in coastal Ghana (Owusu & Adjei, 2021) have

expressed these barriers, indicating a need for policy intervention. The results also revealed that the fishermen in the zone do not have satisfactory livelihood opportunities. For example, it emerged that fishermen do not own their houses or canoes used for fishing and have insufficient income to cover their household expenses. Apart from fishing, the zone's fishermen lack viable alternative sources of livelihood, contributing to their income insufficiency. The fishermen would greatly benefit from engaging in alternative sources of livelihood. The binary logistic regression analysis revealed that the fishermen's income insufficiency status could significantly decrease if they own their houses, canoes, and fish year-round. Therefore, government and other relevant institutional support could be beneficial to the fishermen. Financial institutions should lower interest rates and provide more flexible payment options to fishermen to boost their confidence in borrowing to support their activities.

Building on Paper 10 for improved policies for fishermen, Chapter 5 (Paper 11) employed a qualitative approach to provide deeper insights into how climate variability impacts coastal livelihoods. Paper 11 posited that while the interconnection between climate variability falls under the purview of the "hard sciences," a large amount of knowledge in this domain stems from qualitative analysis, which is useful for enhancing policy decision-making. Therefore, using a qualitative approach, the result from Paper 11 established coastal livelihood initiatives that could improve livelihood conditions, sustain fishermen's activities, and improve their general well-being.

Policymakers received strong recommendations in Paper 11 for the development of additional fishing opportunities, such as aquaculture for fishermen. Previous studies by Matera (2016) and Katikiro (2016) reported that fishermen greatly benefit from the development of alternative livelihood opportunities in coastal areas. Policy implementation of a diverse range of alternative livelihood options has the potential to mitigate the issues of overfishing and the harmful practices of fishermen, such as light fishing, indiscriminate fishing, and chemical usage in the coastal waters of Ghana. A policy initiative of this nature will not only sustain the fishermen but will also protect the fish species and sustain stock.

The Ministry of Fisheries and Aquaculture Development also has a crucial role to play in maintaining price stability and ensuring the reliability of premix fuel to safeguard the activities and livelihoods of fishermen and the fishing sector as a whole. While the Ministry's provision of a subsidised premix fuel policy is commendable, it is important to remove the bureaucratic procedures attached to its implementation. A direct communication channel between the Ministry and the fishermen in premix fuel delivery is

essential to prevent fuel hoarding and reselling at higher prices by intermediaries outside the fisheries sector. Also, the government, through the Ministry of Fisheries and Aquaculture Development, should implement effective policy measures aimed at curbing high-sea transhipment (saiko) activities. Foreign fishermen's presence in the coastal waters of Ghana poses a threat to the operations of the small-scale fishermen, as they depend solely on fishing for their livelihoods.

7.6. Analyses the influence of climate change on shoreline change and the impacts of erosion on the ecosystems and their implications on the communities in the coastal savannah agroecological zone of Ghana

Using remote sensing, geographic information systems, and field observation techniques, the data presented in Chapter 6 (Paper 12) analysed long-term shoreline change, the influence of erosion, and adaptation strategies on the central and eastern coasts of Ghana. The review in Chapter 1 (Paper 4), which highlighted the limited use of remote sensing and field observation approaches in presenting shoreline change and coastal erosion evidence for improving policy recommendations across the West African region, motivated the use of a multimethod approach in Paper 12. The data in Paper 12 revealed that Ghana's central and eastern coasts have eroded at rates faster than they are accreting. For example, between 1972 and 2021, the end point rate and linear regression rate statistics revealed that about 95.0% and 99.3% of the coast experienced erosion, compared to just 5% and 0.7% accretion, respectively. Both increased human interventions and hydrodynamic processes such as wave direction, frequency, and intensity contribute to the erosion of the central and eastern coasts of Ghana. The central and eastern coasts of Ghana are home to major economic, industrial, and historical sites (Boateng, 2012). These benefits attract a lot of people and increase human concentration, which exerts substantial pressure on the shoreline. Wave activities also have a significant impact on the coast, particularly the eastern coast, due to its soft geology and geomorphology (Boateng et al., 2017; Boateng, 2012; Ly, 1980).

