Science Corner

Climatic Impact-Driver framework for unfolding climate change hazards along the Indian coast

Reshma Gills*, Shelton Padua, C. Ramachandran, Eldho Varghese, K. R. Ratheesh, Grinson George, Rose P. Bright, E. Vivekanandan, J. Jayasankar and A. Gopalakrishnan
ICAR-Central Marine Fisheries Research Institute, Kochi, Kerala

* Email: reshma1818@gmail.com

ABSTRACT

Climate change, driven largely by anthropogenic activities, has led to global shifts in climate patterns, resulting in rising temperatures, frequent extreme weather events, and ecosystem disruptions. These changes pose significant threats to natural habitats, agriculture, public health, and coastal livelihoods, particularly in regions like India. This paper examines the hazard-proneness of India's coastal districts using the CIDs (Climatic Impact-Drivers) proposed in the AR-6 of the Intergovernmental Panel on Climate Change (IPCC) framework, highlighting the physical manifestations of climate risks, including cyclones, floods, heatwaves, sea level rise, and shoreline erosion. The paper emphasized the importance of localized impact assessments alongside global climate risk evaluations, revealing regional disparities shaped by localised cultural factors. By integrating scientific insights with local contexts, this analysis provides a foundation for crafting tailored, equitable adaptation and mitigation strategies to enhance resilience in the face of escalating climate threats.

Keywords: *Risk, Climatic Impact-Drivers, Hazards,*

Introduction

Climate change is a long-term shift in global or regional climate patterns, largely attributed to human activities. It manifests in rising temperatures, more frequent extreme weather events, and significant changes in ecosystems (Shivanna, 2022). This phenomenon disrupts natural habitats, affects agriculture, and poses challenges to human health and safety. The consequences are widespread, impacting everything from sea levels to biodiversity. Rising global temperatures result in melting polar ice caps and glaciers, contributing to sea-level rise, which threatens coastal communities. Extreme weather events, including more intense hurricanes, floods, and droughts, become increasingly common, disrupting ecosystems and human life (Clarke, et al., 2022). Like in every other part of the globe, climate change in India has led to increased temperatures, resulting in more frequent and intense heat waves that impact public health and agriculture (de Bont et al., 2024; Hussain et al., 2024). For example, a severe heatwave in March 2022 saw temperatures surpass 43°C, causing crop failures and fatalities (Bal et al., 2022; Ravindra et al., 2024). Precipitation pattern changes have triggered both flooding and droughts, disrupting the monsoon-dependent agricultural sector. Extreme rainfall events have become more frequent, leading to floods that damage infrastructure and displace communities, while some areas face prolonged dry spells, affecting water supplies and crop yields. The melting of Himalayan glaciers threatens long-term water security, and climate change exacerbates urban air pollution, particularly in cities like Delhi. In the same way, the livelihoods of more than 4 million population (BOBP, 2023) reliant on coastal and marine fisheries in India are under growing threat from climate change. Rising sea levels, eroding shorelines, and extreme weather events are causing significant damage to fishing infrastructure, such as boats and nets, while also increasing risks for those working at sea. Coastal communities face displacement as critical fish landing centres become submerged. Additionally, climate change is taking a toll on ocean ecosystems. Ocean warming is disrupting fish migration patterns and breeding cycles, leading to a decline in traditional fish stocks. Coral reefs, vital for marine biodiversity, are suffering from bleaching due to rising sea temperatures, resulting in habitat loss and further straining fisheries-dependent livelihoods.

