Statistical interface of Climate Change Impact in the Indian Ocean Region

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Abstract

In a report by *FAO (2017)* it is indicated that globally there would be a decline in fish production value of 21% by 2050 resulting in annual losses of *USD 311 million* for the fishing sector due to increased ocean water temperature. As per the report, fisheries and aquaculture provide livelihoods for *10-12%* of the world population[3]. Currently the blue economy is contributing *5% (USD 2.5 trillion)* to the world's economy [2].Aquaculture, fishing, mariculture, tourism, maritime transport and offshore gas production are some of the activities which contribute the most. Coral reefs, predominantly located in tropical waters, contribute approximately *$375 billion* annually to the global economy through tourism, fisheries, and coastal protection[4]. The (IPCC) reports that up to *30%* of species are at risk of extinction if global temperatures rise by *1.5°C to 2°C.* In addition to that around *3 billion* people live near coastal areas and almost *300 million* people are depending on marine related activities for their livelihood. More than *70%* of earth's surface is water and almost *90%* of anthropogenic emission of greenhouse gas is absorbed by the ocean. The underwater ecosystem which includes biotic components like fishes, marine animals, coral reefs are impacted due to effects of climate change. The rising atmospheric CO_2 and climate change will impact marine ecosystems in many ways, such as rise in temperatures, circulation, stratification, nutrient input, ocean acidification, leading to a range of biological effects such as coral bleaching eventually impacting overall ecosystem functioning and services. Warming, deoxygenation, acidification, and changes in primary productivity by marine phytoplankton can be considered as four major stressors of open ocean ecosystems that are intensified by climate change.

Climate change till now:

Recent reports by the World Economic Forum *(WEF)* [1] and the *Intergovernmental Panel on Climate Change* (IPCC) emphasize the urgency of keeping global warming below *1.5* degrees celsius before the end of *21st* century and to reduce the CO_2 emissions, it is necessary that CO_2 concentration must peak by *2025* and then significantly decrease by *43%* till *2030.* Unachievement of the target will trigger the "***Climate tipping point***" (*refers to threshold climate change after which it is irreversible to change the condition back*) by *2040*.and ultimately leads to unfavorable consequences such as low latitude coral reef die off, melting of Greenland and Antarctic ice sheets. Although various agreements and global groups like COP are formed to tackle the issue, no major impact on the ground has been made. The existing policies are very much influenced by the west and do not address the issue accompanying the interest of stakeholders, characteristics of the ocean concerned based on local population and its unique features.

Rise in Ocean heat content:

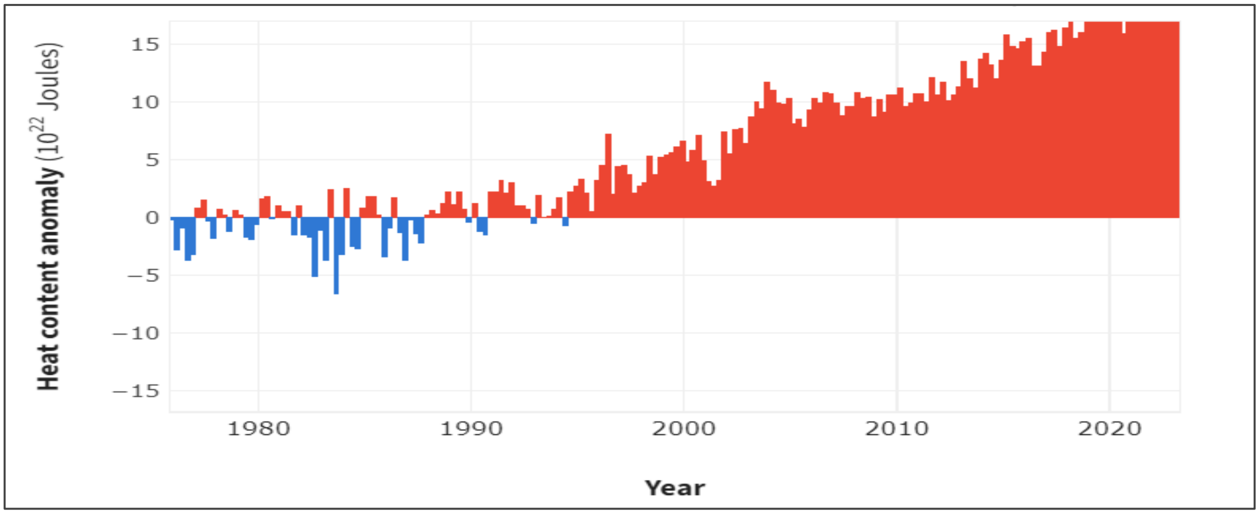

Fig: Time series plot of anomaly in Ocean heat content in world ocean.

