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Review Paper

Climate Change and Coral Reef Ecosystem: A Study on Ecological and Socio-Economic Perspectives in the Indian Ocean

Sujoy Kumar Tarafder[*] and Sumon SK
Department of Geography, Nagar College, Murshidabad, West Bengal, India
sujoytarafder27@gmail.com

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Abstract

Coral reef ecosystems in the Indian Ocean, covering less than 1% of the ocean floor, extend around 25% of marine biodiversity and are crucial to the livelihoods, food, and cultural assimilation of millions in coastal buffers as well as island-based communities. This study examines the ecological and socio-economic impactsof climate change on these reefs, drawing on recent scientific literature, satellite data, and institutional reports. Key climatic phenomenon drivers—uplift of sea temperatures, ocean acidification, and sea-level rise—are assessed for their cascading effects on reef physical health and the human environment. Findings show that the accelerated rate of ocean warming (projected to increase by 1.7–3.8°C per century), more frequent marine heatwaves, and rapid acidification have trended to widely extend to coral bleaching, biodiversity loss, and structural changes in reef ecosystems and biodiversity. These environmental changes have unavoidable socio-economic consequences, including declining fishery productivity, decreased tourism economic atmosphere, and increased vulnerability of coastal communities to natural disasters and extreme weather. This study highlights the immediate need for coordinated efforts to compel scientific research, policymaking, and local expertise to strengthen the resilience of coral reefs. It calls for urgent global action to reduce greenhouse gas emissions as well as use, in a similar fashion, region-specific and community-driven initiatives to prevent further biodiversity loss andensure socio-economic security for Indian Ocean littoral states.

Keywords: Marine biodiversity, Ocean acidification, Coral bleaching, Vulnerability, Socio-economic stability.

Introduction

Coral reefs, frequently called "rainforests of the sea", are one of the most complex and liberatingecosystems on earth. They are created by coral polyps that secrete calcium carbonate.Coral reefs constitute less than 1% of the ocean surface, yet 25% of marine species depend on this ecosystem. In the Indian Ocean, coral reefs acttoprotect coastlines from storm impacts and erosion, provideasourceoffisheriesfor more than 1.5 million people, and generateasourceof income for countries based on tourism. For example, reef-based tourism contributes as much as 19% of the GDP oftheMaldives[1].

However, coral reefs in the Indian Ocean are being under unprecedented threat from climate change. The impacts of climate change are causing ocean watertemperature and acidification to rise, reefsto lose their biodiversity and ecological function are declining, and resilience isdiminishing[2]. Therisks to countries, such as Kenya, Tanzania, Madagascar, Seychelles and India, is high. Countries in the Indian Ocean, areatincreased risk in regions such as the Andaman and Nicobar Islands, Gulf of Mannar, Gulf of Kutch, Palk Strait and Lakshadweep. Of these regions, many of the reefs are under some form of management and monitoring regime including in India, through the Coastal Regulation Zone (CRZ) policy, thereismounting ecological destruction and socio-economically vulnerable communities require a full assessment of risk.

The purpose of this study is to assess the interconnectedness among ecological and socio-economic impacts of climate change to Indian Ocean coral reefs to understand threats to the reef health and broader impacts on associated communities and economies, and to provide planning and policy recommendations to support sustainable management.

Study Objectives: i. Investigate the dynamics of climate change on coral reefs, and identify the primary climate drivers effecting coral reef systems. ii. Review the ecological effects and socio-economic impacts of climate change effects on reef systems. iii. Assess the current and future measures to create resilience for coral reefs, and long-term sustainability.

Literature Review: Climate change is now widely recognized as a key driver of coral reef decline, globally, and particularly in the Indian Ocean - a region home to one-third of the global population, and someofthelargest marinebiodiversity plans. This review explores how climate change intersects with otheranthropogenic pressures, influencing ecological and socio-

economic aspects ofcoral reef vulnerability in the Indian Ocean, considered trends, existing debates and key gaps that also inform the rationale for this study.

Table-1: Coral cover metrics for global coral reefs and for each of five oceanic regions from 1997 to 2018[3].

