

Research Article

Climate Change, Associated Risks and Environmental Damages in Mozambique: A Systematic Review

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Abstract

Climate change is one of the most significant environmental and societal challenges of the twenty-first century. Its effects are expressed through changes in temperature and precipitation patterns, the increasing frequency and intensity of extreme events, environmental degradation, and growing risks to human livelihoods and well-being. Mozambique is particularly vulnerable because of its exposure to floods, droughts, tropical cyclones, coastal erosion, and other climate-related hazards, as well as its limited adaptive capacity in many communities. This article aims to review the state of the art on climate change and associated environmental risks, with particular emphasis on studies conducted in Mozambique. It also seeks to identify the main theoretical approaches, research trends, and knowledge gaps in the analysis of climate variability, vulnerability, impacts, resilience, and adaptation. The study adopted a qualitative approach based on a narrative literature review of scientific articles, reports, and other relevant academic publications addressing climate change, climate variability, environmental risks, vulnerability, resilience, and Mozambique. The reviewed literature was analyzed thematically in order to identify the principal concerns, methodologies, and findings presented by previous studies. The review shows that the international literature has substantially advanced the understanding of the environmental and human consequences of climate change, particularly in relation to vulnerability, adaptation, resilience, and disaster risk. In Mozambique, however, most studies focus on the impacts of natural disasters, vulnerability assessments, resilience, adaptation strategies, and projected climate-change scenarios. Comparatively fewer studies provide robust statistical analyses of historical temperature and precipitation records to demonstrate observed climate anomalies and long-term climatic trends. This limitation reduces the empirical basis for distinguishing between climate variability and anthropogenic climate change at local and regional scales. The article concludes that future research in Mozambique should combine vulnerability and impact assessments with systematic analyses of observed climatic data, climate indices, and regional climate projections. Such an integrated approach would strengthen the scientific basis for environmental planning, risk reduction, adaptation policies, and sustainable territorial development.

Keywords

Climate Change, Climate Variability, Climate Risks, Extreme Events, Mozambique

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1. Introduction

Climate change refers to long-term shifts in temperature and precipitation patterns, primarily driven by human activities and compounded by natural factors. These changes generate risks with significant implications for both the environment and human societies, particularly regarding environmental damages and the identification of the most affected components. The objective of this article is to provide a reflection on scientific trends in research concerning climate change, associated risks, and environmental damages, as well as to offer a briefing on studies conducted in Mozambique. Accordingly, this paper comprises the following subsections: (i) conceptual nexuses and distinctions among climatic change and climate variability; (ii) the science of climate change; (iii) a synthesis of the six IPCC assessment reports; (iv) climate extreme events; (v) theories underpinning climatic changes; (vi) studies on climate change and environmental damages in Mozambique; followed by final considerations and key references.

2. Materials and Methods

This study systematically reviewed the literature on climate change and the risks associated with extreme events. The review included 80 peer-reviewed articles: 80% adopted a global perspective, while 20% focused specifically on Mozambique. Reports from the Intergovernmental Panel on Climate Change (IPCC) were also examined. Materials were selected based on recency and peer-review status. The resulting theoretical framework synthesizes the cited authors' findings in language accessible to both scientific and general audiences, supporting the dissemination of information relevant to society, particularly in Mozambique.

For this purpose, the following search platforms were used: ScienceDirect (<https://www.sciencedirect.com/>); Google Scholar (<https://scholar.google.com.br/>); and MDPI (<https://www.mdpi.com/>). The three platforms selected for this research encompass a substantial number of leading journals publishing studies related to climate change.

3. Results and Discussion

3.1. Climate Change and Climate Variability: Conceptual Nexuses and Distinctions

Key conceptual studies on climate change include Marengo Valverde (2021); Carvalho (2017); Confalonieri (2003); Magalhães et al. (1988); Xavier et al. (1992, 1994); Marengo (2002); Marengo and Soares (2003); Marengo and Silva Dias (2006); Berlato and Fontana (2003); Souza Filho (2003); Tucci (2003a, b); IPCC (2001, 2014, 2018); Alexander et al. (2006); Vincent et al. (2005); Milly et al. (2005); Charrua et al. (2021); Haylock et al. (2006); and Marengo et al. (2007).

Drawing on these authors, the main interpretations of the concepts can be synthesized as follows:

Although “Climate Change,” “Environmental Damage,” and “Climate Variability” are closely related, each has a distinct emphasis and meaning, as explained below:

“*Climatic Change* refers to significant, persistent shifts in the statistical patterns of Earth's climate caused by natural processes or human activities” [32, 64, 65]. “*Climate Variability*, by contrast, focuses on natural fluctuations in the climate system across all temporal scales, ranging from months to millennia” [64, 65]. It describes inherent oscillations, such as the El Niño–La Niña phenomenon, which induce temporary alterations in climatic patterns, including temperature, precipitation, and atmospheric pressure. Unlike climate change, which implies a long-term trend in climatic patterns, climate variability characterizes short- to medium-term fluctuations within those patterns.

Nexuses and Distinctions Among the Concepts:

- 1) *Conceptual Scope:* All two concepts are interconnected in that they describe processes influencing Earth's climate system. Climate variability constitutes a natural component of the climate system, whereas climatic change may be viewed as a deviation from these natural patterns, whether due to natural or anthropogenic drivers. Climate change encompasses both phenomena, emphasizing modifications in the climate irrespective of their origin.
- 2) *Causality and Effects:* Climate variability can influence the perception and measurement of climatic change, as short-term fluctuations may obscure or amplify long-term trends. Conversely, long-term climatic changes can change the characteristics of climate variability.
- 3) *Temporal Scales:* A critical point of interconnection lies in temporal scale. Climate variability operates over shorter timeframes, whereas climatic change refers to trends observed over decades to centuries. Climate change provides an integrative perspective on how the climate is evolving across both short and long temporal horizons.