According to the Intergovernmental Panel on Climate Change (IPCC) framework, climate change impact assessment and risk assessment are closely intertwined. Together, they provide a comprehensive understanding of the risks posed by climate change, informing policymakers about where and how to act (Simpson et al., 2021). By integrating these assessments, the IPCC framework enables more effective prioritization of adaptation and mitigation efforts, ensuring that strategies are tailored to reduce vulnerability and enhance resilience in the face of growing climate risks at global level. Impact assessment focuses on identifying and quantifying the effects of climate change on specific sectors like agriculture, water resources, health, or biodiversity. The IPCC uses risk assessment as a core methodology to evaluate the potential consequences of climate change on natural and human systems (IPCC, 2022). On a global scale, it helps identify overarching threats, such as rising sea levels, extreme weather events, and disruptions to critical ecosystems, enabling coordinated international efforts to mitigate these risks. However, these global trends often mask regional and local nuances, where the impacts of climate change are shaped by geographic, socio-economic, and cultural factors. Hence, though the global assessments provide valuable insights, there is increasing recognition of the importance of conducting region-specific and local-scale evaluations to address unique challenges and contexts effectively. By integrating dual perspectives both global insights and localized data, risk assessments are crucial for crafting tailored solutions that consider the specific needs and vulnerabilities of affected regions, ensuring more effective and equitable responses to climate change. Against this backdrop, this paper delves into the hazard-proneness of India's coastal districts, a critical component of the climate change risk analysis framework outlined by the Intergovernmental Panel on Climate Change (Gills et al., 2024). By focusing on hazard-proneness, the study highlights the physical manifestations of climate risks specific to Indian coastal districts. This is particularly relevant given the nation's extensive coastline of over 7,500 kilometers, where densely populated areas, economic hubs, and biodiversity hotspots intersect. The findings contribute to a deeper understanding of the risks posed by climate-induced hazards and serve as a foundation for assessing the interplay of exposure and vulnerability.

Frameworks for climate risk assessment: concept, dimensions and metrics

Concept of risk and risk assessment

The concept of risk in the IPCC framework has undergone significant refinement between its AR5 (Fifth Assessment Report) and AR6 reports (Sixth Assessment Report), reflecting the evolving understanding of climate change impacts and the need for actionable solutions. Till the AR5 Vulnerability was the central theme for the assessment and was often treated as a static condition, determined by socio-economic factors, geographic location, and the adaptive capacity of communities. This approach emphasized the identification of at-risk populations and ecosystems, laying the groundwork for understanding climate-related risks as a product of external drivers and local sensitivities. By 2022, the IPCC Sixth Assessment Report introduced a more dynamic perspective on risk and vulnerability, emphasizing the interconnectedness of human and natural systems and the concept of risk became central to the approach for evaluating and conveying the potential adverse impacts of climate change, as well as the available response options, to decision-makers. In the context of climate change, risks arise from the interaction of climate-related hazards with the exposure and vulnerability of affected human or ecological systems. The magnitude, likelihood, and dynamics of hazards, exposure, and vulnerability can vary over time and space due to socio-economic changes and human decisions, adding layers of uncertainty. Similarly, in climate change responses, risks stem from the potential failure to meet intended objectives or from trade-offs and negative side effects on other societal goals, like the Sustainable Development Goals. These risks may arise from uncertainties in the implementation, effectiveness, or outcomes of policies, investments, technologies, and system transitions (Reisinger et al., 2020). Thus, risk assessment in the new framework considers three key components: hazard (the climate-related events such as heatwaves, floods, or storms), exposure (the presence of people, assets, or ecosystems in harm's way), and vulnerability (the sensitivity and adaptive capacity of the affected systems).

Redefining hazards

Over successive IPCC assessment reports, the conceptual framework for understanding climate change and risk has evolved, leading to technical refinements in key constructs such as hazards, exposure, and vulnerability. For instance, the IPCC Fifth Assessment Report (AR5) defined hazard as *"the potential occurrence of a natural or human-induced physical event, trend, or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources."* This definition emphasized dimensions such as climate-related physical events, trends in the frequency or intensity of such events, and assumes that all hazards inherently carry the risk of harm. However, the Sixth Assessment Report (AR6) introduced a more refined perspective, clarifying that the term "hazard" should not be used generically to describe all climatic events or trends. Instead, it highlighted that not all such phenomena lead to adverse consequences for every aspect of an affected system. For instance, an increase in temperature may harm agriculture in tropical regions but extend growing seasons in colder climates. Similarly, increased rainfall can cause flooding in vulnerable areas but benefit water-scarce regions. This conceptual refinement separating the potential occurrence of a climate phenomenon from its contextual outcomes, ensures a more precise and context-sensitive understanding of hazards, focusing on their potential to cause harm based on the interplay of exposure and vulnerability. Hence it was suggested to use the concept of 'Climatic Impact-Drivers (CIDs)' to provide a more distinguished approach to understanding how climate factors directly influence human and ecological systems (Ranasinghe et al., 2021; Ruane et al., 2022). A key distinction between CIDs and hazards lies in their scope and applicability. CIDs are defined as physical climate system conditions that affect living organisms or built environments and can be beneficial, neutral, or harmful, depending on the context. Unlike traditional notions of hazards, which focus solely on adverse consequences, CIDs encompass a broader range of climate-related phenomena, such as temperature changes, rainfall variability, droughts, frost events, and extreme weather conditions. This influence can manifest in various forms, such as extreme events (like hurricanes or heatwaves), episodic occurrences (like seasonal rainfall), or even long-term average conditions (such as gradual temperature changes or shifting rainfall patterns).

