Climate change hazards along the Indian coastal districts: spatial analysis on a climatic impact-driver framework

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Concepts, approaches and frameworks for assessing the impacts of climate change are evolving quickly. Due to their particular geographic location, proximity to oceans, concentration of populated regions, and infrastructure, coastal communities are particularly sensitive to the effects of climate change. The present study aims to develop a thematic map based on the CID (climatic impact-drivers) framework proposed in the assessment report-6 of the Intergovernmental Panel on Climate Change (IPCC) to evaluate the climate change's physical hazards in the coastal districts of India. The study points out that West Bengal and Odisha are the two states with the highest cyclone hazard index values making them most vulnerable to cyclones. At the same time, Kerala, Andhra Pradesh and West Bengal respectively fall in the extremely severe category of flood, heatwave and shoreline change hazards. The maritime state of Gujarat along with Diu and Daman experiences maximum severity for the sea level rise hazard. The multi-hazards index developed in the study by considering 14 threshold-based CID indices showed that the coastal state of Andhra Pradesh has the highest proneness to the physical hazards due to climate change.

Keywords: Cyclone, flood, heatwave, multi-hazard, sea level rise, shoreline change.

CLIMATE change is no longer an issue for the future[1], but has become an increasingly important worldwide emergency of the present[2–5]. The Earth's climate is undergoing profound changes due to human activities, resulting in more frequent and severe weather events like severe storms, droughts, heatwaves, etc. which have become the new norm[6–10]. Globally, people, animals, and ecosystems are all affected by the far-reaching effects of climate change, which lead to cataclysm, loss of biodiversity, economic instability and detrimental health repercussions[11–13]. While global assessments are important, there is a growing recognition of the need for region-specific and even local-scale assessments. Being one of the most populous nations, India confronts numerous threats from climate change in severe forms[14,15]. According to the World Bank assessment[16], by 2030, India would see a very high, unpredictable summer monsoon with extremely rainy conditions and associated hazards occurring every ten years, compared to the country's previous return rate of every 100 years. However, the current climate change situation in India is more adverse, as a recent study found that 314 days out of 365 days in 2022 were reported with at least one extreme event, resulting in the loss of close to 3000 lives, destruction of approximately 420,000 homes, and loss of nearly 2 million hectares of cultivated land and crops[17].

Since climate, biodiversity, ecosystem and human societies are interwoven[18], climate change vulnerability and its impact on the ecosystems substantially varies with regional positioning, patterns of societal developments, marginalization, inequalities, governance mechanism, etc.[19]. The topography and geography of India are diverse enough that different climate change responses are happening for different regions. Coastal areas are the hardest hit by uneven climate change and climate-related extremes[20]. The coastal regions of India, approximately within 50 km of the 7516.6 km coastline[21] in the 9 maritime states, which are home to approximately 250 million of the country's 1.40 billion people[22] are experiencing coastal erosion[23–25], sea-level rise[26,27] and natural disasters such as tropical storms and cyclones[28,29]. Systematic assessment of the various dimensions of climatic vulnerabilities is essential to the proper management of climate change-induced risks[30]. Despite the fact that numerous studies have been conducted to assess the climate change risk of specific regions or resources based on specific hazards[30,31], a district-level comprehensive assessment of physical hazards based on the 'climatic impact-drivers (CIDs)[1,32,33] was lacking in India's coastal districts[34]. At the same time, even while

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the studies focused solely on the changes in the physical climate variables or hazards in terms of their number, frequency, time period, etc. a significant number of earlier studies in the climate change regime had unseeingly used the term ‘risk assessment’ which has led to an imprecise analytical analysis framework and flawed inferences. Since Intergovernmental Panel on Climate Change’s (IPCC’s) assessment report 6 (AR6) had taken a conceptual deviation in the risk assessment framework from the previous assessment reports with a more clarified conceptual abstracting for terms like risk, exposure, physical hazards, vulnerabilities, etc.[35] necessitated the need for physical climate information at global, regional and local scales, for proper understanding of climate system responses and risk assessment[1,36]. Against this backdrop, the present study was planned to map the coastal districts of India based on the spatial analysis of various ‘physical hazards’, which is one among the three components of the ‘inclusive climate change risk analysis framework’ conceptualized in IPCC’s AR6 (refs 1, 18).

