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Investigating the Impacts of Climate Change on Marine Ecosystem Services Through Earth and Planetary Science Methods

P. Mahadevan [1*], Muthukumar [2]

[1*] Department of Nautical Science, AMET University, Kanathur, Tamil Nadu, India.
E-mail: pandian.mahadevan@ametuniv.ac.in

[2] Department of Marine Engineering, AMET University, Kanathur, Tamil Nadu, India.
E-mail: muthuganga@ametuniv.ac.in

Abstract

Marine ecosystems such as fishing grounds, biodiversity havens, carbon sinks, and coastal protectors have begun experiencing increased strains with the ever-mounting impacts of climate change. This work examines the problem using Earth and Planetary Science approaches, including satellite remote sensing, oceanographic modeling, and geochemical assessments of waters and sediments. We analyze changes such as the increase in biological productivity of living marine species, sea surface temperatures, ocean acidification, deoxygenation, and changes in marine currents. Through ecosystem service models, we also assess the sustainability of human populations, food security, and coastal resilience in regions impacted by climate change and the exacerbation of stressors on the oceans. Special attention is given to the widespread decline in coral reefs' health, disruptive global carbon cycles, and the many commercially valuable fish species' range shifts towards the poles. Areas of low adaptive capacity and high exposure are highlighted for urgent conservation intervention. This study demonstrates the importance of Earth and Planetary Science in temporal and spatial modeling of ecological change. Based on the results, policies and actions that aim to sustain the culture and supporting services marine ecosystems provide should focus more on climate change impacts. To put it in other words, this research aims to guide the management policies of marine resources, considering the marine ecosystems' services for the environment and human health.

Keywords:

Change in climate, services of marine ecosystem, modeling of oceanographers, monitoring from space, cycling of carbon, neural networks.

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Corresponding Author: P. Mahadevan, E-mail: pandian.mahadevan@ametuniv.ac.in

Introduction

Oceans constitute over 70% of the Earth's surface, regulate the world climate, sustain biodiversity, and nourish human life. Marine ecosystems proffer a diversity of services, including provisioning food, carbon sequestration, nutrient cycling, stabilizing shores, and providing cultural services (Costanza et al., 2014). These services support ecological balance and help billions of people, particularly those living on islands or coastal areas (Barbier, 2015). Due to climate change in recent decades, attention has been diverted towards stressed marine environments. The greater greenhouse gas concentration has caused weather and ocean systems to change in several ways, including increased temperature of sea surfaces, acidification of oceans, increase in sea level, and changes to the hydrological cycle (IPCC, 2023). All these factors threaten ecosystems by changing structure, functionality, and productivity, which places core services of marine ecosystems in dire need while posing alarming risks to human welfare and world sustainability (Hoegh-Guldberg et al., 2023). Comprehending the ecosystem services from marine systems, ecosystem mapping requires attention from all branches of science using a holistic approach to understand the relations of climate drives and impacts on marine systems, which needs an interdisciplinary path (Jelena & Srđan, 2023). Methods of Earth and Planetary Science (EPS) enable one to study environmental shifts concerning space and time. For example, satellite remote sensing provides real-time monitoring of chlorophyll concentration, coastline erosion, and even sea surface temperatures, revealing trends on scales that could not previously be examined (Praveenraj et al., 2024). Oceanographic modeling allows the simulation of future climate scenarios alongside projecting ecological outcomes. At the same time, geochemical and sedimentary analyses help reconstruct historical ocean conditions to identify long-term patterns (NASA, 2020). The conglomeration of these techniques offers a powerful platform to gauge the degree to which climate-induced stressors affect marine resources (Ozyilmaz, 2023). One of the greatest threats is warming oceans, which changes species' location, breeding cycles, and migratory activity (Mach et al., 2016). Coral reefs, some of the most biologically and economically productive ecosystems, are especially vulnerable to thermal bleaching (Hughes et al., 2017). Oceans absorbing excess atmospheric CO_2 lead to acidification, which erodes the ability of calcareous (corals, mollusks, and plankton) organisms to construct shells and skeletons, weakening trophic structures and diminishing biodiversity (Akila et al., 2023).