According to the IPCC's AR6 (2022), Climatic Impact-Drivers (CIDs) are categorized into seven different types, each representing specific climate-related conditions that can affect human and ecological systems. These categories include dry and wet conditions, wind, snow and ice, coastal conditions, oceanic conditions, and other climate-related factors. Within each of these categories, a variety of indices can be used to quantify and describe the specific features of the climate impact-driver that are most relevant to different sectors or regions. In total, the IPCC has identified 33 distinct indices that help capture the diverse impacts of CIDs, ranging from temperature changes and precipitation patterns to extreme weather events and oceanic phenomena. These indices allow for more targeted assessments of how specific climatic drivers might affect ecosystems, economies, and communities. When experts determine that a CID is harmful to a particular system, it is often classified as a hazard. This classification is based on the severity of the CID as defined by certain indices and thresholds. For example, a heatwave or a hurricane might be considered a hazard in certain areas due to its potential to cause harm. The threshold for a Climatic Impact-Driver refers to the specific point at which the interaction between the CID and the exposed or vulnerable system leads to significant changes in impact, risk, or opportunity. These thresholds can be determined by various factors, including the magnitude, duration, frequency, timing, and spatial extent of the CID. For example, a threshold might be reached when a temperature rise surpasses a certain degree, triggering crop damage or public health issues.

CIDs relevant to coastal hazard analysis

Recent studies have highlighted several Climatic Impact-Drivers (CIDs) from the IPCC AR6 framework that are particularly relevant to the Indian context, especially concerning coastal hazards. However, there was a lack of region-specific studies detailing the CIDs pertinent to coastal areas in India. As a result, this study adopted a deductive approach to identify and select appropriate CIDs based on sector-specific research, previous studies on coastal hazards, and expert consultations and selected, five key coastal hazards having significant potential to adversely impact the coastal socio-ecosystems. These hazards include sea-level rise, flood proneness, shoreline changes, heatwaves, and cyclone proneness. To assess the CIDs associated with these coastal hazards, the study selected the appropriate CID types from the IPCC

AR6 framework. The three key CID types chosen for the assessment were coastal, heat & cold, and wind. Under each of these CID types, specific CID categories were identified and assessed using relevant threshold-based CID indices. For the coastal CID type, five categories were considered: sea level rise, coastal flood, coastal erosion, stable coastal line and accretion. These categories reflect critical coastal hazards that directly impact infrastructure, ecosystems, and human communities. These indices are calculated using data from sources like Copernicus NCCR, MoES and the Indian Meteorological Department (IMD). Similarly, extreme heat event was included under the heat & cold CID type, reflecting the growing risks posed by increasing temperatures in coastal regions (Data source; IMD). For the wind CID type, eight categories including 'Sustained Surface Winds in CS,' 'Sustained Surface Winds in SCS', 'CS Return Period', 'SCS Return Period', 'Landfall Count', 'Storm Surge', 'Probable Rainfall in SCS' and 'Probable Rainfall in CS', as these are particularly pertinent to the region's vulnerability to storms and extreme weather events (Data source; IMD). In total, 14 threshold-based CID indices were selected to quantify the intensity of these Climatic Impact-Drivers and assess the risk levels of different coastal hazards.