Climatic impact-drivers and physical hazards assessment

Climate impact assessment is an ongoing, reiterative process that involves continuous monitoring, evaluation and adjustment of strategies as new information emerges. Early climate impact assessments often focused solely on physical changes (e.g. temperature and precipitation) and their direct effects. Modern assessments take a more holistic approach, considering interactions between climate changes and social, economic and environmental systems. In accordance with the changes in the conceptual framework, various constructs (e.g. hazards, exposure, vulnerability and risk) also underwent abstract technical modifications over various IPCC assessment reports. The IPCC AR5 (ref. 37) defined hazard as ‘the potential occurrence of a natural or human-induced physical event or 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’. The typical dimensions taken into account under the word ‘hazard’ included climate-related physical occurrences, trends in the incidence of events, the physical impact produced by events, etc.[9]. However, the most recent IPCC AR6 (ref. 35) has made it clear that it is unacceptable to use the generic term ‘hazard’ to describe climatic events or trends that may not have adverse consequences on every component of an impacted system. It was suggested to use the word CID, which is impartial in its influence and does not presuppose that the consequences will always be beneficial or detrimental. Results from CIDs and their modifications may be favourable, unfavourable or insignificant (or a combination of these). Therefore, any physical or climatic situation that has an immediate influence on society or ecosystems is considered a CID. It might be depicted as an extreme occurrence of an event, a common episodic event, or a long-term average condition.

According to IPCC AR6 (ref. 38), CIDs can be recorded in seven different types. These include dry and wet, wind, snow and ice, coastal, oceanic, and other conditions. There may be a variety of indices for each CID category (IPCC defined a total of 33) that capture the sector or region-relevant features of a CID[35,39]. CID can be referred to as a ‘hazard’ when experts determine it as harmful to a particular system depending on the indices and the thresholds of a particular CID[40]. The indices of the CID can be calculated quantitatively using one or more climate variables intended to evaluate the strength of a climate impact-driver or the likelihood that a threshold will be exceeded. The value beyond which a CID interacts with vulnerability or exposure to produce, increase, or decrease an impact, risk or opportunity is known as a threshold for the CID. Thresholds can be measured with the size or severity, duration, frequency, timing, and spatial extent of a CID[33,40,41]. The CID is classified as a hazard if it is having a negative effect.

Materials and methods

Identification of climatic impact-drivers and indices to study the physical hazards

Climate change has the ability to affect a wide range of characteristics of the climate system. However, for developing successful climate-responsive measures, evaluation should be more concentrated on the smaller set of changes (CIDs) that may have an impact on the ecosystem components that society cares about[33,40,42]. The CIDs chosen for the specific climatic variables must capture the various aspects of the physical circumstances of the climate system in one of the three forms, i.e. means, events, or extremes. Some recent studies[43] have identified different categories of CIDs from the IPCC AR6 (ref. 36) defined CID types that are relevant to the Indian context. Since region-specific studies mentioning CIDs pertinent to coastal hazards were absent, a deductive approach to select suitable CIDs was followed in the present study. Based on the sector and region-specific previous studies[44–47], focus group discussions and expert consultations, five different hazards (sea level rise, flood proneness, shoreline change, heatwave and cyclone proneness) having the potential to adversely affect the coastal socio-ecosystems were selected for the hazards mapping and physical hazards assessment. The relevant CID types that could cause coastal hazards were chosen from the framework of CIDs proposed in IPCC AR6 (ref. 40). These include coastal, heat and cold, and wind. Under each CID type, different CID categories were assessed with different relevant threshold-based CID indices. The different CID categories included in the present study are