The data also revealed that there has been a significant increase in artificial coastal structures since 1972. The shoreline armouring index in the central coast increased from 0.12 ('Average' class) in 1972 to 0.72 ('Maximal' class) in 2021, which shows a 60% increase. That on the eastern coast showed a 'Minimal' class index from 0.00 in 1972 to 0.08 in 2021, showing an 8% increase. Despite the increase in shoreline armouring, erosion is common on the coast. For example, the central coast, despite having 60% shoreline

armouring, still experienced erosion events of 97.2%, as revealed by the net shoreline movement statistics. That of the eastern coast is worse, with 8% shoreline armouring experienced erosion events of 100.0%. Field observation revealed that breakwaters armour the central coast, while jetties and groynes armour the eastern coast. According to Molina et al. (2019), breakwaters are more effective at retaining sediments than shore-normal structures like jetties. On the central coast, depositional events occur in the armoured areas, and more erosion events occur in the downdrift-exposed areas with no armouring, such as the open sandy beaches and the open coconut plantations. The armouring on the eastern coast is permeable and generates accretion and erosion updrift and downdrift, respectively (Anfuso et al., 2012). Thus, field observation revealed that the adaptation strategies (coastal armouring) implemented on the central and eastern coasts are hard engineering protection measures with no soft engineering or nature-based measures. This supports the global review in Chapter 1 (Paper 2), which highlighted coastal communities' low use of nature-based strategies to mitigate sea level rise impacts, such as shoreline change.

7.7. Highlights of the key policy implications of the thesis

The findings presented in Chapters 2–6 of this thesis have assessed and established how climate change and climate variability impacts have affected the socio-ecological systems (i.e., inhabitants, smallholder farmers, small-scale fishermen, shoreline change, and erosion of the coast) of Ghana's coastal savannah agroecological zone. The increasing impacts of climate change and climate variability on the zone warrant policy decisions and interventions to protect the people and sustain their livelihoods. The key policy initiatives recommended to policymakers and relevant stakeholders in Chapters 2–6 (Papers 5–12) are as follows:

1) To protect and sustain farming activities in the zone, regular monitoring of drought and wetness event incidences is necessary.
2) Meet the need for an early warning system, continued mass media awareness creation, and improved academic engagement in addressing the present and potential climate risks in the zone.
3) Implement the government and financial institutions targeted policies to support and address the unequal power dynamics faced by women smallholder farmers in accessing resources such as land and capital.

4) Introduce/Apply the Ministry of Food and Agriculture subsidies for farm inputs to safeguard farmers' agricultural practices and improve their livelihoods.
5) Fill the need for enhanced policies on irrigation systems in the zone to ensure year-round farming.
6) Boost fishermen's confidence in borrowing, financial institutions should lower interest rates and provide more flexible payment options.
7) Improve a policy initiative that prioritises providing practical training and support for fishermen to participate in additional livelihood activities such as agriculture (crops, livestock, and poultry), small business, occasional wage labour, and handicrafts. Fishermen in Port Antonio, Jamaica, Mtwara district, southern Tanzania, and the Providencia and Santa Catalina islands in Colombia have effectively utilized these alternative livelihood opportunities (Epstein et al. 2022; Katikiro 2016; Matera 2016), and Ghanaian policy decision makers can incorporate these activities.
8) Maintain the Ministry of Fisheries and Aquaculture Development price stability and ensure the reliability of premix fuel to safeguard the activities and livelihoods of fishermen and the fishing sector as a whole.
9) Apply, through the Ministry of Fisheries and Aquaculture Development, effective measures to curb high-sea transhipment activities.
10) Improved policy initiatives on soft engineering and nature-based coastal protection measures for Ghana's central and eastern coasts.