Furthermore, ocean deoxygenation remains an increasing threat to marine organisms, especially those in mid-water and coastal regions (Breitburg et al., 2018). Changes in ocean circulation patterns can disrupt nutrient transport, reducing primary productivity and fish stock productivity and reproductive rates, or bioenergetics (Polovina et al., 2011). The resulting impacts compromise essential ecosystem services, particularly fisheries, that provide food and income to millions worldwide. With the escalating consequences of climate change on marine systems, it is critical to convert scientific comprehension into defined actions (Dhanya & Balakrishnan, 2024). This includes pinpointing marine areas most at risk, estimating ecological and socio-economic impacts, and developing adaptive management plans (Doney et al., 2009). This discipline bestows grand challenges, combining physical, biological, and socio-economic datasets with forecasting models to project changes in the world’s oceans and seas (Mach et al., 2016). Such methodologies allow researchers to aid policy decisions to grant biodiversity protection and maintain essential ecosystem services. The preservation of marine ecosystem functions is increasingly becoming imperative from the perspective of environmental conservation and a fundamental area of attention for sustainable development, nutrition, and climate adaptation globally (Halpern et al., 2015; Stock et al., 2011).

Motivation of the Research

- Climate change is fundamentally affecting the ocean's temperature, acidity, and oxygen levels, endangering the health, productivity, and resilience of the marine ecosystems that are the foundation of billions of livelihoods.
- Cutting-edge tools in Earth and Planetary Science, such as Satellite remote sensing and Oceanographic modeling, need to be employed to analyze, monitor, and predict the ecosystem service drivers' relations at global and regional scales, both spatially and temporally.
- The need of the hour is scientific research to design appropriate policy frameworks alongside active adaptive management protocols that consider the changing realities of marine ecosystem services essential for environmental balance, food, and sustainable development.

Objective of the Research

- Assess the impacts of climate change on selected marine ecosystem services by applying methodologies from Earth and Planetary Science, including satellite remote sensing, geochemical analysis, and oceanographic modeling.
- To refine marine biodiversity conservation policies and strategies to enhance their resilience against climate change by monitoring and modeling ecosystem changes through remote sensing and oceanography, enabling informed policy decisions.

Literature Survey

In the past few years, researchers have studied the consequences of climate change on marine ecosystem services, focusing on the ecological, biogeochemical, and socio-economic aspects (Natheem et al., 2023). Climate-induced stressors like increasing sea surface temperatures, ocean acidification, and deoxygenation are noted to have dramatically impacted marine ecosystems' structure and function. Coral reefs have been highlighted as being particularly vulnerable to thermal stress; they undergo mass bleaching due to large scale trademark shifts and biodiversity decline, which transforms reef and service function ecosystems (Polovina et al., 2011; Hoegh-Guldberg et al., 2007) Likewise, (Doney et al., 2009) assessed the impact of heightened atmospheric CO_2 concentration resulting in the ocean's acidification on the survivability of corals, foraminifera, and pteropods posing great jeopardy as calcifying organisms. These impacts reverberate through marine food chains, weakening ecosystem productivity (Bebianno et al, 2021). Additionally, the research conducted in (Breitburg et al., 2018) discussed the universally declining oceanic oxygen levels with soaring temperatures detrimental to fish spawning activities, particularly in upwelling areas and enclosed seas (Papadopoulos & Christodoulou, 2024). Ecosystem-based adaptation strategies raised by (Arauz & Marzo, (2021). have significantly advanced the discourse on marine impacts stemming from climate change, emphasizing the need for mitigation, strategic governance, and restoration of habitats alongside sustainable policies governing ecosystem resources (Dhurgadevi et al., 2022). Collectively, these stressors undermine the ecosystem service function of fisheries, carbon capture, and shoreline defense. Earth and Planetary science techniques have notably advanced research into these changes. For example, satellite remote sensing has been implemented extensively to monitor sea surface temperature anomalies, chlorophyll-a concentration, and sediment transport, which are helpful for estimating primary productivity and transitions in the coastal ecosystem (McClain, 2009; Salman & Alomari, 2023). Moreover, the IPCC assessment reports have oceanographic models, which estimate physical responses and ocean biogeochemical responses for every emission scenario. These models were beneficial in assessing the future changes in ocean currents, stratification, and nutrient cycling, all fundamental for understanding ecosystem dynamics. Also, the estimate of climate-ocean interaction is done with the help of sediment cores and isotopic analysis, which provides a broader vision of the marine system's resilience. Several studies focused on the socio-economic dimension of change in the marine ecosystem resulting from climate change (Soy & Balkrishna, 2024; Argo, 2022). These studies address the ecosystem services provided by marine ecosystems with climate-induced stress, growing markup, and demand for ecosystem-based management and Nature-based solutions for conservation (Barbier et al., 2011). In a united form, these findings highlight the examination of multi-physical, ecological, and socio-economic parameters towards formulating a conservation plan and policy.