Oceanic region	Mean coral cover (%)	SD coral cover (%)	n	Reef area (km²)
Global	31.7	19.4	2949	143075
Red Sea	37.6	15	37	8886
Arabian Gulf	39.6	22.9	47	892
Indian Ocean	32.6	18	321	22632
Pacific Ocean	35.6	19.6	1944	97556
Atlantic Ocean	17.7	11.6	600	13109

*n= Number of sites per oceanic region; SD= Standard Deviation.

Anagha highlights the blue economy as an important pathway for sustainable development in the Indian Ocean Region (IOR). She highlights the significance of coral reefs in maintaining fisheries noting how climate-induced warming and acidification jeopardizes fish stocks threatening food security and livelihoods among coastal communities. While provides insight on fisheries, she does not include the socio-economic dimension of many other sectors, including coastal tourism and cultural heritage, which fronts on healthy coral reef ecosystems. While the work provides valuable insights into one aspect of a salt-water economy, it serves to justify more integrated approaches to research that considers both the socio-economic aspects, as well as the aspects of reef health[4].

Obura et al. conducted an ecological assessment of coral reef vulnerability in the Western Indian Ocean that pulls together a lot of different ecological scholarship. Using the International Union for Conservation of Nature Red List of Ecosystems framework, they assess key indicators of the entire region, to understand potential threats. In their assessment, they il-lustrate how reef vulnerability spatially varies from critically endangered reefs on island coasts - in-fluenced by climate warming - to vulnerable reefs on the continent, influenced primarily by over-fishing. This depth of ecological assessment is important in recognition that climate change very rarely operates in a vacuum but affects multiple local stressors, leading to risk landscapes that are complex. Unfortunately, however, even in taking a deeply ecological vantage point, the study does not address how these ecological changes apply socio-economically or to adaptive capacity in local communities. Failing to address social vulnerability as part of ecological vulnerability inhibits the ability of this study to apply directly to integrated adaptation[5].

Sully et al. conducted a global investigation to characterize coral reef "bright spots" and "dark spots," mapping regions characterized as 'exceptional coral health' or 'poor coral health' based on historical climate data and ongoing climate change projections. The authors characterize threats such as marine heatwaves as increasing in intensity and highlight some areas may function as climate refuges. While the authors highlight the impacts of climate change are geographically uneven and their methods could be related to spatial prioritization of conservation and management responses beings implemented, the global research scope fails to include region-specific content such as socio-economic contexts and associated local governance issues, the region of Indian Ocean addresses. Furthermore, it emphasizes ecological data without regard to whether the proposed ecological changes to coral ecosystems will threaten food security, tourism, and therefore, livelihoods at the community level[3].

Wambua et al. introduces an innovative microbial lens on coral reef health throughits study of near-coral microbial communities on the Kenyan coast and their response to local anthropogenicstressors and climatechange. The identification of microbial genes associatedwith pollution adaptionsuggests microbes may be sensitive indicators of reef health associated with environmental change, especially climate change compounded by anthropogenic stress. This methodrepresents a potential promising quickmethodfor reef monitoring, whilealso ecological, does not account for how the microbial changemayalter human benefits or management frameworks related to coral reef ecosystems[6].

Trends, Debates, and Gaps: Across these studies, there is acleartrend in that approaches recognize climate change as a key primary threat to coral reefs that operates synergistically with local pressures such as over-fishing, habitat loss, and pollution. Evenifthesestudiesare aware and agree about the ecological drivers of declines in reef ecosystems, these studies reveal a persistent disciplinary divide: ecological studies (Obura et al.[5], Sully et al.[3], Wambua et al.[6]) and socio-economic studies (Anagha) are rarely combined, leading to a fragmented understanding of how climate change affects human and ecological systems simultaneously.

Debates centre on what is the best approach for conservation and adaptation: Obura et al. argue for ecosystem-based management and climate action; Wambua et al. are more focused on the idea of microbial monitoring as a potentiallyimportantwaytoidentify shifts in coral reef health sooner, for example, for the coast of Kenya in the Western Indian Ocean. However, both methods require more rigoroustesting to evaluate socio-economic implications, particularlyregarding balancing the conservation imperative, equity and adaptation of local livelihoods. The existing body of literature reveals key gaps whichdemonstrate the need for this research:

Socio-ecological integration: There is a lack of empirical research that connects ecological degradation (for example coral bleaching) with specific socioeconomic implications (for example loss of livelihoods, tourism decline, cultural decline) in an Indian Ocean case study context.