Src:https://www.climate.gov/news-features/understanding-climate/climate-change-ocean-heat-content

The net increase in the ocean heat content (OHC) which is a measure of heat encompassed within the upper layer (typically the upper 700m) over the years has led to an increase in the world's ocean average temperature and subsequently high sea surface temperature (SST) which is typically the temperature of ocean's surface layer. SST changes are influenced by the heat content of the upper layers of the ocean; as the upper layers absorb more heat, SST rises. In fact, the climate change in tropical region waters are the ones which show the largest OHC relatively. This is attributed to the fact that tropical regions receive the maximum insulation as they overlap with the equator. Other factors which contribute to variability of SST include ocean currents, monsoon winds, ENSO, greenhouse gasses etc.

Urgency of addressing climate change in tropical waters

Climate change in tropical waters presents a significant threat to the world economy, biodiversity, and unique ecological features. Tropical waters are home to some of the most productive fishing grounds in the world. Climate change-induced coral bleaching and ocean acidification threaten these vital ecosystems. Many of these species are found in tropical waters, where the impact of warming is more pronounced. Mangroves and seagrass meadows are unique to tropical regions and play crucial roles in carbon sequestration, nutrient cycling, and providing habitats for diverse marine life[5]. Mangroves alone can store up to five times more carbon per hectare than tropical forests. Tropical oceans influence global weather patterns and climate regulation through heat distribution and ocean currents. For example, *Atlantic Meridional Overturning Circulation (AMOC)* is a large system of ocean currents, including the Gulf Stream, which transports warm water from the tropics to the North Atlantic. This heat distribution is critical for regulating climate in Europe, making it much warmer than other regions at similar latitudes. Another example is that of tropical cyclones which distribute heat energy from the ocean surface to the atmosphere. These storms play a role in regulating the Earth's heat balance by transporting heat away from the tropics toward the poles. Changes in these patterns due to climate change can have far-reaching impacts, including altered monsoon systems and increased frequency of extreme weather events. In the tropical water, the Indian ocean (IO) is heavily impacted due to rapid heating at a rate above the global mean. IO serves around one-third of the world's total population[6] and is an important region for many countries economically and strategically. The Indian Ocean Region (IOR) is shifting from the "Ocean of the South" to the "Ocean of the Centre" and "Ocean of the Future."

The region is pivotal for global trade, industry, labor, environment, and security.

Indian Ocean Region

The Indian Ocean (IO) is experiencing one of the fastest rates of surface warming among the world's oceans[7],The Indian Ocean has experienced a rise of approximately 1.2°C over the past century. In comparison, the Pacific Ocean has seen an increase of about 0.6°C, while the Atlantic Ocean's SST has risen by approximately 0.7°C. This comparison highlights the varying impacts of global warming on different ocean basins, with the Indian Oceans showing particularly significant changes. Between 1982 and 2021, the area of surface waters exceeding *28°C*, known as the IO Warm Pool, has significantly expanded. This rapid warming is particularly concerning because the Indian Ocean is rich in minerals, biodiversity, and fisheries, providing essential protein food sources and livelihoods to approximately *2.7 billion* people[6]. A unique feature of the IO is its vulnerability to anthropogenic climate change, exacerbated by the Asian continent blocking northward heat transport from the sea. This blockage results in the accumulation of heat in the Indian Ocean, particularly in the northern regions, leading to higher sea surface temperatures (SST) compared to other tropical oceans[8]. Additionally, the northern Indian Ocean is characterized by seasonally reversing ocean currents due to distinctive monsoon circulation, which drives coastal and open water upwelling and results in higher rates of primary productivity compared to the central and southern regions. Changes in sea surface temperature (SST) and ocean currents affect the habitats of marine species. Warmer temperatures and altered currents can lead to coral bleaching, shifts in species distribution, and the decline of sensitive species. Many species of fish depend on the current pattern for spawning and feeding but are getting affected by this change ultimately having its impact on the economy.