Methodology

This research employs a multidisciplinary approach based on Earth and Planetary Science to assess the effects of climate change on marine ecosystem services (Sigman & Boyle, 2000). The study utilizes remote sensing, oceanographic models, and geochemical techniques to analyze and understand physical and biological change within marine environments (Stock et al., 2011). Sea surface temperature (SST), chlorophyll-a, phytoplankton biomass, ocean color indicators, and coastal morphology were tracked over time using satellite data from NASA's MODIS and ESA's Sentinel missions (Nieto Balmori, 2023; Priego, 2024). These indicators aid in quantifying productivity and stress levels of marine ecosystems and assist in chronicling alterations induced by climate change over extended periods. In conjunction with these models, ocean response is simulated with the Regional Ocean Modeling System (ROMS) and the MITgcm (MIT General Circulation Model) under different greenhouse gas emission scenarios (Shchepetkin & McWilliams, 2005; Marshall et al., 1997). Superimposed on these simulations are current patterns, salinity distribution, vertical mixing, and oxygen levels, which are vital in understanding shifts in marine habitats and fishery migration (Veerappan, 2023). CMIP6 datasets are incorporated into the modeling framework to evaluate prospective changes. Earth's system models have been documented to carry out considerable marine biogeochemical cycles relevant to marine ecosystem activities (Kavanaugh et al., 2021; Eyring et al., 2016). Validation takes place using data from the ocean buoys, Argo floats, and the World Ocean Database historical records to assess the precision and reliability of the model forecasts (Boyer et al., 2013; Sigman & Boyle, 2000; Morris et al., 2024). Further examination involves geochemical studies of sediment cores and isotopic signatures to reconstruct past oceanographic conditions for specific areas in coral reefs and on continental shelves (Wright & Heyman, 2008). Understanding marine ecosystems' responses to past climate changes aids in setting benchmarks and forecasting future ecosystem services (Sharma & Rajput, 2024; Bopp et al., 2013). Applying these combined methodologies within a GIS environment facilitates spatial analysis and risk assessment of vulnerable areas by integrating ecological data with socio-economic factors (Stock et al., 2011). An all-inclusive approach is adopted to develop a robust, systems-based evaluation of the impact of climate change on marine ecosystem services (NASA, 2020).