Cumulative impacts: While local stressors are recognized, studies often fail considering how local stressors might be cumulated with climate change to influence reef vulnerability and community resilience.

Equity and inclusion: Discussions rarely attend to marginalized voices mainly of Indigenous communities and small-scale fishers, thus attention to their perspectives is absent in relation to their pivotal role in reef caretaking and vulnerability.

Practicality of solutions posed: Tools such as ecosystem-based management and microbial monitoring are very much underutilised in the context of the barriers to implementation, particularly in locally dependent communities reliant on reef resources which might clash with conservation goals.

With the identified gaps this research purpose is to bridge the gaps for disciplines, combining ecology-focused monitoring with socio-economic focused analysis focusing on the voices of local communities. By taking an interdisciplinary, equity-focused approach, this research attempts to identify how climate change shapes ecological and socio-economic systems. This process is necessary for forwarding not only ecological outcomes but forms the basis of sustainable livelihoods and community adaptation in Indian Ocean development.

Study Area: This research concentrates on representative sites across the Indian Ocean, an expansive body of water that stretches from the eastern coast of Africa to the western shores of Australia and includes the coastal areas of South Asia. The Indian Ocean also contains some of the most biodiverse coral reef ecosystems to be found anywhere in the world, including the Western Indian Ocean (WIO) which possesses the second most diverse coral fauna globally with approximately 369 coral species. Coral reef ecosystems in the Indian Ocean are characterized by highly dynamic oceanographic regimes including the south equatorial current and localized gyres that engorge quite unique ecological communities that host high levels of genetic diversity as well[7]. The study is focused on coral reefs in the northern title of the Mozambique Channel, selected island nations across the Western Indian Ocean and significant areas in the Central Indian Ocean. These areas are selected to represent all reef types, included fringing, barrier, and atoll reefs, differing levels of exposure to climate change impacts, and varying levels of human dependence, and provides a reasonable framework to consider both ecological and socio-economic implications. These reefs are vital to support biodiversity and food security as well as cultural connections; thus the study area provides an excellent context to consider the interacting vulnerabilities and adaptive implications to coral reef ecosystems and the communities that depend on them.

Research Design and Database

This research employs a qualitative research approach to examine the environmental and socio-economic effects of climate change on coral reef ecosystems in the Indian Ocean. Specifically, the research uses secondary data only, by aggregating the results from existing research articles, satellite data, and institutional reports to form a general overview of the climate-related threatsto habitats and societies connected to these critical ecosystems.

Data Sources: i. The secondary data for this research were drawn from a variety of sources, but this research used the following sources in particular. ii. Scientific papers in Nature Sustainability and Nature Communications. iii. Reports and databases from trusted organizations including NOAA, Copernicus, CORDIO East Africa. iv. Reports from governments and NGOs. v. Remote sensing data to assess coral health and bleaching events and give approximate accounts of the surrounding environmental conditions.

Table-2: Coral Reef Vulnerability in the Indian Ocean: A Comparative Literature Analysis.

Characteristic	Anagha[4]	Obura et al.[5]	Sully et al.[3]	Wambua et al.[6]
Focus	Socio-economic and fisheries aspects	Ecology and IUCN Red List categories	Global, bright & dark spots	Microbial dimension of Coral health
Climate Change Role	Ocean warming threatens fish stocks	Climate drives critically endangered reefs	Intensifying marine heatwaves	Interacts with anthropogenic stressors
Socio-Economic Impact	Ecological degradation cascades into social domains	Does not address socio-economic impacts	Overlooks regional socio-economic dynamics	Does not incorporate human benefits
Limitations	Narrow sectoral focus (fisheries)	Lacks link to socio-economic impacts	Overlooks regional idiosyncrasies	Primarily ecological, lacks human dimension
Conservation/ Adaptation	Blue economy for sustainable development	Ecosystem-based approach for climate action	Spatial prioritization of conservation	Microbial monitoring for reef health

Figure-1: Location of the study area on the world map[8]

Data Collection Methods: The systematic literature review was accomplished using academic databases and the organizational portals of government and non-government organizations focused on climate change in marine coral reef ecosystems. The electronic search was limited to the Western and Central Indian Ocean in order to capture the more recent trends and vulnerabilities. The keyword searches included climate change, coral bleaching, Indian Ocean, and reef degradation.