7.8. Methodological considerations

This thesis used a multimethod and interdisciplinary approach to assess climate change and climate variability impacts in the coastal savannah agroecological zone of Ghana. The impacts of climate change and climate variability continue to be a major issue in the twenty-first century (Easterling, 2007). Their adverse effects on socio-economic development and environmental sustainability have become a matter of utmost importance (FAO, 2017), necessitating assessment at various spatial scales (Wilbanks & Kates, 1999). The use of a multimethod approach such as mixed-method (quantitative and qualitative approaches), community interactions, field observations, and diverse data sources ensured triangulation, which allowed for the understanding of how the impacts of climate change and climate variability are affecting the socio-ecological systems in the coastal savannah agroecological zone of Ghana. For example, using a multimethod enabled smallholder

farmers and small-scale fishermen to share their in-depth experiences and social positions on how climate change and climate variability impact their activities and livelihoods. These experiences and positions are particularly relevant as they depict local knowledge of the diverse impacts that emerge from the changing and variable global climate. This local knowledge can be useful in climate risk adaptation decisions.

Several researchers, including Bhaskar et al. (2010) and Simonovic and Davis (2006), have encouraged the use of interdisciplinary approaches in studying climate change and climate variability impacts. Interdisciplinary approaches facilitate collaborations and interconnections between disciplines (Castree et al., 2014; Schipper et al., 2021), which aid in providing solutions to climate change and climate variability problems. Thus, through an interdisciplinary approach, this thesis has been able to address a relevant research gap on climate change and climate variability impacts in the coastal savannah agroecological zone of Ghana, contributing to improved policy decisions and the scientific literature.

The use of multimethod and interdisciplinary approaches in this thesis has enhanced the understanding of climate change and climate variability impacts in the coastal savannah agroecological zone of Ghana. However, it is important to carefully examine certain methodological considerations before making any generalisations about the findings due to the participation of different community groups (small-scale fishermen and smallholder farmers). In this thesis, the sample size of small-scale fishermen (Paper 10) was representative of the entire zone. However, the sample size of smallholder farmers (Paper 7) lacked representation due to the unavailability of community-specific data on the number of farmers at the municipal or district level and the difficulty in identifying smallholder farmers in the zone.

7.9. Further research

Although this thesis has provided valuable understandings into the impacts of climate change and climate variability in the coastal savannah agroecological zone of Ghana, there are still some unanswered questions that necessitate further research. First and foremost, there is a need for further research on drought assessment in the zone from an agricultural and hydrological perspective using multi-drought indices. The data presented in Paper 5 analysed meteorological droughts, which is an essential step in researching agricultural and hydrological droughts in the zone. The use of multi-drought indices, incorporating both site-based and remote sensing-based indices (Heim, 2002), will further enhance our

understanding of drought incidences in the zone. Again, there is a need to extend the day-to-day temperature variability framework from Paper 6 to the national level in order to improve the formulation of national climate change policies. Furthermore, research involving a larger representative sample of women smallholder farmers in the zone is required to understand the domination and power dynamics they encounter when accessing resources such as land and capital, as well as how they deal with such situations. The thesis did not address this policy recommendation. Conducting research to understand the challenges women smallholder farmers in the zone face in patriarchal society would provide a justification for improving policies to support their activities, as recommended in this thesis. Moreover, there is a need for further research on the livelihood conditions of the fishers in the zone to aid in broader policy decisions. Examining the livelihood conditions of other fisher groups, such as fish sellers, along with those of small-scale fishermen will be beneficial for improving policy decisions. Finally, there is a need for more research to characterise how physical oceanographic forcings, such as wave conditions, contribute to shoreline change and erosion on Ghana's central and eastern coasts.

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Annex

Annex 1

HOUSEHOLD QUESTIONNAIRE SURVEY FOR SMALLHOLDER FARMERS

My name is Johnson Ankrah. I am a PhD student at the Faculty of Arts and Humanities, Department of Geography, University of Porto, Porto, Portugal. I am conducting research on the impacts of climate change and variability in the coastal Savannah agroecological zone of Ghana, which will result in the award of a doctoral degree. The study aims to understand how climate change has affected the coastal Savannah agroecological zone, using evidence from both social and ecological systems. As the research presents the impacts of climate change and variability, it is equally important to understand your risk perception and adaptation strategies to the impacts of climate change and variability. Your experience as a smallholder farmer is valuable in this regard, as you will be able to drive policy direction.