Climate Change in IO

Rise in Sea Surface temperature (SST)

Projections based on CMIP6 models suggest that the sea surface temperatures (SST) of the tropical IO will increase by *1.7 to 3.8°C* from 2020 to 2100, depending on different emission scenarios and associated climate changes. An ocean-atmosphere-based analysis using coupled model simulations has revealed that changes in ocean circulation are intensifying warming in the Arabian Sea, while cloud-induced shortwave radiative fluxes control warming in the southeastern IO. This rapid warming has raised the temperature of the upper water layer of the IO basin above 28°C, leading to a dramatic expansion of the Indian Ocean Warm Pool (IOWP) over the past two decades, now covering nearly 100% of the northeast and central IO. Additionally, the heat content of the IO has increased abruptly, contributing to more than a quarter of the global ocean heat gain in the upper 700 meters over the recent decade. This increased heat content significantly impacts global climate dynamics, as SST variability in the IO influences the evolution of the El Niño–Southern Oscillation (ENSO) and modulates atmospheric circulation in the Pacific Ocean on interannual and decadal timescales. Furthermore, large-scale climate models such as the Indian Ocean Dipole (IOD), defined by the SST difference between the western and eastern equatorial IO regions, along with ENSO, are major drivers of SST and its interannual variability. Rising temperatures have also caused widespread coral bleaching across the IO, compromising the habitats of associated marine organisms and highlighting the urgent need for regional marine heat waves (MHW) alert systems and ecosystem-based management strategies to protect critical marine ecosystems and sustain the biodiversity and productivity of the IO.

Deoxygenation and stratification

Decadal trends in the depth distribution of the 12 m depth in the central basin of the Indian Ocean (IO) show that global stratification, which reduces vertical mixing of water masses, is primarily restricted to the upper 200 m. A recent review of Oxygen Minimum Zones (OMZs) revealed that the low oxygen concentrations ($<\sim 0.05$ µM, indicating functional anoxic conditions) observed in coastal areas of the Arabian Sea and Bay of Bengal pose a direct threat to marine life and impact nitrogen cycles in these ecosystems. With continued warming, OMZs are expected to expand, further intensifying anoxic conditions in the coastal IO zones. The Arabian Sea and Bay of Bengal, which comprise 21% by volume of the oceanic waters in the northern IO, are already experiencing microbial hypoxia (< 20 µM). The Arabian Sea OMZ, with a mean concentration of ~10.45 µM, is larger, more intense, and has functional anoxia. In contrast, the Bay of Bengal's OMZ, with a mean concentration of ~14.51 µM, is on the verge of becoming functionally anoxic, while south of 8°N, the minimum oxygen concentrations exceed 20 µM.

Observations from 1960 to 2019 show the horizontal expansion of OMZs in the Arabian Sea and Bay of Bengal, correlating with increasing temperatures. This expansion and the corresponding decrease in dissolved oxygen concentrations, particularly in the northern IO, could impact the entire ecosystem, from microbes to higher trophic level organisms. Multi-model projections (CMIP6) for changes in subsurface (100–600 m) oxygen concentration show robust predictions for the southern IO, with decreases of up to 30 µM under the high emission scenario (SSP5–8.5) by the end of this century. These projections indicate significant ecological shifts and are significant because they influence marine biodiversity, nutrient cycling, and the overall health of marine ecosystems. The expansion of OMZs can have direct economic implications, particularly for fisheries. Fish and other marine organisms that require higher oxygen levels are forced to migrate to areas with adequate oxygen, which can disrupt local fisheries and impact food security for communities dependent on marine resources. (*Source: FAO 2020*). The alteration of species distributions affects the entire marine food web. Predator-prey relationships are disrupted, which can lead to cascading effects throughout the ecosystem. OMZs influence carbon and nutrient cycling by altering the rates of decomposition and nutrient regeneration. Hence highlighting the urgent need for effective management and mitigation strategies to address the expanding OMZs and their impacts on marine life and biogeochemical cycles in the IO.