Hazard index calculation

The Hazard Indices derived from these CIDs are the Sea Level Rise Hazard Index (SLRHI), Flood Hazard Index (FHI), Heatwave Hazard Index (HWHI), Shoreline Change Hazard Index (SLCHI), and Cyclone Hazard Index. The Sea Level Rise Hazard Index (SLRHI), Flood Hazard Index (FHI), and Heatwave Hazard Index (HWHI) were developed using a quotient-based indexing method. Sea level rise data from the Copernicus database (in meters) was used to calculate the SLRHI, while the IMD data on hazard events from 1969 to 2019 informed the FHI and HWHI. District-level data for sea level rise, floods, and heatwaves were normalized using the Min-Max procedure, scaling values between 0 and 1. The state-level hazard index was derived by averaging the district-level hazard indices. The Shoreline Change Hazard Index (SLCHI) was calculated based on three important dimensions: stable, erosion and accretion, in which erosion and accretion status are quantified into high, moderate, and low levels based on the rate of change (m/year). To account for varying coastal lengths across maritime states, the data was normalized by converting the shoreline change into a proportional change, calculated by dividing the coastal length at each level by the total coastal length of the states and districts. This adjustment ensures the index reflects the intensity of shoreline change relative to the state's and district's coastal size. Experts assigned weights to different shoreline alteration levels for calculation. The three accretion levels (high, medium, and low) were given weights of 50, 33, and 17, respectively, while the erosion levels received the reverse weights. The stable level (no shoreline change) was assigned a weight of 1. The shoreline change index for each coastal district was then calculated by summing the weighted levels of shoreline change. Similarly, the Cyclone Hazard Index (CHI) calculation uses data from eight CID indices related to cyclonic activity within 50 nautical miles of coastal districts between 1961 and 2020. To standardize the data, all CID indices were normalized to a unitless range of 0 to 1. Expert opinions were used to assign weights to different CIDs to reflect the severity of cyclones. For example, longer return periods for cyclones were assigned negative weights of -2 and -4 for cyclonic storm and severe cyclonic storm return periods, respectively. Other CIDs like surface wind and maximum rainfall in a cyclonic storm were given a weight of 1, while landfall count, surface wind in a severe cyclonic storm, and maximum rainfall in a severe cyclonic storm were assigned a weight of 2. Given its significant impact, storm surge was assigned the highest weight of 5. The Cyclone Hazard Index was then calculated by summing the weighted normalized CIDs.

The Multi-Hazards Index (MHI) a composite metric that represents the relative proneness of coastal districts to multiple physical hazards included in the study was also derived. It consolidates the effects of various individual hazards, such as sea level rise, floods, cyclones, heatwaves, and shoreline changes, into a single index. To calculate the MHI, the normalized values of each individual hazard were summed and then rescaled to a uniform range of 0 to 1 (Equation 1). This approach ensures that the index provides a standardized measure of multi-hazard proneness across coastal districts, offering a clearer understanding of cumulative risk levels and enabling more informed decision-making for disaster management and climate adaptation strategies.

$$\mathrm{MHI} = \sum_{t=1}^{5} W_t \mathrm{NHI}_t \qquad \text{(Equation 1)}$$

where,

NHI_t= Normalised Hazard Index calculated for the t^{th} physical hazard considered in the study
W_t = weightage given to the t^{th} physical hazardindex (in the present study we assumed equal weightage W=1).

Hazard proneness of coastal districts and maritime states of India

The normalized hazard indices for India's coastal states and Union Territories reveal significant variations in vulnerability to multiple physical hazards, including cyclones, floods, heatwaves, shoreline changes, and sea level rise (Fig. 1). Odisha and West Bengal emerge as the most cyclone-prone, with scores of 1.00 and 0.96, respectively, while Andhra Pradesh exhibits the highest vulnerability to heatwaves (1.00). Flood risk is particularly severe in Kerala (1.00) and Andhra Pradesh (0.79). Shoreline change is a critical concern for West Bengal (1.00) and Puducherry & Karaikal (0.74), while Daman & Diu (1.00) and Gujarat (0.93) are the most affected by sea level rise. The composite Multi-Hazard Index (MHI) identifies Andhra Pradesh (1.00) as the most vulnerable overall, with significant risks across all hazard categories, followed by Odisha (0.48) and Gujarat (0.42). States like Goa (0.00) and Daman & Diu (0.08) have minimal multi-hazard exposure but still require localized interventions for specific risks. These findings highlight the need for region-specific adaptive strategies to address the diverse climate-related challenges across India's coastal regions.