In summary, while climatic change often denotes long-term impacts on Earth's climate including the role of human activities, climate variability describes natural fluctuations within this system. A clear understanding of these concepts is fundamental to studying and addressing contemporary climate challenges.

3.2. The Science of Climate Change

Climate and the climate system are foundational concepts in atmospheric science, each playing a critical role in understanding how Earth sustains its diverse environmental condi-

tions, [29]. The climate system, by contrast, is a more comprehensive entity that encompasses not only the atmosphere but also the hydrosphere (water), cryosphere (ice), lithosphere (land), and biosphere (life). This system is characterized by dynamic interactions among its components, wherein each part can influence and be influenced by the others. “Driven by solar energy which is unevenly distributed across Earth’s surface due to planetary motions relative to the Sun, this energy flux powers atmospheric and oceanic circulation, thereby shaping global climate patterns,” [22]. The science of climate change is reflected in the works of Argenal [6, 8, 11, 12, 17, 28, 30, 32, 49, 63, 66]. These studies seek to relate climatic shifts to diverse interconnections and feedback mechanisms.

3.2.1. Interconnections and Feedbacks

Interactions among components of the climate system can generate feedbacks that either amplify or dampen climate change. For instance, the melting of polar ice, a cryospheric component reduces the amount of solar radiation reflected back to space (albedo effect), thereby increasing heat absorption by Earth’s surface and leading to further warming, “Such complex interactions are essential for understanding contemporary climate change and projecting future climatic variations,” [24].

In summary, climate describes long-term atmospheric patterns in a specific region, whereas the climate system denotes the interconnected ensemble of physical, chemical, and biological components that collectively shape and modify Earth’s climate. Climate science strives to elucidate both concepts in detail, leveraging observations and numerical models,” [57, 78]. *The science of climate change comprises the following core components:*

- 1) *Evidence of Climate Change:* Collection of data on global temperatures, precipitation patterns, frequency and intensity of extreme events, glacier and polar ice cap melt, and sea-level rise. This is achieved through direct observations and analysis of paleoclimatic records, such as tree rings, ice cores, and ocean sediments.
- 2) *Causes of Climate Change:* Identification and analysis of natural drivers (e.g., volcanism, orbital variations, solar activity) and anthropogenic drivers (primarily fossil fuel combustion and deforestation). A central focus is the accumulation of greenhouse gases such as CO₂, CH₄ (methane), and N₂O (nitrous oxide) in the atmosphere.
- 3) *Climate Modeling:* Development and application of climate models to simulate past, present, and future climates. These sophisticated computational tools integrate physical and chemical laws to project how the climate system will respond to varying greenhouse gas emission scenarios.
- 4) *Impacts of Climate Change:* Assessment of climate change effects on natural and human systems, including human health, agriculture, water resources, and biodiversity. This component also evaluates societal vulnerability and adaptive capacity.

- 5) *Mitigation and Adaptation:* Research on strategies to reduce greenhouse gas emissions (mitigation) and to adjust societies to cope with climate impacts (adaptation). This encompasses renewable energy policies, energy efficiency measures, reforestation, and the development of carbon capture and storage technologies. However, this reveals to us that “Climate change may increase occupational health and safety risks, particularly through extreme heat and changing working conditions” [1]. Similarly, “The analysis of underestimated climatic variables can improve understanding of vegetation responses to regional climatic conditions” [37].

3.2.2. Challenges and Advances

A primary challenge in climate change science lies in the inherent uncertainty of future projections, stemming from the climate system’s complexity and unpredictable human variables, such as governmental policies and technological breakthroughs. Nevertheless, advances in climate modeling, enhanced observational resolution and coverage, and improved understanding of climatic processes are progressively reducing these uncertainties, thereby delivering more accurate information for policymakers and the public. Climate change science remains a vital and rapidly evolving research domain, essential for guiding the global response to climate change and fostering a sustainable future.

3.3. Synthesis of the Six IPCC Assessment Reports

The Intergovernmental Panel on Climate Change (IPCC) is an international body established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). Its primary mandate is to deliver comprehensive scientific assessments on climate change, its associated impacts and future risks, and to propose mitigation and adaptation strategies. This subsection presents an analysis of the IPCC’s First through Sixth Assessment Reports, identifying greenhouse gas types and sources, the impacts of climate change on humans, animals, and the environment, and strategies to combat climate change. Emphasis is placed on the Sixth Assessment Report (AR6), drawing on insights from,” [16]:

- 1) The First through Sixth IPCC Assessment Reports evaluate greenhouse gas emissions, their sources and sinks, and provide historical data on the rise in global surface temperature.
- 2) The reports underscore the anthropogenic nature of greenhouse gas emissions, notably from fossil fuel combustion, agriculture, and landfills.
- 3) They address stratospheric ozone depletion and the negative radiative forcing induced by halocarbons and chlorofluorocarbons (CFCs).
- 4) The assessments highlight the need for further research to enhance understanding and address uncertainties in

climate change science.

- 5) They identify greenhouse gas types and sources and delineate their contributions to climate change.
- 6) The reports outline mitigation strategies proposed by the IPCC to counteract climate change.
- 7) They furnish the scientific basis required to address the adverse effects of climate change and global warming.