This research is solely for academic purposes, and your responses will be used as such. This survey will take approximately 20 minutes of your time. Thank you for your time.

Please, tick [✓] and comment where necessary.

Socio-demographic characteristics

1. Age (a) <30 years [ ] (b) 30−40 years [ ] (c) 41−50 years [ ] (d) >50 years [ ]

2. Gender (a) Male [ ] (b) Female [ ] (c) Prefer not to say [ ]

3. Marital status (a) Married [ ] (b) Single [ ] (c) Divorced [ ] (d) Widow(er) [ ]

4. Highest educational level (a) Primary school [ ] (b) Junior secondary school/JSS (middle school) [ ] (b) Secondary/senior high school/SHS [ ] (c) Tertiary [ ] (d) No formal education [ ]

5. What is your household size? (a) Two [ ] (b) Three [ ] (c) Four [ ] (d) Five [ ] (e) >five [ ]

6. Are you native of this community (a) Yes [ ] (b) No [ ]

7. If No to question 6 above, when did you move this community and what was your reason?……

8. For how long have you been farming? (a) < 20 years [ ] (b) 20−30 years [ ] (c) > 30 years [ ]

Perceived causes of climate change and variability

9. Have you heard about climate change? (a) Yes [ ] (b) No [ ]

10. If Yes to question 11, from which source did you hear it? (a) Television [ ] (b) Radio [ ] (c) Newspaper [ ] (d) Other specify……...

11. What is causing climate change? (a) Natural events [ ] (b) Negative human actions [ ] (c) Both negative human actions and natural events [ ] (d) Punishment from God [ ] (e) Other specify……..

12. In your view, which of the following factors contributes to climate change? (a) Bush burning [ ] (b) Deforestation [ ] (c) A natural event [ ] (d) Vehicular fumes/carbon monoxide [ ] (a) Urbanization [ ] (a) Other specify ……..

Perception on climate change and variability

13. How do you perceive the temperature over the last two decades? (a) Increased [ ] (b) Decreased [ ] (c) No change [ ] (c) Don't know [ ]

14. How has the dry season temperature been over the last two decades? (a) Increased [ ] (b) Decreased [ ] (c) No change [ ] (c) Don't know [ ]

15. How has the rainy season temperature been over the last two decades? (a) Increased [ ] (b) Decreased [ ] (c) No change [ ] (c) Don't know [ ]

16. How has the length of the hot periods been over the last two decades? (a) Increased [ ] (b) Decreased [ ] (c) No change [ ] (c) Don't know [ ]

17. How has the length of the cold periods been over the last two decades? (a) Increased [ ] (b) Decreased [ ] (c) No change [ ] (c) Don't know [ ]

18. How do you perceive the rainfall over the last two decades? (a) Increased [ ] (b) Decreased [ ] (c) No change [ ] (c) Don't know [ ]

19. How has the wet season rainfall been over the last two decades? (a) Increased [ ] (b) Decreased [ ] (c) No change [ ] (c) Don't know [ ]

20. How has the dry season rainfall been over the last two decades? (a) Increased [ ] (b) Decreased [ ] (c) No change [ ] (c) Don't know [ ]

21. How has the intensity of rainfall events been over the last two decades? (a) Increased [ ] (b) Decreased [ ] (c) No change [ ] (c) Don't know [ ]

22. How do you perceive the wind over the last two decades? (a) Increased [ ] (b) Decreased [ ] (c) No change [ ] (c) Don't know [ ]

23. How has the intensity of the dry season wind been over the last two decades? (a) Increased [ ] (b) Decreased [ ] (c) No change [ ] (c) Don't know [ ]

24. How has the intensity of the wet season wind been over the last two decades? (a) Increased [ ] (b) Decreased [ ] (c) No change [ ] (c) Don't know [ ]

Perception on climate change and variability risk

25. Does climate change pose any risk to your activities? (a) Yes [ ] (b) No [ ]

26. If you answered yes to question 25 above, please select the climate-related risk that affects your activities from the table below. Please check all of the boxes that apply.