District-level analysis of physical hazard severity across west coast and east coast

Among the west coast states, in Gujarat, sea level rise hazard is critically high, particularly in the districts along the Saurashtra coast and Diu. Cyclone and shoreline change hazards are relatively low, while heat wave severity is minimal. Gir Somnath and Devbhumi Dwarka report the highest HWHI in the state, with Gir Somnath also showing higher cyclone hazard severity. Maharashtra records flood hazards as its most severe concern, particularly in Mumbai City, Thane, and Ratnagiri. Cyclone and sea level rise hazards fall into moderate severity, with Palghar, Mumbai City, and Thane being the most affected. Shoreline change is most severe in Palghar, while districts like Ratnagiri and Mumbai suburban show moderate impacts. Goa experiences moderate severity for sea level rise and cyclone hazards, while shoreline change is more pronounced in North Goa compared to South Goa. The southern district faces greater risks from sea level rise and cyclones. Kerala leads in flood hazard severity. Cyclone and heat wave hazards are minimal, and Thiruvananthapuram has the highest FHI. Similarly, the states on the East Coast also showed a varying degree of proneness to different hazards. Tamil Nadu is highly prone to cyclone hazards, particularly in northern districts, with Ramanathapuram being the most vulnerable (CHI: 0.76). The state also exhibits moderate sea level rise risk, with Cuddalore and Villupuram particularly affected. Chennai experiences significant susceptibility to flooding (FHI) and heat waves (HWHI). Shoreline change is most severe in Thiruvarur and Villupuram, while Puducherry and Karaikal face minimal flood and heat wave hazards but high sea level rise risks. Heat waves and cyclones are the most severe hazards in Andhra Pradesh, with HWHI and CHI values indicating high vulnerability. Flood risks are also significant, while sea level rise and shoreline change hazards are relatively lower. West Godavari and Vizianagaram are the most affected districts by heat waves and cyclones, respectively. Cyclones present

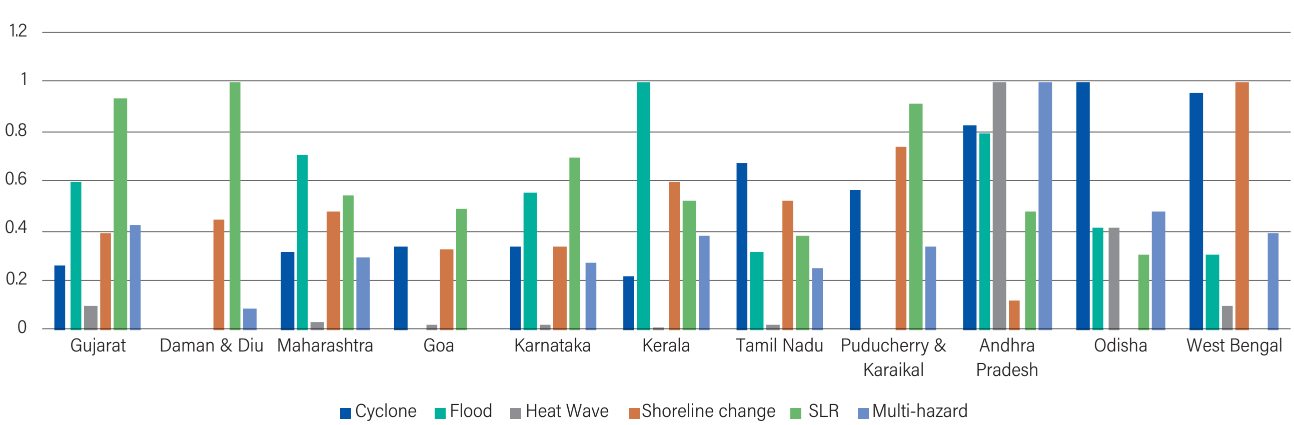

Fig.1. Hazard proneness of coastal states and Union territories of India based on normalised hazard index

extremely high severity in Odisha, with the state having faced 260 storms in the last century. Baleshwar is the most vulnerable district to cyclonic hazards. Floods and salinization are additional consequences. Shoreline change and heat wave hazards are minimal, with Bhadrak being the least prone to shoreline changes among Indian coastal districts . Similarly, Cyclones and shoreline changes are the most severe hazards in West Bengal. North 24 Parganas is highly vulnerable to shoreline erosion, while sea level rise poses the lowest risk among the hazards studied. The state demonstrates an alarming trend for erosion-driven shoreline changes, with all three coastal districts—East Midnapore, South 24 Parganas, and North 24 Parganas—being significantly affected .