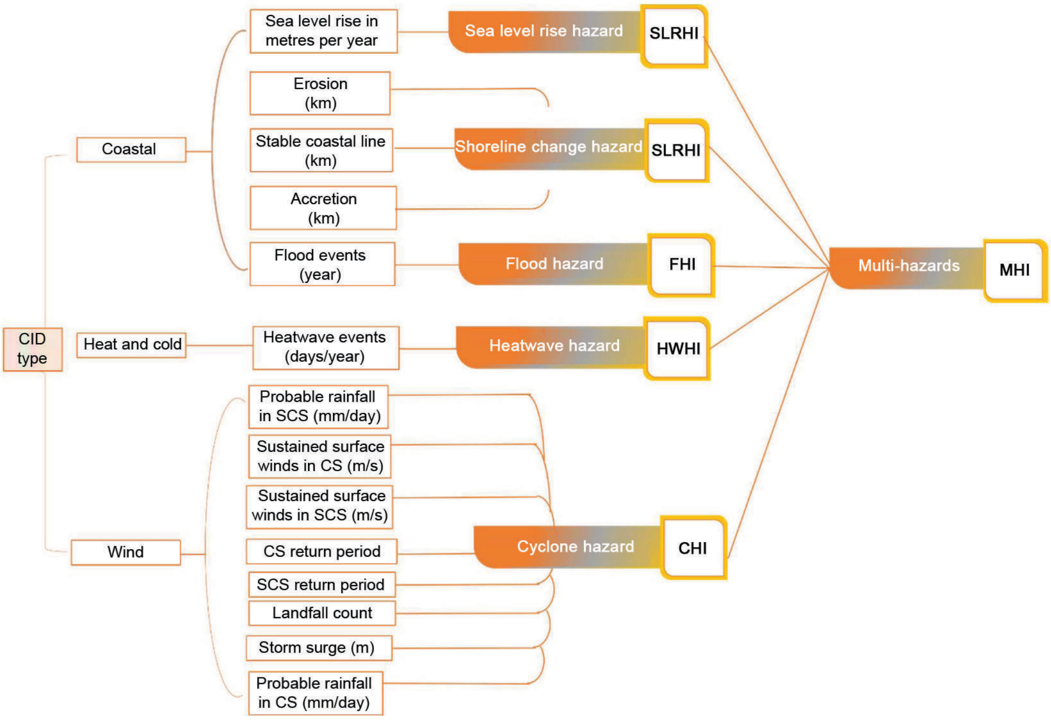

Figure 1. Framework of climatic impact-drivers (CIDs) used in the present study. CS, Cyclonic storm; SCS, Severe cyclonic storm.

as follows: the coastal CID type consisted of three CID categories, i.e. relative sea level, coastal flood and coastal erosion. Similarly, extreme heat was included under the heat and cold CID type. Mean wind speed and tropical cyclone were the two CID categories included in the wind CID type. Further, a total of 14 threshold-based CID indices were considered for the numerical quantification of the intensity of CIDs. A detailed description of the framework of CIDs used in the present study is given in Figure 1.

Development of hazards index

Various coastal hazards were assessed based on the index constructed using threshold-based CID indices. The spatial scale was fixed at the district level for calculation of the hazard index which was further aggregated to get the state-level picture.

Shoreline change hazard index: The shoreline change status along the Indian coast prepared by the National Centre for Coastal Research (NCCR), Chennai[48] was used for the preparation of shoreline change hazard index (SLCHI) at the coastal district level. The shoreline change was indicated as shoreline length in kilometre under three components (CID indices), i.e. erosion, stable and accretion. Further, both erosion and accretion status were quantified as three different levels, viz. high, moderate, and low, based on the rate (m/year)[48]. Since the shoreline change was calculated in kilometre and different maritime states have varying coastal lengths, to capture the intensity of the shoreline change with a weightage to the coastal length of the districts, the actual data was converted as proportional change by dividing coastal length at each level by the total coastal length of the district as given in eq. (1).

$$\mathrm{psl}_{id} = \frac{\mathrm{sl}_{id}}{\mathrm{Tsl}_d}, \tag{1}$$

where psl_{id} is the proportional change of the ith level of the shoreline change with respect to the total shoreline length in the dth district, sl_{id} the shoreline change in the ith level in the dth district and Tsl_d is the total shoreline of the dth district.