S/N	**Climate-related risks**	**Tick**
1	Drought	[ ]
2	Flood	[ ]
3	Pest and diseases on crops	[ ]
4	Heavy storms	[ ]
5	Livestock diseases	[ ]
6	Erosion/soil fertility loss	[ ]
7	Heat waves	[ ]
8	Delayed onset of rainfall	[ ]
9	Early cessation of rainfall	[ ]
10	Extreme temperature	[ ]

Perceived impacts of climate change and variability

27. Indicate the major effects that temperature changes have had on your farming activities

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28. Indicate the major effects that rainfall changes have had on your farming activities
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29. Indicate the major impacts that the changes in wind have had on your farming activities.
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30. Indicate the major impacts that extreme events have had on your farming activities.
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31. In your view, what are the overall impacts of the changes in the climate variables in Questions 27 –30?

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Adaptation strategies to climate change and variability

32. Please indicate the adaptation or coping strategies you use to manage the risk of climate change and variability.

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33. Which major constraints or barriers limit your adoption of the adaptation or coping strategies indicated in Question 32?

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INTERVIEW GUIDE FOR CHIEF FARMERS

My name is Johnson Ankrah. I am a PhD student at the Faculty of Arts and Humanities, Department of Geography, University of Porto, Porto, Portugal. I am conducting research on the impacts of climate change and variability in the coastal Savannah agroecological zone of Ghana, which will result in the award of a doctoral degree. The study aims to understand how climate change has affected the coastal Savannah agroecological zone, using evidence from both social and ecological systems. As the research presents the impacts of climate change and variability, it is equally important to understand your risk perception and adaptation strategies to the impacts of climate change and variability. As the chief farmer, I consider your experiences important to this study, as your responses will be able to drive policy direction.

This research is solely for academic purposes, and your responses will be used as such. This survey will take approximately 20 minutes of your time. Thank you for your time.

1. What is your age?

2. What is your marital status?

3. What is your highest level of education?

4. For how long have you been farming?

5. What are your responsibilities as a chief farmer?

6. Have you heard of climate change? If so, what do you think is causing it?

7. How have temperature, rainfall, and wind levels been over the past two decades?

8. Have you noticed any seasonal changes? Are there differences in temperature, rainfall, and winds, for example, during the wet, minor, and dry seasons?

9. Is climate change having an effect on your activities, as well as the activities of the other farmers you represent?

10. If climate change is impacting your activities, can you please tell me how it affects your activities as well as those of the other farmers you represent?

11. Do you farm all year or just during the growing season with your group? If not, what do you and your group do if you know of any during the non-farm period?

12. Apart from the impacts on your activities, does the changing climate also affect you personally? If so, how?

13. How serious is the climate change and variability issue to you and your group?

14. How do you adapt to or cope with the impacts of climate change and variability?

15. How about the farmers you represent? Are you aware of their adaptation or coping strategies?

16. Is the government making efforts to support the farming activities of you and your group from the impacts of climate change and variability?

17. Are there any other institutions or organizations that support your activities?

Annex 2

QUESTIONNAIRE SURVEY FOR FISHERS

My name is Johnson Ankrah. I am a PhD student at the Faculty of Arts and Humanities, Department of Geography, University of Porto, Porto, Portugal. I am conducting research on the impacts of climate change and variability in the coastal Savannah agroecological zone of Ghana, which will result in the award of a doctoral degree. The study aims to understand how climate change has affected the coastal Savannah agroecological zone, using evidence from both social and ecological systems. As the research presents the impacts of climate change and variability, it is equally important to understand your perception of climate-related impacts and how they affect your livelihood. Your experience as a fisher is valuable in this regard, as you will be able to drive policy direction.

This research is solely for academic purposes, and your responses will be used as such. This survey will take approximately 20 minutes of your time. Thank you for your time.