Marine heat waves (MHW)

Marine heatwaves (MHWs) are defined as periods of elevated ocean temperatures above the 90th percentile that persist for days to months, potentially spanning thousands of kilometers and penetrating the subsurface. Future predictions indicate that the Indian Ocean (IO) may be approaching a state of near-perpetual MHWs. These events, along with low chlorophyll-a (Chl a) occurrences, typically arise in regions where SST and Chl anomalies are strongly negatively correlated. The combination of ocean warming and fishing pressure has been identified as a primary cause of damaged coral habitats in the IO. Recent heat waves, such as those in 2016, have led to mass bleaching of coral reefs in areas like southeast Africa, Sri Lanka, the Maldives, Indonesia, and northwestern Australia, adversely affecting their fishing industries. To mitigate these impacts, ecosystem-based surveys and management strategies should be incorporated for the IO. This approach would raise awareness among scientific institutions, policymakers, and managers about the crucial role of coral reefs as breeding and sanctuary areas for fish and other marine organisms, emphasizing the need for their conservation.

Ocean acidification

There has been a substantial increase in ocean acidification (OA) in the Indian Ocean (IO) surface waters over recent decades. The surface seawater partial pressure of CO2 (pCO2) has increased on average by ~1.6 µatm per year, with model projections under the RCP8.5 scenario predicting increases up to 8.3 µatm per year for the period 2061–2100. This increase in pCO2 has led to a significant decrease in pH over the past 40 years, a trend observed across other oceans as well. Regional differences in pH decline exist within the IO, with the southern and northern regions, including some coastal areas, experiencing a slightly larger decrease than the warmer central areas. However, the rates of pH decrease in the IO are like or less than the mean global ocean value of acidification. Projections indicate that pH could decrease by an average of 0.1 under a low-emission, high mitigation scenario (SSP1-2.6), and by as much as 0.4 under a high emission scenario (SSP5-8.5) over the century.

Clear differences in CO2 content exist between the southern and northern IO. For instance, a zone of CO2 uptake has been identified in the north between 15°S-35°S, primarily driven by the solubility pump, and another in the south between 35°S-50°S where both biological and solubility pumps are significant. This suggests that continued CO2 uptake and acidification will heavily depend on temperature (solubility) in the northern IO, while changes in biological CO2 drawdown and export to deeper layers will influence the fate of anthropogenic CO2. Continued CO2 uptake and increasing OA are influenced by wind systems and warming, which affect solubility. Fresher water, which increases CO2 solubility and dilutes buffering ions, thus decreasing aragonite saturation in the surface water, is particularly relevant in areas influenced by glacial meltwater and river runoff, such as the northern Bay of Bengal.

Decreasing saturation states of calcium carbonate (aragonite or calcite) pose a threat to calcifying organisms by reducing calcification rates and/or increasing dissolution rates. Aragonite saturation states in the IO are decreasing, approaching critical thresholds for corals. Studies in the Arabian Sea have shown the first signs of thinning foraminiferal shells, likely due to anthropogenic OA. Nutrient-enriched coastal waters with high biological productivity can create oxygen minimum zones (OMZs), where high CO2 levels lead to hypoxic and OA environments. The combined effects of hypoxia and OA are more detrimental to marine organisms than either condition alone. Comparing chlorophyll, a (Chl a) concentration over the last two decades reveals an increasing trend in some regions of the northwestern Arabian Sea, whereas many coastal areas show decreasing trends. Furthermore, seasonal variability in Chl a concentration exhibits increasing interannual trends in several regions, indicating significant changes in marine productivity patterns.