The IPCC's Sixth Assessment Report (AR6), the most recent and thus most pertinent to this study offers a comprehensive evaluation of anthropogenic disruption of the climate system, its impacts on ecosystems and society, and the urgency of mitigation and adaptation responses. AR6 includes projections under future emission scenarios, examines the role of tourism in climate change, addresses urban dimensions of climate change, and discusses the communication of IPCC products. The report provides a consistent assessment of global mean temperature outcomes across multiple climate models and evaluates the effectiveness of mitigation pathways in limiting global warming. Accordingly, "the IPCC 2014 Synthesis Report emphasized the need for combined mitigation and adaptation actions to reduce climate risks" [48]. However, knowledge gaps remain regarding the integrated impacts of climate change on tourism and the efficacy of adaptation strategies at the destination scale. In this regard, "The IPCC Fourth Assessment Report consolidated the evidence that warming of the climate system is unequivocal" [26]. Furthermore, "The IPCC Fifth Assessment Report highlighted that the impacts of climate change are already affecting human and natural systems" [27].

AR6 also emphasizes society's carbon footprint but overlooks the social carbon footprint and the challenges faced by developing nations and their urban populations in mitigation and adaptation efforts. Furthermore, it discusses implications of assessment methodologies and introduces a Python package to reproduce temperature assessments, thereby offering a community tool for evaluating emission pathways and their corresponding temperature outcomes.

3.4. Climate Change and Risks: Foundational Theories

In this regard, "Climate extreme indices derived from the CMIP5 ensemble allow the assessment of future projections of the frequency and intensity of extreme events" [28, 30, 60] accordingly, "Projections based on CMIP5 and CMIP6 models suggest the persistence of quasi-resonant amplification patterns associated with extreme summer events" [22]. In this regard, "Global warming results from the progressive retention of infrared radiation by greenhouse gases in the atmosphere" [7]. Foundational theories on climate change and environmental risks are essential for understanding planetary-scale transformations. This analysis draws on seminal works by: "Mitigation Needs Adaptation: Tropical Forestry and Climate Change", [20]; "Well Known to a Few People: Attribution of Excess Atmospheric CO₂ and Resulting Global Temperature

Change to Fossil Fuel and Land Use Change Emissions", [32, 58]; "Improved Attribution of Climate Forcing to Emissions by Pollutant and Sector", [56]; "Changes in the Mean and Variability of Temperature and Precipitation over Global Land Areas", [5]; "Projected Changes in Quasi-Resonant Amplification by CMIP5 and CMIP6 toward the Persistence in Extreme Summer Weather Events", [27]; "Global Warming: A Critique of the Anthropogenic Model and its Consequences", [50]; "Global Warming and Greenhouse Gases", [10]; "Global Warming: A Study of Erratic Fluctuations in Land and Oceanic Temperature as Influenced by Heightening Industrial Activity and Population Growth", [19]; "Global Change: More Than Climate", [31]; and, "Scientific Basis for the Greenhouse Effect", [29]. These studies converge around the following theoretical pillars:

- 1) *Global Warming*: The most widely accepted theory posits that Earth's mean temperature is rising due to anthropogenic emissions of greenhouse gases primarily carbon dioxide (CO₂), methane (CH₄), and nitrogen oxides stemming from fossil fuel combustion, deforestation, and intensive agriculture. Global mean annual temperature over land areas increased during the recent period (1991–2020) relative to the reference baseline (1951–1980), [4, 10, 29]. The most pronounced warming occurred in subtropical and mid-latitude zones (+0.7 °C), followed by tropical regions (+0.5 °C). Temperature variability across global land areas remained largely unchanged.
- 2) *Greenhouse Effect*: A natural process wherein solar energy absorbed by Earth's surface is partially re-emitted as heat and trapped by atmospheric greenhouse gases, maintaining conditions suitable for life. "Anthropogenic amplification of these gases intensifies this effect, causing excessive warming" [33].
- 3) *Shifts in Climatic Patterns*: Climate change induces significant alterations in climatic regimes, including increased frequency and intensity of extreme events (storms, droughts, heatwaves) and modifications in precipitation patterns and mean land temperatures.
- 4) *Climate Feedbacks*: Multiple feedback mechanisms within the climate system can either accelerate or dampen warming. For instance, Arctic ice melt reduces surface albedo, enhancing heat absorption and further amplifying global warming, with cascading impacts on diverse ecosystems.
- 5) *Radiative Equilibrium Theory*: This theory addresses the balance between solar energy absorbed by Earth and thermal radiation emitted to space. Perturbations to this equilibrium—driven by elevated greenhouse gas concentrations or variations in solar activity, can trigger climatic shifts.
- 6) *Climate Forcing Theory*: Closely linked to radiative equilibrium, this framework examines external "forcings" that alter Earth's energy balance, including solar variability, volcanic eruptions, and anthropogenic activities

such as fossil fuel combustion and land-use change.

- 7) *Natural Climate Variability Theory*: This perspective explores how natural factors—oceanic oscillations (El Niño–La Niña), volcanic activity, and orbital variations, contribute to short- and long-term climate variability.
- 8) *Anthropocene Theory*: Although not strictly a climatic theory, it is pivotal for contextualizing contemporary climate change. It posits that humanity has entered a new geological epoch defined by dominant human influence, marked by profound alterations to the climate system.
- 9) *Energy Transition Theory*: Primarily a response-oriented framework, it emphasizes the shift from fossil fuels to renewable energy sources as a core mitigation strategy to reduce greenhouse gas emissions.

These theories are underpinned by extensive empirical evidence and are fundamental to comprehending environmental risks associated with climate change. Mitigation and adaptation remain central domains of scientific inquiry and policy action, aimed at reducing risks and safeguarding ecosystems and human societies. However, “Some critical approaches question the magnitude and implications attributed to anthropogenic emissions in global warming” [50].