Please, tick [✓] and comment where necessary.

Socio-demographic characteristics

1. Age (a) <30 years [ ] (b) 30−40 years [ ] (c) 41−50 years [ ] (d) >50 years [ ]

2. Gender (a) Male [ ] (b) Female [ ] (c) Prefer not to say [ ]

3. Marital status (a) Married [ ] (b) Single [ ] (c) Divorced [ ] (d) Widow(er) [ ]

4. Highest educational level (a) Primary school [ ] (b) Junior secondary school/JSS (middle school) [ ] (b) Secondary/senior high school/SHS [ ] (c) Tertiary [ ] (d) No formal education [ ]

5. What is your household size? (a) Two [ ] (b) Three [ ] (c) Four [ ] (d) Five [ ] (e) >five [ ]

6. How long have you lived in this community? (a)10−20 years [ ] (b) 21−30 years [ ] (c) 31−40 years [ ] (d) 41−50 years [ ] (e) 51 years and above [ ]

7. How long have you been involved in this activity? (a)10−20 years [ ] (b) 21−30 years [ ] (c) 31−40 years [ ] (d) 41−50 years [ ] (e) 51 years and above [ ]

Perceived causes of climate change and variability

8. Have you heard about climate change? (a) Yes [ ] (b) No [ ]

9. If you answered "yes" to question 8, from which source did you hear it? (a) Television [ ] (b) Radio [ ] (c) Newspaper [ ] (d) Other specify…….....

10. What is causing climate change? (a) Natural events [ ] (b) Negative human actions [ ] (c) Both negative human actions and natural events [ ] (d) Punishment from God [ ] (e) Other specify…….. ……..

11. In your view, which of the following factors contributes to climate change? (a) Bush burning [ ] (b) Deforestation [ ] (c) A natural event [ ] (d) Vehicular fumes/carbon monoxide [ ] (a) Urbanization [ ] (a) Other specify ……

Climate-related impacts

12. Which of the following impacts has been the most common in this area over the last two decades, in your opinion? (a) Coastal erosion [ ] (b) Sea level rise [ ] (c) Storms

and waves [ ] (d) Rising temperatures [ ] (e) Unpredictable rainfall [ ] (f) Other specify ……

13. Which factors do you think contribute to the option selected in Question 12? (a) Sand mining [ ] (b) Shoreline change [ ] (c) High wave energy [ ] (d) Increased carbon dioxide (CO_2) concentration in the atmosphere [ ] (e) Warming of the Sea [ ] (d) Other specify ……

Impacts on fish and fish stocks

14. Does climate change have any impact on fish populations? (a) Yes [ ] (b) No [ ]

15. Do you think changes in sea surface temperature affect fish and fish stocks? (a) Yes [ ] (b) No [ ]

16. What about the changes in sea surface salinity? Does it have any effect on fish? (a) Yes [ ] (b) No [ ]

17. How do you perceive the total number of fish caught annually over the last two decades? (a) Increased [ ] (b) Decreased [ ] (c) No change [ ] (d) Don't know [ ]

18. If you answered "decreased" in question 17, will you blame this solely on the impacts of climate change?

(a) Yes [ ] (b) No [ ]

19. If you answered "no" to question 18, what other factors could be causing the low fish catch?

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20. What is the major problem you face that limit your fishing activities?

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……

Livelihoods

21. Do you own the house you live in? (a) Yes [ ] (b) No [ ]

22. Do you own the canoe or boat you use for fishing? (a) Yes [ ] (b) No [ ]

23. Is the income you make from fishing enough to pay for your living expenses and those of your household? (a) Yes [ ] (b) No [ ]

24. If you answered “no” to question 23, where do you find income to supplement your households’ living expenses? (a) Borrow money from relatives [ ] (b) Borrow from fish sellers [ ] (c) Government support [ ] (d) Other specify ……...