Net Primary production

The Indian Ocean (IO) exhibits seasonal variations in net primary productivity (NPP), with the highest NPP occurring during the summer and winter monsoons in the western north, and during the inter-monsoon periods in the same region, with mean values of 1.10 and 1.42 g C m. However, several studies have noted declining trends in NPP in the IO, attributed primarily to warming-induced stronger stratification, leading to a reduction in nutrients. Model simulations consistently project declines in NPP in the tropical IO, with output from earth system models indicating up to a 25% reduction in phytoplankton carbon in most IO regions when comparing 1990–1999 and 2090–2099 under CMIP5 and CMIP6 scenarios. While NPP declines are mostly observed in the northwestern IO, the monsoon wind patterns play a crucial role in driving productivity in the region, particularly in coastal areas. Therefore, the change in NPP represents a significant source of future uncertainty for the IO, emphasizing the need for further research and monitoring to understand and manage the potential impacts on marine ecosystems and associated industries.

India's dependence of blue economy

India's blue economy plays a crucial role in the country's economic landscape, supporting 95% of its business through transportation and contributing an estimated 4% to its Gross Domestic Product (GDP). The nation is the third largest fish producer and the second largest aquaculture fish producer globally. The fisheries sector alone provides livelihoods to about 16 million fisherfolk and fish farmers at the primary level, with nearly twice that number supported along the value chain. Additionally, seaports are a significant source of employment, with jobs in smaller ports increasing from 1,933 in 2003 to 19,102 in 2017. Over the past five years, smaller ports have outpaced major ports in cargo volume growth due to their strategic locations, modernized infrastructure, and efficient operations. Fishing, marine tourism, shipping, and offshore exploration are vital sectors within the blue economy. Many of these sectors, especially fishing and marine tourism, rely on pre-existing skill sets. However, due to various climatic and environmental changes in the marine ecosystem, these existing skill sets will not suffice to meet the growing demand for fish, necessitating policy interventions. Similarly, shipping and ports require skilled manpower, and the evolving demands in these sectors call for re-skilling and upskilling initiatives. Recognizing this need, the Ministry of Shipping recently partnered with the Ministry of Skill Development and Entrepreneurship (MSDE) to capitalize on the vast employment opportunities in the maritime sector and to certify the necessary skill sets.

Source:*https://www.teriin.org/article/blue-economy-ocean-livelihood-opportunities-india*

Existing problems and their possible approach

The Indian Ocean Region (IOR) faces challenges such as unsustainable resource harvesting and a lack of cooperation among countries. A common framework is needed to mitigate these challenges along with climate change's impacts on the global economy. The framework should consider the unique characteristics of the IOR and reflect the interests of stakeholders, incorporating the socio-economic, political, and cultural conditions of the local population. This approach will address environmental concerns while meeting the needs of local communities. One such common framework is the UDA framework.

Research gaps

This paper discusses how climate change has increased net ocean heat content, leading to higher sea surface temperatures (SST) and altered factors such as sea surface salinity and alkalinity in the Indian Ocean. These changes can significantly impact the underwater ecosystem, where even slight variations can cause cascading effects that ultimately reduce ocean productivity. The expanding warm pools in the Indian Ocean necessitate planned marine spatial planning (MSP)[9] to minimize impacts on the underwater ecosystem.

- The need for technology systems to study ocean parameters like SST, salinity, and alkalinity etc. and to forecast potential dangers (if any) to the underwater ecosystem from changing climatic conditions.
- Ensuring data accessibility for all requires combining marine spatial planning with digital transformation, possibly using artificial intelligence models to forecast climate risks based on historical data.

UDA framework approach

Most of the challenges and opportunities in ocean governance exist below the surface, making Underwater Domain Awareness (UDA) a critical tool. However, the global community often opts for easier solutions, neglecting the complexities beneath the surface. There is a pressing need for a common framework that addresses these underlying issues, filling policy gaps and considering relevant stakeholders, particularly with respect to tropical water conditions. Enhanced surveillance and monitoring technologies are essential for collecting data on relevant ocean parameters. Marine Spatial Planning (MSP)[9] is also crucial, as it involves the coordination of activities and balancing competing uses of the ocean to achieve sustainable development. MSP is a holistic approach that considers the ecological, economic, social, and cultural values of marine areas. Technology can be used to map and monitor water quality, identify areas of concern, and evaluate the effectiveness of management measures. Effective MSP requires coordination among stakeholders and balancing competing interests to ensure the sustainable management of marine resources.

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