Data Analysis Approach: i. A quality content analysis method was used to identifypotential themes and impacts on ecosystems that are a result of climate changeandother incidental events such as increasing sea-surface temperatures, ocean acidification, and coral bleaching events. ii. Quantitative data -and outputs - (e.g. bleaching rates, temperature anomalies, reported in other sources, climate/satellite datasets) were extracted and summarized, and used to substantiate thematic results. iii. A comparison summary analysis was used to establish the spatial distribution and rangeof ecological and socio-economic impacts across different sub-regions of the Indian Ocean.

Justification and Limitations: The use of secondary data allows for a multi-year perspective of the changes, and challenges that coral reef ecosystems have faced in the Indian Ocean, incorporating previously published depth of monitoring and research. Some limitations include: the potential of gaps in the data, inconsistencies in data methods of measures, and of course, the absence of primary field-verifications. Socio-economic impacts were highlighted as per hapsmo regeneralized and lacking localized and contextual facets in the published reports.

Bias and Reliability: Only peer-reviewed and institutionalize data sources were used to remove possible bias, and lento data reliability. To counter internal validity threats, data triangulation (where cooperative data sources were independently cross-referenced) was used to provide confirmatory analysis of the key findings thataugmented the reliability of the overall study.

Ecological Importance of Coral Reefs

Coral reefs within the Indian Ocean are found on less than 1% of the ocean floor. However, that less than 1% contains around 25% of all marine biodiversity, making them indispensable to ocean ecosystems[1]. These reef systems provide a structural complexity providing 3-dimensional environments to which marine life can attach to and come back to for shelter and some important breeding grounds for many other marine resources including fish, invertebrates, and marine mammals. This biodiversity is a vital component for the health of tropical marine ecosystems, as they are responsible for many critical ecological services such as nutrient cycling and primary production. Coral reefs act as natural break waters and play an important role in coastal stabilization by absorbing wave action thereby reducing the effects of erosion and storm, particularly bad weather events. The role reefs play in reducing storm surge along coastal areas is necessary to manage erosion and has implications for maintaining coastal habitats, such as mangroves and seagrass beds that are critical for marine biota, and terrestrial biodiversity.

Socio-Economic Importance of Coral Reefs

From a social and economic perspective, at least 1.5 million people who rely on coral reef ecosystems in the Indian Ocean region for their livelihoods and food security through small and artisanal fisheries. Coral reefs provide nursery habitat for commercially important fish species on which many coastal communities rely for protein and income generation. In addition, coral reefs drive tourism and it was estimated that the Indian Ocean region receives about 1.4 million tourists every year related to coral reefs and generates an estimated $2 billion to the overall economy. In some island nations, such as the Maldives, coral reef tourism is worth approximately 19% of GDP, demonstrating the importance to the national economy[1].