The philosophical foundations most relevant to this study, aligned with the aforementioned theories, can be synthesized into two neopositivist-oriented frameworks: *Dynamic Climatology* and *General Systems Theory*.

1) *Dynamic Climatology*

“The ensemble of meteorological phenomena characterizing the mean atmospheric state over a given location on Earth’s surface,” [40, 51], cites Hann’s (1882). Köppen’s conception of climate as “the mean atmospheric state and ordinary weather process at a given place, acknowledging that weather varies while climate remains constant.” These definitions foreground the notion of averages, reflecting what, [9], terms “separatist climatology.” In contrast, [62], redefined climate as “the atmospheric environment constituted by the series of atmospheric states at a given location in their habitual succession,” thereby introducing *Dynamic Climatology*. Sorre’s contribution was paradigm-shifting, introducing the concepts of “rhythm” and “succession” into climatic definition, complemented by key advances from, [40, 52, 59, 66]. In this sense, “the study of air masses is fundamental to understanding the origin and dynamics of regional rainfall patterns” [40],

Rhythmic analysis of weather types proposes a climatic study wherein elements are integrated within the temporal unit of “weather,” revealing daily climatic variability. The rhythm of this succession depends on atmospheric fluxes governed by pressure centers, thus elucidating the genesis of climatic phenomena. “Standard years” represent varying degrees of approximation to the “habitual” rhythm, correlated with years of rhythmic irregularity. In contemporary research, *Dynamic Climatology* has emerged as the foundational theoretical approach to climate.

Dynamic Climatology focuses on understanding and modeling the forces driving Earth’s climate systems, distinguishing itself from traditional climatology which emphasizes observation and description of mean climatic conditions by integrating principles from physics, chemistry, and mathematics to analyze interactions among climate system components. In this framework, “Dynamic climatology makes it possible to analyses rainfall variability in Southeast Africa based on regional atmospheric circulation” [67]. Its core aspects include:

- a) *Atmospheric Circulation Systems*: Examination of air movement patterns, including jet streams, high- and low-pressure systems, and circulation cells (Hadley, Ferrel, and Polar).
- b) *Ocean–Atmosphere Interaction*: Analysis of critical couplings between oceans and atmosphere, exemplified by El Niño and La Niña.
- c) *Climate Modeling*: Development of computational simulations using mathematical equations to represent physical and chemical processes, essential for projecting future climate states.
- d) *Climate Feedback*: Investigation of feedback mechanisms, such as ice–albedo feedback, wherein polar ice loss accelerates warming.
- e) *Climatic Variations and Anomalies*: Assessment of natural (volcanic activity, solar variability) and anthropogenic (greenhouse gas emissions) drivers of climate change.
- f) *Climate Teleconnections*: Study of how climatic changes in one region (e.g., Pacific sea surface temperatures) influence distant regions (e.g., North America, Europe).

This field is indispensable for advancing climate understanding and formulating adaptation and mitigation strategies. Researchers continually refine model accuracy and deepen comprehension of the climate system’s complexity.

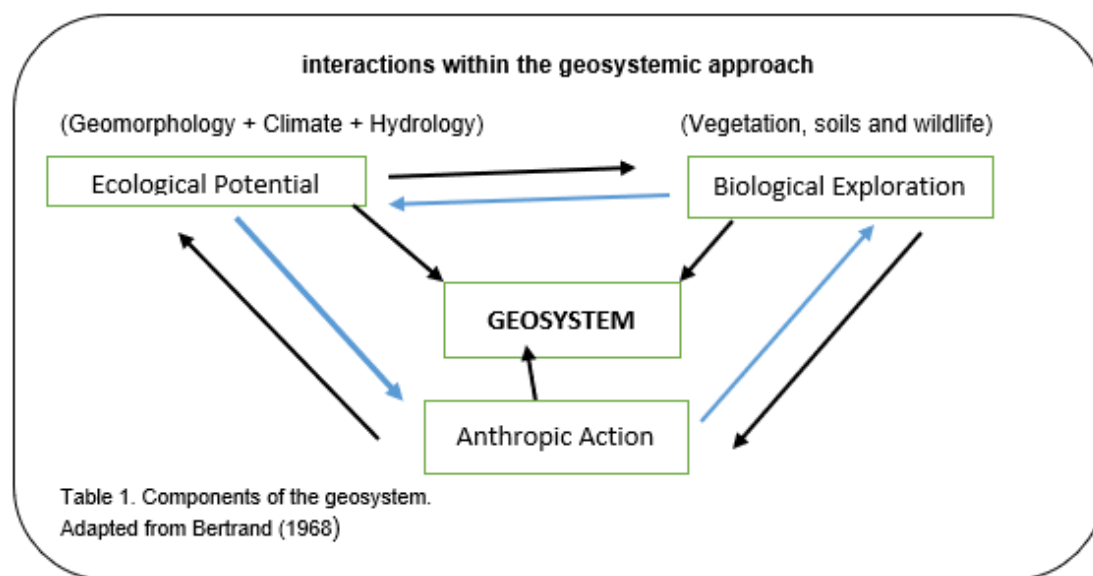
2) *General Systems Theory* vs. *Geosystems*

Rooted in the second law of thermodynamics, *General Systems Theory* was proposed by Ludwig von Bertalanffy (1901) to enable cross-disciplinary system analysis. This gave rise to conceptual and morphological modeling frameworks, including Tricart’s (1977) *Ecodynamics* and the *geosystem* models of Sothava (1977) and Bertrand (1979). The *geosystem* model seeks to integrate biotic and abiotic components under the naturalist paradigms of Von Richthofen and Von Humboldt, during a period when Geography was heavily influenced by uniformitarianism, descriptive methods, and evolutionary theories. Although originating in Russia through Sothava, the *geosystem* approach gained global traction via French scholarship, notably Bertrand’s (1968) contributions.