25. Is it easy to secure loans from banks (both private and public) to improve your fishing activities? (a) Yes [ ] (b) No [ ]

26. Does the changing climate have any impact on your health? (a) Yes [ ] (b) No [ ]

27. If you answered "yes" to question 26, please describe the negative related sickness you experience

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28. Do you go fishing all year? (a) Yes [ ] (b) No [ ]

29. If you answered “no” to question 28, indicate the activity you engage in when not fishing.

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30. Can you say that the activities mentioned in question 29 helped you cope with the situation and improve your livelihood? (a) Yes [ ] (b) No [ ]

INTERVIEW GUIDE FOR FISHING LEADERS

My name is Johnson Ankrah. I am a PhD student at the Faculty of Arts and Humanities, Department of Geography, University of Porto, Porto, Portugal. I am conducting research on the impacts of climate change and variability in the coastal Savannah agroecological zone of Ghana, which will result in the award of a doctoral degree. The study aims to understand how climate change has affected the coastal Savannah agroecological zone, using evidence from both social and ecological systems. As the research presents the impacts of climate change and variability, it is equally important to understand your perception of climate-related impacts and how they affect your livelihood. As the leader of the fisher group, I consider your experiences important to this study, as your responses will be able to drive policy direction.

This research is solely for academic purposes, and your responses will be used as such. This survey will take approximately 20 minutes of your time. Thank you for your time.

1. What is your age?

2. What is your marital status?

3. What is your highest level of education?

4. For how long have you been involved in this activity?

5. How many people are in your family?

6. Have you heard about climate change? If so, what is it about, and what is causing it?

7. What major climate change impacts have you observed in this area since you started fishing?

8. Is this impact the result of natural variability or is it due to negative anthropogenic activities?

9. Does climate change have an impact on fish populations and stocks?

10. Does the total number of fish caught by your group keep increasing every year or is it the opposite?

11. If the annual catch by your group has been decreasing, could you attribute this to the increase in sea surface temperature, or are there other significant factors causing this?

12. Can you please share with me the major challenges you and your group face that affect your fishing activities?

13. Apart from the impact of climate change on your fishing activities, does it affect you personally as well as your group?

14. Do you own the house in which you and your family live? How about your group members? Do you know if they own their homes or if they rent them?

15. How about the canoe or boat you use for fishing? Is it yours, or does it belong to someone else?

16. Are you satisfied with the income you make from fishing? Is it enough to cater for your family's expenses? How about your group members?

17. Does the government provide subsidies or incentives to support your fishing activities?

18. Is it easy for you or anyone in your group to obtain financing from public or private banks?

19. The break season for fishing for some months during the year imposed by the government prevents you from fishing all year. Do you and your group follow this regulation?

20. Do you and your group engage in other income-earning activities during the break season to improve your livelihoods?

21. Do you consider these activities as livelihood coping strategies?

Annex 3

INFORMED CONSENT FOR SMALLHOLDER FARMERS

My name is Johnson Ankrah. I am a PhD student at the Faculty of Arts and Humanities, Department of Geography, University of Porto, Porto, Portugal. I am conducting research on the impacts of climate change and variability in the coastal Savannah agroecological zone of Ghana, which will result in the award of a doctoral degree.

The study aims to understand how climate change has affected the coastal Savannah agroecological zone, using evidence from both social and ecological systems. As the research presents the impacts of climate change and variability, it is equally important to understand your risk perception and adaptation strategies to the impacts of climate change and variability. I am interested in understanding your perceptions of climate-related risks, the impacts they have on your farming activities, and how you cope with or adapt to them. There is no risk to you; rather, your experience as a smallholder farmer is valuable in this regard, as you will be able to drive policy direction. This will take about 20 minutes of your time.

This research is solely for academic purposes. You will remain anonymous, and your name will not appear anywhere. Except for me, no one will have access to your personal information or responses. I will make every effort to ensure your confidentiality. I will assign code references to your responses. The references will be transferred into an electronic format and will be password-secured. All resulting hard copies shall be destroyed in accordance with the University of Porto's ethical guidelines. If I write an article about this study, I will protect your identity and not reveal any of your personal details. I will assign numbers or letters, not your name.