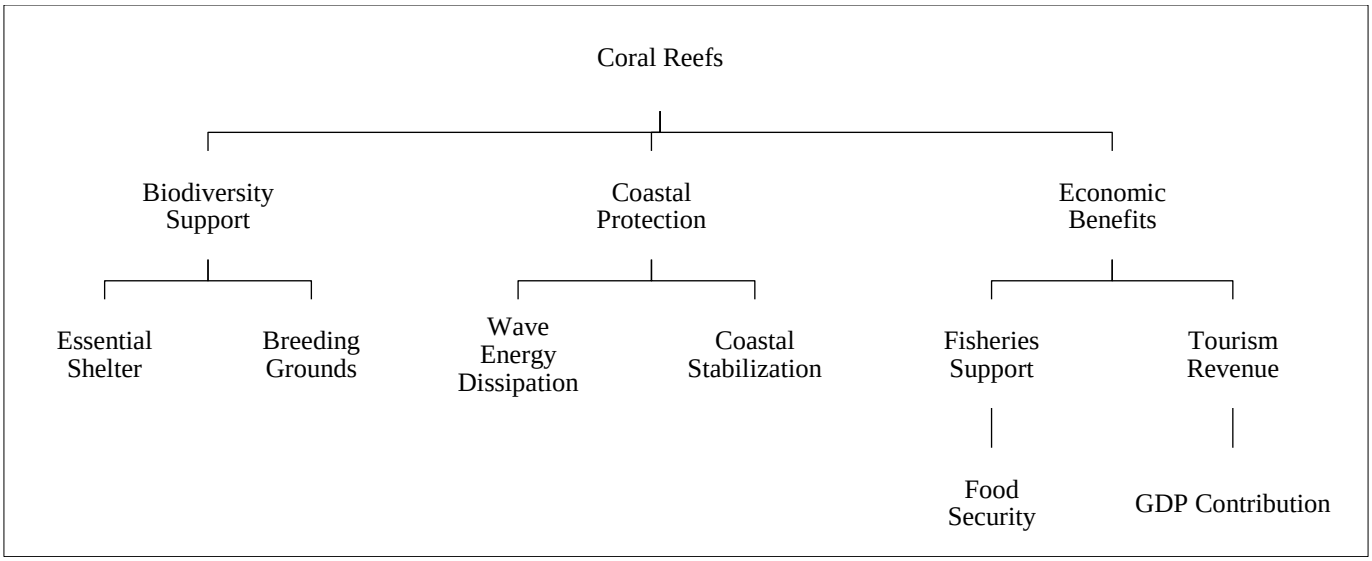

Figure-2: Ecological and Socio-Economic Importance of Coral Reefs.

Climate Change Drivers Affecting Coral Reefs

Change of climate is imposing different types and the dispute began to intensify threats to coral reef ecosystems in the Indian Ocean. Three primary drivers—rising sea temperatures, ocean acidification, and sea level rise—interact and amplify the risks to both reef health and the coastal communities that depend on them.

Rising Sea Temperatures: A recent publication in Science Direct highlights the Indian Ocean warming at alarming rates, with a 1.7 – 3.8°C increase projected per century from 2020 to 2100 with unabated green house gas emissions. The alarming pace of ocean warming has the potential to cause thermal stress to coral reefs resulting in wide spread coral bleaching and mortality events. The applicable changes in coral reefs threaten the rich biodiversity that reefs support, and have a range of socio-economic impacts on fisheries and tourism, both essential sources of income for millions of people in the Indian Ocean region[9].

Ocean Acidification: As the Indian Ocean continues to experience a decline of pH from 1980-2019 (i.e., ocean acidification), these characteristics provide further evidence for the increasing acidification of the ocean, and is largely connected to the uptake of anthropogenic carbon dioxide (CO_2). Acidification reduces pH and carbonate ion saturation states, which negatively impact the skeleton formation of coral. Further, climatic patterns (e.g., El Niño and positive Indian Ocean Dipole) further exacerbate these characteristics[10].

When jeopardizing acidification and the subsequent decline in calcification occurs, reefs are compromised as habitat-forming ecosystems, which has direct consequences for biodiversity and food security.

Sea Level Rise: Sea-level rise in the Indian Ocean is now co-occurring phenomena related to extreme sea level (ESL) events, which continue to threaten approximately 2.6 billion people in vulnerable coastal contexts. Observations from satellite and tide-gauge records indicate that extreme levels of sea level have either become more frequent, intensified or prolonged, especially in the Arabian Sea and Indian Ocean island contexts.

Significant mean sea level (MSL)/surge, >75% of ESL drivers, coupled with tropical cyclones, yields intersectional threats. Any ocean warming of 0.5 °C could have implications for ESL events being triggered twice as much. This, in turn, results in less light reaching the reefs and more sediment build-ups that compromise structure and ability to protect coastlines—making communities, infrastructure, and cultural sites more vulnerable[11].