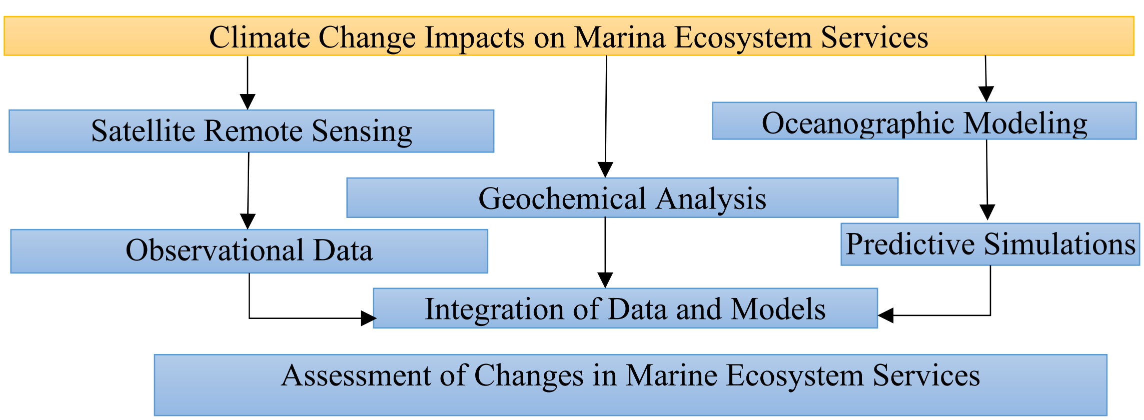

Figure 1. Proposed model flow

Figure 1 shows the methodological framework used for assessing the impacts of climate change on marine ecosystem services with Earth and Planetary Science tools. Remote sensing satellite, oceanographic modeling, and geochemical analysis make up the three primary components in the flow of the process. Ranges of sea surface temperature and chlorophyll concentrations serve as remote sensing data, while oceanographic modeling accounts for future changes in ocean circulation, temperature, biogeochemistry, and biogeochemical cycling, along with various oceanic attributes and components included in predictive simulations. In addition, geochemical analysis involves using sediments and isotopes to construct a historical context reconstructing past marine conditions enables the interpretation of former marine environments thereby providing historical narratives. All the aforementioned procedures result in two primary products: observational data and predictive simulations. The two are later integrated in "Integration of Data and Models." This approach is paramount for validating model accuracy through real-world data because it checks realism over various times and spaces. The methodology utilizes direct observation data combined with simulations to assess shifts in marine ecosystems; this is done holistically for predicted and ongoing changes. After dealing with the changes, the final step "Assessment of Changes in Marine Ecosystem Services" concerns the evaluation of service impacts like fisheries, carbon fixation, and the support of biodiversity. This process, as described in the diagram, implements a systems-thinking approach to ensure that climate impacts and the management and policy considerations for ocean systems are all interconnected. Such relations allow for deeper understanding and informed decision-making on strategy revision that aid conservation and resource allocation.

Results and Discussion

This study indicates that by 2050, climate change will likely cause a further reduction in the functionality of essential marine ecosystem services. Applying methods from Earth and Planetary science, such as satellite remote sensing, oceanographic modeling, and geochemical analysis, the research shows declines in the production of fisheries, carbon burial, biodiversity, and coastal protection. It is projected that due to ocean warming, acidification, deoxygenation, and habitat destruction, there is a 20-35% index value loss of services emitted at present levels. These changes result in the loss of ecological systems, food safety, coastal economic activities, and social resilience for human beings, particularly in the vulnerable coastal belt. The results highlight the focus on climate-driven adaptive approaches and the need to take actionable interventions to prevent the loss of biodiversity and ecosystem services.

Table 1 compares the current and predicted future conditions of four critical ocean ecosystem services Fishery Production, Carbon Sequestration, Biodiversity, and Shoreline Protection on a 0–100 scale index. Each service currently sustains high functional capacity with an index value of 78 to 90. However, these services are projected to undergo severe climate change impacts by 2050 due to increased oceanic stressors. The mid-level service score of Fishery Production is 85, but it is expected to plummet to 60 owing to increased sea temperature, deoxygenation, and changes in fish migratory and reproductive behaviour. These disruptions adversely affect the dependability and accessibility of fish stocks, vital food sources, and income for millions. Carbon Sequestration is expected to fall from 90 to 65 because warmer and more acidic oceans will affect phytoplankton productivity and the ocean's role as a carbon sink. Biodiversity, which currently has a value of 78, is projected to decline drastically to 50 owing to prominent coral bleaching, habitat destruction, and cascading marine food web effects that elicit weakening of ecological balance. Lastly, the current score of Shoreline Protection is 88, but this value is expected to drop to 70. This stems from the loss of coastal barriers such as coral reefs and mangroves, which are being eroded by rising sea levels and extreme weather. Collectively, these declines illustrate the overarching, profound impacts of climate change on ocean health and humanity. The information strengthens the need to implement climate-adaptive marine management and conservation strategies to reduce losses and protect key ecosystems.

Table 1. Ecosystem services

Ecosystem Service	Present Index (0–100)	Future Index (2050, Projected)	Explanation of Change
Fishery Production	85	60	Decline due to rising sea temperatures, reduced oxygen levels, and disrupted fish stocks.
Carbon Sequestration	90	65	Ocean acidification and stratification weaken carbon uptake and biological pump systems.
Biodiversity	78	50	Coral bleaching, habitat loss, and food web collapse reduce species richness.
Shoreline Protection	88	70	Sea level rise and erosion damage protective coastal ecosystems like reefs and mangroves.