Your participation in this study is voluntary, and you have the right to withdraw at any time. You are also free to request that your already-captured responses be withdrawn from or deleted from the research if you so desire. After signing this consent form, you still have the right to withdraw at any point in time. If you want more information about the research at any time, please do not hesitate to get in touch with Mr. Ankrah (mobile number: +351938140383, email: up201701629@edu.letras.up.pt).

CONSENT

I have read the study and agreed to participate in it. I am aware that I am free and have the right to withdraw from the study at any point in time without justification.

_____ _____

Signature Date

Annex 4

ETHICS COMMITTEE APPROVAL

U.PORTO
FLUP FACULDADE DE LETRAS
UNIVERSIDADE DO PORTO

LEGAL OPINION OF THE ETHICS COMMITTEE OF FLUP

Resolution N.º 31 /CEFLUP/

Project reference:

Project title: Assessing climate change and climate variability impacts in the coastal Savannah agroecological zone of Ghana.

1. **Submission Date of the Project to the Ethics Committee**: 07/12/2022
2. **Proponent /Principal investigator**: Ankrah Johnson
3. **Research team**: Prof. Doutora Ana Monteiro, Prof. Doutora Helena Madureira
4. **Documents attached to the request** (description): Summary of the research project; questionnaires and interview scripts; the information sheet for participants, an informed consent form, a protocol for data management, a curriculum vitae.
5. **Nature and context of the project** (project to be developed by):
6. **Funding**:
   - ☐ Funded
   - ☒ Not Funded
7. **Location or Places where the research will be carried out**: Costal areas of Ghana, West Africa

Research objetives: The study takes place as part of a PhD thesis and aims to understand how climate change has affected Ghana's coastal savannah agro-ecological zone, analysing the impact from both a social and environmental perspective on this zone with significant impact on the country's GDP.

The study defines five specific objectives:

- Assess climate change and climate variability.
- Project possible future scenarios of climate change and climate variability.
- Analyse the influence of these changes on rainfall variability.
- Analyse the impacts of these changes on marine and freshwater fish harvest.
- Analyse the influence of these changes on the effects of shoreline erosion and the impacts of this erosion on ecosystems and communities.

8. **Activities to be carried out**: The study is multidisciplinary in nature and employs multiple methodologies in order to assess the environmental, physical and social impact of climate change and climate variability. Field studies, surveys and community interaction approaches will be used to achieve the study objectives.
9. **Data collection techniques**: Observations, questionnaires and interviews will be administered to smallholder farmers and fishers in the zone.
10. **Participants**: Smallholder farmers and fishers.
11. **Inclusion criteria** (If applicable): The study aims to administer questionnaires through convenient sample to the smallholder farmers and fishers in the zone as well as chief farmers (leaders of samallholder farmers) and leadrs of fishers´groups, who are regarded as key informants for the study.

12. **Risks/ benefits of the research for the participants**: The study pose no risks and instead stands to benefit smallholder farmers and fishers along Ghana´s coast.
13. **Informed consent and confidentiality of the information**: The researcher provides in the informed consent document for the possibility for anyone to withdraw from participation.
14. **Data Manegement**: All resulting hard copies from the inqueries sahl be destroyed in accordance with the University of Porto's. ethical guidelines.
15. **Project end date**: December 2024

RESOLUTION:	
The Rapporteur: The Research Project "Assessing climate change and climate variability impacts in the coastal Savannah agroecological zone of Ghana", is part of a PhD thesis. The personal data of research participants (smallholder farmers and fishers) are collected and protected in keeping with the GDPR rules. This research does not involve any risk or disadvantage for the participants. The Ethics Committee considers that the ethical implications of the research are protected, approving the study presented. Assinado por: **Thomas Juan Carlos Husgen** Num. de Identificação: PASDE-C4W16XC Data: 2023.01.08 10:14:33+00'00'	The Head of the Ethics Committee: Assinado por: **Maria Isabel Correia Dias** Num. de Identificação: 07396720 Data: 2023.01.08 15:17:40 +0000 CHAVE MÓVEL