Based on the expert's valuation, weights were given to different shoreline alteration levels for further calculation. The three accretion levels (high, medium and low) were given weightage of 50, 33 and 17 respectively. In a similar manner, the three erosion levels were given the same weightage but in the opposite magnitude. The stable level (no change in shoreline) was given a weightage of 1. Further, the SLCHI for a given coastal district was calculated by summating the weighted levels of shoreline change (eq. (2)).

$$\mathrm{SLCHI}_d = \sum_{i=1}^{i=7} W_i \mathrm{psl}_i, \tag{2}$$

where SLCHI_d is the shoreline change hazard index for the dth district in the state and W_i is the weightage given for the ith level of proportional shoreline change ($i = 1, 2, \ldots, 7$).

District-level shoreline change hazard index was normalized to a dimensionless range of 0–1, using (eq. (3)).

$$\text{Normalized SLCHI}_d = \frac{\text{SLCHI}_d - \text{SLCHI}_{\min}}{\text{SLCHI}_{\max} - \text{SLCHI}_{\min}}, \quad (3)$$

where $\text{SLCHI}_{\min}$ and $\text{SLCHI}_{\max}$ are the lowest and highest possible scores of SLCHI among the coastal districts respectively.

Cyclone hazard index: The cyclone hazard index (CHI) in the present study indicates the proneness of the particular coastal district to cyclones in all intensities. Annual average data on eight different CID indices concerning the cyclonic incidence (in all intensities) within 50 nautical miles of coastal districts for a period of 1961–2020 (ref. 48) was considered for the construction of CHI (Table 1). Since CID indices were measured in varying units, a first-stage normalization was carried out to get unidirectional, unitless indices for each CID with a range of 0–1 by following (eq. (4)).

$$\text{NX}_{dj} = \frac{X_{dj} - \bar{X}_j}{\sigma_j}, \quad (4)$$

where NX_{dj} is the normalized X_{dj}, X_{dj} the observation for the *j*th CID in the *d*th district ($j = 1$ to 8 and $d = 1$ to 70), $\bar{X}_j$ the mean of the observation the *j*th CID and σ_j is the standard deviation of the *j*th CID.

Further, based on the expert opinion, weights (W_j) were assigned to different CIDs to capture the severity of the cyclones over the concerned district. Since a long return period indicates smaller number of cyclonic landfalls over a year, a negative scoring of –2 and –4 respectively, was assigned for the normal cyclonic storm (CS) return period and severe cyclonic storm (SCS) return period. The remaining CIDs, like surface wind and maximum probable rainfall in a cyclonic storm, were assigned a weightage of 1; whereas CIDs like landfall count in all intensities of cyclonic storm, surface wind and maximum probable rainfall in SCS were assigned a weightage of 2. Since storm surge is the most calamitous cyclone associated CID[49], a weightage of 5 was assigned to it. Thus, the CHI for the coastal district was calculated by summating the weighted normalized CIDs (eq. (5)).

$$\text{CHI}_d = \sum_{j=1}^{8} W_j \text{NX}_{dj}, \quad (5)$$

where CHI_1 is the cyclone hazard index for the *d*th coastal district and W_j is the weightage given to *j*th CID of cyclone hazard. The minimum–maximum (min–max) procedure was used to normalize CHI_d to set them in the range of 0–1.

Sea level rise hazard index, flood hazard index and heatwave hazard index

The hazard indices of sea level rise, floods and heatwaves were created using a quotient-based indexing method. The Copernicus database (a programme of the European Union), which provides sea level rise in metres, was used to calculate the sea level rise hazard index (SLRHI). Simultaneously, the India Meteorological Department (IMD) data on the total number of hazard events from 1969 to 2019 were used to create the flood hazard index (FHI) and heatwave hazard index (HWHI). Data obtained at the coastal district level for sea level rise, floods, and heatwaves were normalized using the min–max procedure to describe hazard indices within a range of 0–1. The state-level hazard index was represented by the aggregated average value of the coastal-level hazards index. Table 1 lists the inputs used to create the index, as well as its measurement level and data sources.