In Sothava’s *geosystemic* conception, natural phenomena should incorporate social and economic dimensions of influencing factors, possessing a dynamic character conducive to future scenario building, [21, 55]. Bertrand proposed a taxonomic subdivision introducing hierarchical units: *Geosystems*, *Geofacies*, and *Geotopes* at lower scales, and *Zone*, *Domain*,

and Region at higher scales, within a spatiotemporal framework. Geosystemic analyses revolutionized Physical Geogra-

phy, integrating climatology with allied subdisciplines, as illustrated below:



Source: Authors (2023), based on https://www.researchgate.net/publication/_abordagem_geossistemica

Figure 1. Interactions within the Geosystemic approach.

According to “Sotchava’s geosystemic conception integrates abiotic, biotic and anthropic components within a dynamic perspective of the territory” [55, 63]. General Systems Theory posits that comprehending complex systems requires holistic analysis of the system and its internal interactions, rather than isolated component examination. Its application to climate studies adheres to the following parameters:

- 1) *Climate System as a Complex System*: The climate system comprising atmosphere, hydrosphere, geosphere, biosphere, and cryosphere is a quintessential complex system wherein subsystem interactions yield emergent behaviors unpredictable from isolated analysis.
- 2) *Interconnections and Feedback*: The theory underscores the significance of interlinkages and feedback loops. In the climate system, interactions among components generate positive (amplifying) or negative (dampening) feedback, e.g., Arctic ice melt enhancing heat absorption (positive feedback).
- 3) *Homeostasis and Equilibrium*: It explores how systems maintain equilibrium, such as Earth’s energy balance, and how external (solar activity) or internal (greenhouse gas emissions) perturbations disrupt this balance.
- 4) *System Modeling and Simulation*: A systemic approach is central to climate modeling, which simulates Earth’s climate system through mathematical equations representing physical and chemical processes.
- 5) *Adaptation and Resilience*: The theory aids in understanding climate system resilience and adaptive capacity—the ability to absorb disturbances and reorganize while retaining essential functions.

- 6) *Holistic Research Approach*: It encourages holistic climate research, recognizing that changes in one subsystem can produce significant, sometimes unforeseen, effects elsewhere. In this framework, “Geosystem theory contributes to the integrated analysis of the relationships between the natural and social components of the territory” [55].

Thus, General Systems Theory provides a valuable framework for understanding the climate system, emphasizing holistic analysis of complex interactions and feedback among its diverse components. For instance, “The ENSO phenomenon influences rainfall variability in different regions of Mozambique, including Maputo, Beira and Lichinga” [15]. For instance, “Indian Ocean sea surface temperatures and the ENSO phenomenon influence the atmospheric systems that condition rainfall in Mozambique” [36].

3.5. An Overview of Climate Change Studies in Mozambique

Climate change research in Mozambique remains notably scarce, with a predominant focus on vulnerability and impact assessments. In this regard, “The study of the rainy season in Mozambique helps to understand the probability of dry periods and the associated atmospheric patterns” [35]. Additionally, “Southern Africa’s climate is conditioned by the interaction between regional atmospheric systems, ocean currents and teleconnection phenomena” [69], for instance, “Indian Ocean Dipole events influence climate variability and rainfall patterns in surrounding regions” [77]. Key studies include:

USAID (2012), “Climate Change Adaptation in Mozambique”; Irish Aid (2016), “Mozambique Climate Actions Report”; USAID (2024), “The Complex Emergency Situation and Tropical Cyclones in Mozambique”; TARP et al. (2011), “Adaptation to Climate Change: An Integrated Biophysical and Economic Assessment for Mozambique”; as well as works by Yamagata (2002), Uamusse (2020), Tyson (2000), Tique (2015), Queface (2009), Manhique (2011), Macie (2016), Coana (2015), and Mavume (2021). The principal findings from these studies can be summarized under the following categories:

- 1) *Increased Frequency and Intensity of Extreme Climate Events*: Mozambique has experienced more frequent and severe cyclones, floods, and droughts.
- 2) *Extreme Events and Impacts on Agriculture*: Agriculture a cornerstone of Mozambique’s economy and livelihoods is highly vulnerable to climate change.
- 3) *Sea-Level Rise and Coastal Impacts*: Mozambique’s extensive coastline faces heightened risks from sea-level rise, leading to coastal erosion, agricultural land salinization, and flooding, thereby affecting coastal communities and ecosystems such as mangroves.
- 4) *Climate Change and Public Health*: Studies examine potential public health implications, including increased vector-borne diseases (e.g., malaria) and health issues linked to heatwaves and air pollution.
- 5) *Adaptation and Mitigation*: Growing emphasis is placed on strategies for adaptation and mitigation, including climate-resilient infrastructure, adaptive agricultural practices, and ecosystem conservation efforts.
- 6) *Government Policies and Planning*: Research underscores the need for robust governmental policies and planning to address climate change, including the integration of climate considerations into economic and urban development frameworks.
- 7) *Community Participation and Awareness*: A recurring theme is the importance of engaging local communities in adaptation and mitigation efforts, alongside the need to enhance public awareness of climate change.

Climate change studies in Mozambique are critical for developing effective strategies to address emerging challenges. They also play a vital role in mobilizing international support and financing to assist the country in adapting to and mitigating climate impacts. However, there is a conspicuous absence of studies conducting detailed climatic analyses or documenting observed anomalies. The prevailing research focus remains on impacts, mitigation alternatives, and resilience-building. Recognizing this gap, the present study centers on climatic analysis and the risks associated with climate change.