The hazard atlas, derived from the multi-hazard index (Figure 2), highlights significant variability in hazard severity across coastal districts. Sindhudurg district in Maharashtra stands out with the lowest score, indicating minimal susceptibility to climate change-induced physical hazards. In contrast, Krishna district in Andhra Pradesh records the highest score, signifying its extreme vulnerability to a combination of hazards such as cyclones, floods, and heatwaves . This divergence highlights the diverse risk profiles of India's coastal regions, influenced by varying geographic, climatic, and environmental factors.

Factoring the hazards index and policy implications

The East Coast maritime states of India exhibit a higher susceptibility to climate change-induced hazards compared to their West Coast counterparts, as indicated by the multi-hazard index . This differential vulnerability is attributable to a combination of natural and anthropogenic drivers, including geomorphological characteristics, regional climatic regimes, monsoonal dynamics, and oceanographic processes. On the West Coast, key hazards such as flooding, shoreline erosion, and sea level rise dominate. The rise in sea levels, primarily driven by thermal expansion of seawater and cryospheric melting,

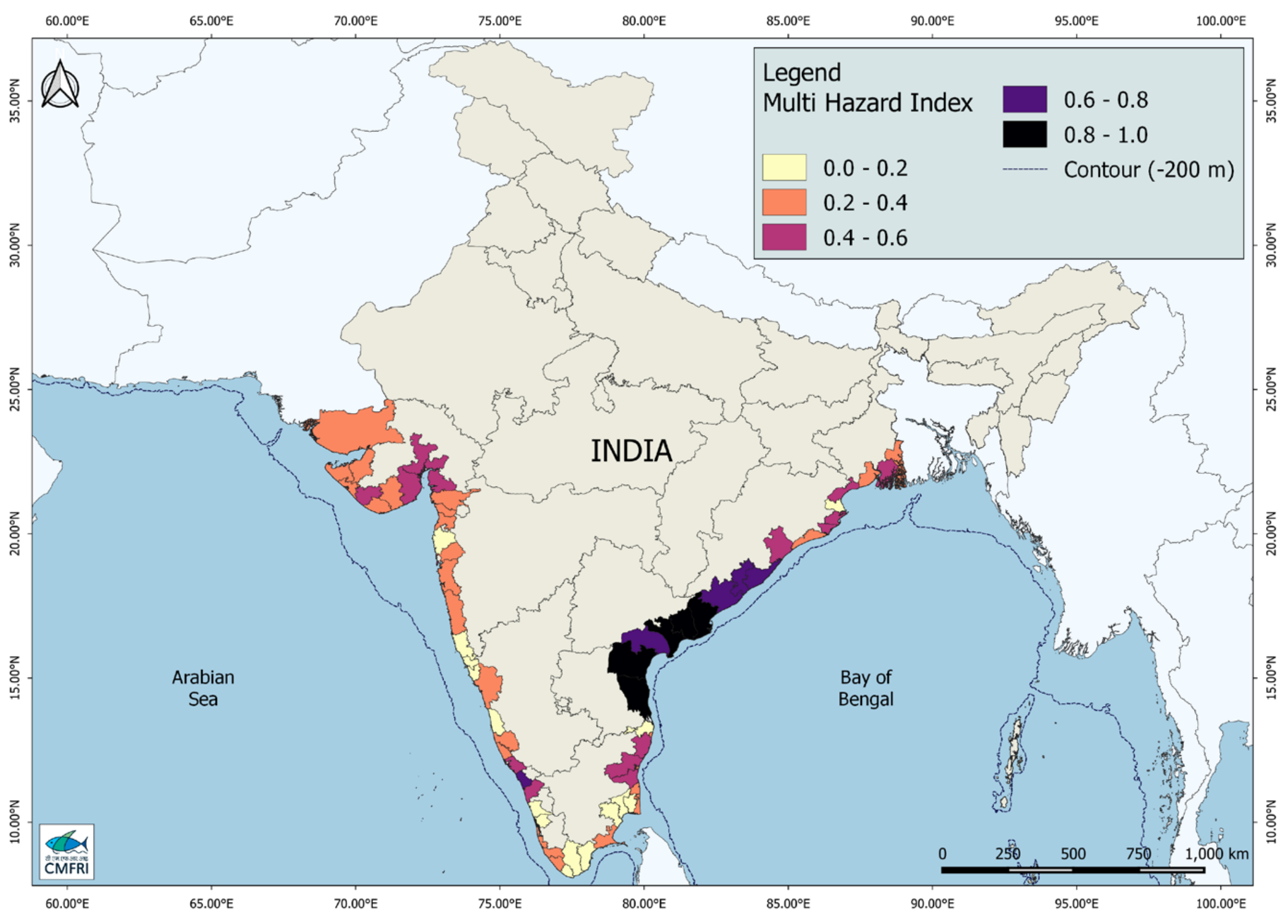

Fig. 2: Map depicting multi-hazard index across the coastal districts

exacerbates coastal flooding, particularly during extreme precipitation and cyclonic events. The region's relatively smooth coastal topography and sediment deposition from riverine systems further contribute to shoreline instability and erosion. Conversely, the East Coast experiences heightened exposure to cyclones and heatwaves, often referred to as "silent hazards," with significant shoreline erosion in states like West Bengal. The Bay of Bengal witnesses nearly fourfold higher cyclone frequency compared to the Arabian Sea, driven by elevated sea surface temperatures, El Niño-Southern Oscillation (ENSO) phenomena, and anomalous ocean-atmosphere interactions. These oceanic and atmospheric dynamics also contribute to the increased incidence of heatwaves, amplifying the region's overall vulnerability to extreme climate-related events .

The findings from the spatial analysis underscore the critical need to tailor mitigation strategies to the distinct hazard profiles of India's East and West Coasts, underpinned by the Climatic Impact-Driver (CID) framework. The East Coast's high vulnerability to cyclones and heatwaves demands scientifically driven interventions, such as enhanced atmospheric and oceanic monitoring systems, real-time cyclone forecasting, and the establishment of heat action plans tailored to local climatic conditions. Structural measures, including robust cyclone shelters and resilient building codes, should be coupled with non-structural strategies, such as community-based disaster preparedness programs. Conversely, the West Coast's challenges, primarily driven by sea level rise, shoreline erosion, and flooding, necessitate ecosystem-based