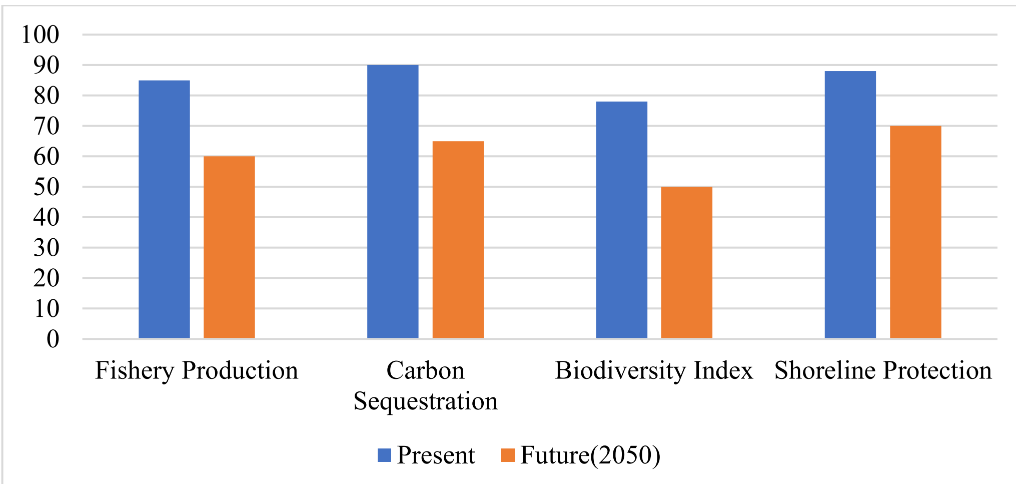

Figure 2. Impact of climate on marine ecosystem services

Figure 2, shows the anticipated reduction in the critical marine ecosystem services compared to today's condition under future climate scenarios. Four of the most essential services diminishing in value are Fishery Production, Carbon Sequestration, Biodiversity, and Shoreline Protection, which are evaluated using an index scale ranging from 0 to 100. Currently, the ecosystem services show relatively high functional capacity, which is supported by an index value range of 78 to 90, indicating that healthy ocean systems exist, which aid the global economy, climate moderation, and coastal resilience through servicing. However, all projections under climate stress for the year 2050 reveal an undeterred, worrying, sluggish movement across all categories. For example, fishery production is projected to drop from an index value of 85 to 60 owing to the increases in ocean temperatures, deoxygenation, and impaired species migration, which disrupts the sustainability of fish stocks. Carbon sequestration declines significantly from 90 to 65 due to ocean acidification and reduced biological productivity, which curb the ocean's ability to absorb CO_2 from the atmosphere. The most severely diminished driving loss of bio diner can't remainder or aliteracy collapse is from 78 to 50. The shoreline protection weakens from 88 to 70 as sea level rises and erosion, induced by climate change, steadily pulls down natural defenses like mangroves and reef systems. These findings highlight the necessity of developing marine policies and conservation strategies that adapt to changing climate conditions, as the consequences of these service depletions threaten substantial damage to ecological equilibrium and human life activities, especially in delicate coastal areas.

Conclusion

Reliable evidence suggests that the harsh impact of climate change on marine ecosystem services due to shifts in oceanic conditions is visible through increased average sea surface temperatures, decreased chlorophyll-a levels, and reduced global fish catches. The use of Earth and Planetary Science techniques, such as satellite remote sensing, offshore surveying, and ocean chemistry, enabled the assessment of both past and future ecosystem changes from various angles, revealing deeper insights. Results indicate that climate change leads to ocean warming and ecosystem disruption by primary production and marine food webs are increasingly subordinate. Fisheries are likely to go unsustainable, carbon capture capabilities become severely reduced alongside coastal defenses, and ultimately, both biodiversity and human life are put at risk. Reduced chlorophyll-a and fish catches are indicative of more shallow waters, deteriorating ocean productivity, and increased ocean stratification, nutrient-sustained ecosystems, and species emigration pathways. This strategy underlines a need for accurate vulnerability assessment of ecosystems for better integration of research approaches within specific spatial and temporal frameworks. In all, the research highlighted the lack of effective adaptive management, policies, international collaboration, and unified approaches to proactively reduce climate measurably effects on oceans around the world. The opposite of depleting marine ecosystems is not simply an ecological issue; it is economically inescapable for the reasons of potential decline in food supply, climate regulation, and sustainable flagship development objectives. Ongoing funding for Earth science technology and ocean monitoring systems optimizes conservation governance and early warning systems. This research, which is framed strongly towards decision making, constructs marine systems to withstand future climates for the coming generations.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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