Ecological Consequences of Climate Change

Climate change is leading to substantial ecological changes in coral reef ecosystems of the Indian Ocean. Elevated sea surface temperature causes coral bleaching–a process where corals become heat stressed and expel their symbiotic algae (zooxanthellae), resulting in bleaching, and potential coral mortality if the stressful conditions persist[2].

This disrupts the primary energy sources for corals and subsequently sets off cascading impacts throughout the reef ecosystem. The degradation of reefs leads to reductions in ecosystem resilience, in turn, reducing their capacity to recover from disturbance events, including storms or outbreaks of disease. Furthermore, these changes alter the ecological roles of coral reefs, including nutrient cycling and the provision of habitat for marine organisms.

Socio-Economic Impacts on Coastal Communities

The ecological decline of coral reefs has acute and considerable socio-economic consequences. Declining fisheries, due to habitat loss, is a primary concern, potentially threatening food security for coastal communities reliant on small-scale and artisanal fisheries. The collapse of reef-based ecosystems may also undermine tourism, such that coral degeneration could reduce tourist industry and participation in marine recreation activities suchas snorkelling and diving, andhinder economic returns for economies dependent on coastal tourism. Further, worsening coral reef health will contribute to increased coastal vulnerability. Healthy reefs provide natural protection against storms and wave action to coastal communities, and in the Maldives, healthy reefs alone prevent an estimated $1.7 billion annually in storm damage[1]. In addition to the monetary costs of coral reef ecological degradation, there will also be major impacts on the cultural identity and heritage of coastal populations for whom coral reefs have social, spiritual, and historic association.

Table-3: Ecological and Socio-economic impacts.

Ecological Impacts	Socio-economic impacts
Coral bleaching and mortality	Declining fisheries productivity and food security
Biodiversity loss	Reduced tourism revenue and local economy impacts
Degradation	Increased vulnerability of coastal communities
Reduced habitat complexity	Higher costs for artificial coastal protection
Weakened ecosystem resilience	Loss of cultural and spiritual heritage

Mitigation and Adaptation Strategies

Dealing with the effects of climate change on coral reefs in the Indian Ocean constitutes a multi-level dilemma that connects the global with the local. It requires coordination from the global scale, through climate frameworks like the Paris Agreement and the UN Sustainable Development Goals, to pedestrian frameworks that can inspire individuals to make greenhouse gas emission reductions that will have long-lasting benefits to coral ecosystems. But taking action regionally and at the local level is equally important. Restoration projects at the local level, such as coral gardening and artificial reefs, are developing fast and help to rebuild damaged habitats, and promoting sustainable fishing in local supply chains lessens additional pressures on reefs. Community-initiated activities are developing from eco-tourism to co-managed fisheries, to rekindling traditional stewardship, which can provide both economic opportunities as well as a collective sense of responsibility for the future of reefs.

In the Maldives and Madagascar, local monitoring and management has allowed communities to adapt to some of the most impacting environmental changes. At the same time new technologies, including remote sensing for monitoring reef health, and satellite/wireless systems for changing conditions, allow practitioners to monitor and respond to bleaching events dramatically faster. Such a layered response is needed to protect coral reefs in the Indian Ocean from the effects of climate change.

Conclusion

Climate change is placing immense pressure on the Indian-Ocean coral reef ecosystems by introducing increases in sea temperature, ocean acidification, and sealevel rise; leading to mass coral bleaching events, biodiversity loss, and degradation of the reefs. The ecological change is jeopardizing important socio-economic services (e.g. fisheries, tourism, coastal protections from nature) which provide means of livelihood and food security to millions of people around the Indian Ocean, particularly in reef dependent nations such as the Maldives, and Kenya. Although continuous reductions inemissions globally is always important to address the driving forces of warming and acidification, timely local and regional actions -including increasing marine protected areas, sustainable fishing practices, and active engagement in coral restoration –will be critical actions to build resilience. There is a delicate balance between ecological science, socio-economic realities and community engagement when developing suitable adaptation solutions. This work contributes to the discussion of the need for good governance and long-term evidence based management of the system, also known as continuous monitoring. This is an urgent call for coordinated action, at global, regional, and local levels, in which we consider the level of ecological threshold the region is quickly approaching towards a total collapse of ecosystems, with significant negative fall out for marine biodiversity and human wellbeing.

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