solutions. These include the restoration and conservation of mangroves and coastal wetlands to act as natural buffers, alongside sustainable coastal zone management practices that limit unregulated development and reduce human interference in fragile ecosystems. Furthermore, integrating these spatial insights into coastal development policies can enable a science-based approach to infrastructure planning and land-use regulation. By incorporating real-time hazard mapping, policymakers can ensure dynamic risk assessments that account for evolving climate patterns. This approach enables prioritization of investments in high-risk districts and promotes climate-resilient infrastructure, such as elevated structures and adaptive drainage systems to mitigate urban flooding. The CID framework also highlights the importance of combining nature-based solutions with engineered interventions to address complex and compound climate risks. Strengthening disaster response mechanisms, fostering community participation, and promoting livelihoods resilient to climate stressors are essential to building adaptive capacity. By aligning policies with global frameworks, India can build a sustainable and inclusive pathway to mitigate the escalating impacts of climate change along its vulnerable coasts.

Conclusion

This study provides critical insights into the spatial variability of climate change-induced hazards along India's coastal districts, emphasizing the differential vulnerability of the East and West Coasts under the Climatic Impact-Driver (CID) framework. The analysis reveals that the East Coast is disproportionately affected by cyclones and heatwaves, while the West Coast contends with hazards such as sea level rise, shoreline erosion, and flooding. These findings underscore the urgent need for region-specific, evidence-based adaptation strategies that address the distinct hazard profiles of these regions. The results highlight the necessity of integrating scientific knowledge with local contexts to formulate effective mitigation and adaptation policies. Policymakers must leverage this spatial analysis to prioritize investments in high-risk areas, foster community resilience, and align local efforts with global climate goals. Through such targeted approaches, India can enhance its adaptive capacity and safeguard the livelihoods and ecosystems of its coastal regions from escalating climate threats.

Suggested Reading

IPCC, 2022: Summary for Policymakers. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–33,. doi:10.1017/9781009325844.001

Reisinger et al., 2020. The concept of risk in the IPCC Sixth Assessment Report: A summary of cross-working group discussions. Intergovernmental Panel on Climate Change, 15, p.130.

Source

Reshma Gills, Shelton Padua, C. Ramachandran, Eldho Varghese, K. R. Ratheesh, Grinson George, Rose P. Bright, E. Vivekanandan, J. Jayasankar and A. Gopalakrishnan. 2024. Climate change hazards along the Indian coastal districts: spatial analysis on a Climatic Impact-Driver framework. *Current Science*, 127 (4): 461 - 474