Mozambique is widely recognized in the international scientific literature as one of the countries most vulnerable to climate change. This vulnerability arises from its extensive coastline, strong dependence on rain-fed agriculture, and recurrent exposure to tropical cyclones, floods, and droughts. In recent decades, the country has experienced severe impacts

associated with extreme events, affecting populations, infrastructure, food security, and ecosystems. This review synthesizes the most influential studies conducted specifically on Mozambique and organizes them around four thematic areas: (i) the characterization of national climate vulnerability and risk; (ii) attribution of the impacts of extreme tropical cyclones, with particular emphasis on Cyclone Idai; (iii) sea-level rise, coastal erosion, and the exposure of populations and cultural heritage; and (iv) impacts on agriculture, food security, and community-based adaptation. “Climate projections for Mozambique indicate changes in temperature and rainfall under different representative concentration pathways” [38].

3.5.1. Climate Vulnerability and Risk Profile in Mozambique

In this context, “the national climate profile confirms Mozambique’s high exposure to droughts, floods and tropical cyclones” [76]. Climate-risk profiles produced by institutions such as the World Bank and USAID have consolidated the characterization of Mozambique as a country exposed to multiple climate-related hazards, including droughts, floods, and tropical cyclones. “These hazards occur recurrently and disproportionately affect poor rural populations, subsistence agriculture, and critical infrastructure” [42, 47]. Ingle and Smith (2018), in the Climate Risk Profile for Mozambique, “emphasize that droughts are the most frequent disaster, occurring approximately every three to four years,” [25]. They represent a major constraint on development because a substantial proportion of the population, particularly the poorest households who lives in rural areas that depend on rainfall for agricultural production. These assessments have been widely used to inform adaptation planning and climate-finance decisions in Mozambique. Similarly, a study by the African Development Bank Group (2021), coordinated by specialists in resilient infrastructure, estimated that Mozambique experienced 78 natural disasters between 1992 and 2019. These events affected more than 17 million people and generated cumulative economic losses equivalent to more than 14% of gross domestic product. The authors argue that climate-related shocks constitute a structural constraint on development, reinforcing the need for investment in resilient infrastructure, disaster-risk reduction, and early-warning systems. “Climate change may affect water availability and, consequently, hydropower production in Mozambique” [70]. Accordingly, “Adaptation strategies in Mozambique should integrate disaster risk management, resilient agriculture and the protection of vulnerable communities” [72].

Mozambique’s vulnerability is also shaped by the interaction between physical exposure and limited adaptive capacity. In your approach to Human Geography, Sorre reveals that “human geography should examine human beings as living organisms subject to specific conditions of existence and reacting to stimuli from the natural environment” [61]. His biological approach emphasizes the influence of climate and the

living environment on human health, food resources, settlement patterns, and the extent of the ecumene, thereby explaining the relationships between people and the geographical environment. Therefore, Mozambique possesses an extensive coastline, numerous river basins, arid areas in the south, and “high concentration of people and infrastructure in hazard-prone locations contribute to the country’s susceptibility to climate-related disasters” [47]. Recent research further indicates that the impacts of extreme events are socially differentiated, with poor households often living in more exposed areas and possessing fewer financial and institutional resources to prepare for, withstand, and recover from disasters. “The disasters in Mozambique are closely associated with climate variability and populations’ exposure to hydrometeorological hazards” [53].

3.5.2. Extreme Cyclones and Impact Attribution: Cyclone Idai

Cyclone Idai, which struck Mozambique in March 2019, stimulated a series of influential studies that placed the country at the Centre of the international debate on the attribution of extreme events to climate change. A team led by Friederike Otto, Mariam Zachariah, Piotr Wolski, Izidine Pinto, Rondrotiana Barimalala, Bernardino Nhamtumbo, and colleagues, [45], demonstrated, through a rapid attribution analysis, that climate change significantly increased the extreme rainfall associated with tropical cyclones affecting south-eastern Africa, including Mozambique, Madagascar, and Malawi. This contribution has been widely cited as evidence that climate change is already intensifying extreme precipitation in regions characterized by high levels of vulnerability. Subsequent research led by Doris Vertegaal, Bart van den Hurk, Ana ã Couasnon, Natalia Aleksandrova, Tycho Bovenschen, Fernaldi Gradiyanto, Tim Leijnse, Henrique Goulart, and Sanne Muis [70], developed a storyline-attribution approach for Cyclone Idai. The study combined hydrological, coastal, flood, and impact models to estimate the effects of climate-related changes in different drivers of compound flooding. The authors found that trends in sea-level rise and wind-driven storm surge produced the largest increase in flood damage, estimated at 6–27% relative to a counterfactual scenario. By contrast, “trends in precipitation generated the greatest increases in flood volume and spatial extent, estimated at 5–19% and 1–4%, respectively. When all climate-related changes in the relevant drivers were considered together, total flood damage increased by approximately 8–35%” [73]. These findings demonstrate the non-linear relationship between hazard intensity and realized impacts. Research on human displacement has further clarified the social consequences of Idai. Mester, Vogt, Bryant, Otto, Frieler, and Schewe (2023) estimated that historical climate change increased the risk of population displacement associated with Cyclone Idai by approximately 12,600–14,900 additional people, corresponding to roughly 2.7–3.2% of the observed displacement. Their findings explicitly connect the climate-related intensification of the event

with the socio-spatial vulnerability of coastal and riverine communities in Mozambique. Furthermore, “Changes in land use and land cover may have amplified the impacts of compound flooding associated with Cyclone Idai” [75]. The estimated effect of intensified winds was approximately twice as large as that associated with sea-level rise, highlighting the importance of considering multiple climate drivers in assessments of displacement risk. Moreover, “Climate change increased the risk of population displacement associated with Cyclone Idai in Mozambique” [39].

More recently, Webb, Vertegaal, Vogel, Jack, and Muis (2026) extended this line of research through a mixed-methods approach combining physical modelling with interviews with key informants. Their study examined how changes in land use and land cover during the two decades preceding Cyclone Idai may have influenced compound-flood impacts. The results suggest that land-use changes, independently of climate change, potentially increase flood hazard. In addition, broader socioeconomic processes, including deforestation associated with charcoal production and the expansion of informal urban settlements, appear to have amplified exposure and vulnerability. The broader scientific literature confirms that Cyclone Idai produced extensive environmental and socioeconomic impacts in central Mozambique. Satellite-based analyses of Sofala Province, for example, identified substantial post-cyclone reductions in vegetation productivity and particularly severe damage to dense vegetation, wetland vegetation, and shrubland. These results demonstrate the value of remote sensing for assessing the spatial distribution of cyclone impacts and supporting environmental recovery and land-management planning. In this context, “Climate actions developed in Mozambique reinforce the need to strengthen adaptation, disaster risk reduction and community resilience” [29].

3.5.3. Sea-level Rise, Coastal Erosion, and Exposure

Studies of Mozambique’s coastline have been essential for understanding the country’s long-term climate risks. “Sea-level rise may expose most African coastal cultural heritage sites to extreme events by the end of the century” [74]. Research coordinated by scholars affiliated with Universidade Nova de Lisboa and international institutions, including Ribeiro et al. (2021), “estimated that approximately 577,000 people are exposed to coastal hazards and erosion” [54]. This represented a 276% increase in the estimated number of exposed people compared with previous scenarios. The authors also identified a concentration of population and infrastructure in low-lying and highly vulnerable coastal areas. Several coastal districts in southern Mozambique—including Zavala, Inharrime, Manhiça, and Mandlakaze, were identified as priority areas of concern. In these locations, more than 90% of the coastline presents high levels of exposure, making them critical areas for present and future coastal development, spatial planning, and adaptation interventions. At the continental scale, Vousedoukas, Clarke, Ranasinghe, Reimann, Khalaf, Duong, Ouweneel, Sabour, Iles, Trisos, Feyen, Mentaschi,

and Simpson (2022) included Mozambique among the African countries in which 100% of coastal cultural-heritage sites could be exposed to extreme 100-year return-period events by the end of the century, regardless of the emissions scenario considered. Under a high-emissions scenario, approximately 21% of the area of coastal heritage sites could be exposed to climate-related hazards. Published in *Nature Climate Change*, this study provides one of the most comprehensive assessments of the exposure of African natural and cultural heritage to sea-level rise and coastal erosion. Its findings highlight the cultural, ecological, and economic dimensions of coastal risk in Mozambique.

In northern Mozambique, studies of local responses to sea-level rise have shown that increases in mean sea level, together with a projected intensification of approximately 10% in storm tides, may substantially increase the potential for coastal flooding and damage by 2100. These processes are expected to contribute to pronounced shoreline retreat in exposed areas. Such findings reinforce the need for coastal-protection strategies and spatial-planning instruments that incorporate sea-level-rise projections, shoreline dynamics, storm surges, and the intensification of extreme events. In addition, “Mozambique’s coastal regions face an increased frequency of extreme weather events, with implications for populations and infrastructure” [34].

3.5.4. Agriculture, Food Security, and Community Adaptation

The literature on agriculture and food security in Mozambique has been dominated by studies linking climate variability, extreme events, and the vulnerability of agrifood systems. Turyasingura and Maviza (2026), in a review of food production and climate resilience in Southern Africa with a particular focus on Mozambique, argue that climate change is increasing rainfall variability, especially in the southern region. This trend is intensifying droughts and floods that directly affect maize production and other subsistence crops, with serious consequences for rural household food security. The authors emphasize that the combination of poverty, dependence on rain-fed agriculture, limited access to irrigation, and recurrent exposure to extreme events make rural communities particularly vulnerable to repeated climate shocks. In this context, climate change affects not only crop yields but also household income, livestock, access to food, and the capacity of communities to recover between successive disasters. In this sense, “Adaptation experiences in Mozambique highlight the importance of institutional strengthening, access to climate information and community engagement” [71]. In a systematic review of climate-induced displacement and food and water security in Mozambique and Zimbabwe, show that cyclones, floods, and droughts routinely disrupt agricultural production, deplete food reserves, and exacerbate hunger. These impacts affect both displaced populations and host communities. The authors therefore call for integrated policies combining social

protection, disaster-risk reduction, food security, water management, and climate adaptation. Their analysis indicates that climate-related displacement should be treated as a critical driver of food and water insecurity rather than as an isolated humanitarian consequence” [41].

Sector-specific studies on fisheries and aquaculture, including research published in *Frontiers in Sustainable Food Systems* (2021), have documented the impacts of Cyclones Idai and Kenneth on Mozambique’s coastal communities. These events caused losses of fishing boats, landing sites, processing facilities, aquaculture infrastructure, and other livelihood assets. The resulting impacts demonstrate the close relationship between extreme events, environmental degradation, and socioeconomic vulnerability. In this perspective, “The scarcity and degradation of natural resources, aggravated by climate change, can intensify social conflicts and vulnerabilities” [44].

In addition, “Female household heads may face double vulnerability resulting from the combination of gender inequalities, poverty and exposure to climate risks” [45]. On the other hand, “Climate change intensifies rainfall variability and compromises food production and the resilience of rural communities in Southern Africa” [68]. The evidence supports the development of sectoral adaptation strategies that integrate disaster-risk reduction, coastal-zone management, ecosystem conservation, livelihood diversification, and support for local production systems. Such strategies should also strengthen community participation, improve access to climate information, and promote locally appropriate measures for reducing exposure and enhancing adaptive capacity. In addition, “Cyclones Idai and Kenneth caused significant losses to the infrastructure and livelihoods of coastal communities dependent on fisheries and aquaculture” [18].

3.6. Social Vulnerability and Climate Risk: Research Trends

In this regard, “The water–energy–food–biodiversity nexus approach allows an integrated analysis of the socio-environmental risks associated with climate change” [46]. In recent years, “Research on human settlements has progressively incorporated more formalized approaches to assess climate vulnerability and risk” [52]. The International literature on disaster risk and vulnerability related to climate change or climate variability, typically adopts local or national scales. Pioneering vulnerability studies focused on the local scale, primarily aiming to identify population groups exposed to high risk from specific disasters in developing countries such as Mozambique. In this perspective, “The scarcity of natural resources, exacerbated by environmental degradation, can contribute to social conflict and instability” [23], according to Adger et al. (2005) and Qiang (2023), analyses in these studies are often confined to highly specific contexts and predetermined vulnerability and risk patterns; consequently, their findings are generally not generalizable

or transferable to other settings. In recent years particularly from the early 21st century through 2023 research has increasingly pursued dual objectives: conducting generalizable analyses at broader scales and responding to demands for more formalized approaches to risk and vulnerability diagnostics. “Vulnerability and adaptive capacity indicators allow the comparison of populations’ exposure and response to climate risks” [2]. Furthermore, “Effective climate change adaptation requires coordinated action at local, national and global scales” [3].

The most prominent methodological trend in vulnerability research applies to the Tyndall Centre’s vulnerability indicators. This model (referenced in AR5) compares vulnerability risk levels by examining socioeconomic and environmental variables and their interactions, assessing how they influence the adaptive capacity of individuals and groups to climate change and its effects at national and global scales, from a deductive perspective.

Lopes (2020), in a study on adaptation and enhancing urban resilience in northern Portugal, employed the Urban Adaptation Support Tool (AST), adapted to the Portuguese context, alongside the Weather Research and Forecasting (WRF) model to generate high-resolution spatial projections. Results indicated an increase in extreme climate events associated with temperature and precipitation variables. The study proposed a set of urban and rural measures to promote sustainable development and climate adaptability.

Also noteworthy is the PEISOR Analytical Model for Human Security and Environmental Issues (Oswald Spring, 2013), comprising five components:

- 1) P (Pressure): Encompasses interactions among eight socio-environmental factors driving global environmental change.
- 2) E (Effects): Captures consequences of interactions arising from scarcity, degradation, and environmental stress.
- 3) I (Impacts): Refers to extreme hydrometeorological events that may escalate into disasters due to human activities and limited governmental and social capacity.
- 4) SO (Social Outcomes): Includes social consequences such as famine, forced and chaotic urban migration, environmental conflicts, resource wars, and state failure (Homer-Dixon, 1999).
- 5) R (Response): Denotes responses by stakeholders and affected populations to dynamic processes of global environmental change, encompassing public, private, and social sectors.

Moreover, “Climate change communication influences public risk perception and the acceptance of mitigation and adaptation policies” [13]. Similarly, “Environmental degradation and extreme climate events may intensify forced migration and require integrated adaptation responses” [14]. For example, “The use of high-resolution climate models makes it possible to identify the increase in extreme events and guide urban adaptation measures” [31].

4. Final Considerations

This conceptual framework underscores that understanding climatic processes ultimately enhances climate predictability. Within contemporary climate debates—driven by the paramount importance of climate to planetary life, topics such as climate variability and climate change constitute critical domains for scientific inquiry. Social vulnerability and climate resilience are heavily contingent upon governance, particularly how local and/or national governments address climate issues without neglecting countries’ socioeconomic conditions.

Research trends on Mozambique predominantly focus on vulnerability, impacts, resilience, and the association of increasingly frequent natural disasters in recent years with climate change. A major gap identified in this review is the lack of studies analyzing the behavior of Mozambique’s distinct climate types to quantitatively identify climatic anomalies, as well as insufficient research on climate modeling and prediction.

The reviewed literature indicates that Mozambique’s climate vulnerability is produced by the interaction of multiple hazards, high exposure, socioeconomic inequality, environmental degradation, and limited adaptive capacity. Recent attribution studies show that climate change has already influenced some of the drivers of extreme events such as Cyclone Idai, although the magnitude of its contribution varies according to the hazard and impact considered. The evidence also demonstrates that climate-related impacts cannot be explained by atmospheric processes alone: land-use change, informal urban expansion, poverty, weak infrastructure, and dependence on rain-fed agriculture frequently amplify the consequences of climate hazards.

Consequently, effective climate policy in Mozambique requires an integrated approach that connects climate adaptation, disaster-risk reduction, coastal planning, resilient infrastructure, food-system transformation, ecosystem restoration, and social protection. Such an approach is particularly important in coastal and riverine areas, where future changes in sea level, storm surges, precipitation, and land use may interact to produce increasingly complex and unequal risks. Furthermore, “The way the media frames scientific uncertainty can condition social mobilization around climate change” [43].

Author Contributions

Americo Antonio Mahumane: Conceptualization, Data curation, Methodology, Resources

Sara Brigida da Cunha Jorge Romao: Data curation, Methodology

Gustavo Sobrinho Dgedge: Formal Analysis, Methodology

Ubaldo Genova Ombe Gemusse: Formal Analysis, Methodology

Conflicts of Interest

The authors declare no conflicts of interest.

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