Multi-hazards index: Multi-hazards index (MHI) is a composite index showing the relative proneness of coastal districts to multiplicity of the physical hazards. The index was calculated by summating various normalized physical hazards and rescaling the same to 0–1, as in eq. (6).

$$\text{MHI} = \sum_{t=1}^{5} W_t \text{NHI}_t, \quad (6)$$

where NHI_t is the normalized HI_t, W_t the weightage given to the *t*th physical hazard index (in the present study we assumed equal weightage for five hazards, i.e. $W = 1$) and HI_t is the hazard index calculated for the *t*th physical hazard considered in the present study.

Results and discussion

The calculation of various hazard indices revealed a spatial variability of these hazards across the districts on India's two coasts, viz. west and east coasts. Based on the index value, the coastal districts were divided into five different categories of hazard severity. The severity ranged from very low (0.0–0.2), low (0.2–0.4), moderate (0.4–0.6), high (0.6–0.8), and extremely high (0.8–1.0).

Comprehensive analysis of spatial variability of physical hazards in coastal regions

Cyclone hazard: When compared to India's west coast, the east coast recorded a higher value for the CHI. Odisha state had the highest CHI value, followed by West Bengal (Table 2). The coastal state of Kerala had the lowest CHI value, indicating less proneness to cyclone hazards (Figure 2 *a*). The district-level analysis revealed that the

Table 1. Details of climatic impact-drivers (CIDs) and indices used for the computation of physical hazard indices

CID type*	CID category*	CID indices	Description of CID indices	Sources of data	Hazard index	Hazard index type
Coastal	Relative sea level	Rate of sea level rise	The average rate of sea level rise in metres for 20 years from 2002 to 2021	Copernicus	Sea level rise hazard index	Quotient based index
	Coastal flood	Flood events	Total number of flood events for a period of 50 years (1969–2019; events with at least one case of human death reported)	IMD[48]	Flood hazard index	Quotient based index
	Coastal erosion	Erosion	Land loss along the coastal line in kilometre for a period of 26 years (1990–2016)	NCCR, MoES[48]	Shoreline change hazard index	Composite index
		Stable coastal line	Stable coastal line in kilometre for a period of 26 years (1990–2016)			
		Accretion	Land gain along the coastal line in kilometre for a period of 26 years (1990–2016)			
Heat and cold	Extreme heat	Heatwave events	Total number of disastrous heatwave days annually for a period of 50 years (1969–2019; events with at least one case of human death reported)	IMD[48]	Heatwave hazard index	Quotient based index
Wind	Tropical cyclone	Sustained surface winds in CS	Maximum annual wind speed in metres per second during a period of 50 years (1961–2020)	IMD[48]	Cyclone hazard index	Composite index
		Sustained surface winds in SCS	Maximum annual wind speed in meters per second during a period of 50 years (1961–2020)			
		CS return period	Return period in years for CS passing within 50 nautical miles of coastal districts for a period of 50 years (1961–2020)			
		SCS return period	Return period in years for SCS passing within 50 nautical miles of coastal districts for a period of 50 years (1961–2020)			
		Landfall count	Frequency of SCS and CS (all intensities) in a coastal district for a period of 50 years (1961–2020)			
		Storm surge	Maximum storm surge measured in metre for a period of 50 years (1961–2020)			
		Probable rainfall in SCS	Maximum rainfall (mm/day) reported in a coastal district during SCS for a period of 50 years (1961–2020)			
		Probable rainfall in CS	Maximum rainfall (mm/day) reported in a coastal district during CS for the time period of 50 years (1961–2020)			

*The categorization is adopted from Ranasinghe, 2021 (ref. 40); CS, Cyclonic storm with an associated maximum sustained wind speed of 34 to 47 knots (62–88 kmph); SCS, Severe cyclonic storm with an associated maximum sustained wind speed of 48 to 63 knots (89–117 kmph).

Baleshwar district of Odisha was most susceptible to cyclone hazards, while Daman city on the West Coast, was the least prone (Figure 2 *b* and Table 3). Some of the recent studies[29,50,51] also showed higher intensity of cyclone hazards along the east coast of India, though there was a recent increase in the frequency of cyclonic landfalls in the west coast states. According to the severity classification, three states, i.e. Andhra Pradesh, Odisha and West Bengal were recorded with high cyclone hazard severity (Table 2).

Flood hazard: Kerala had the highest FHI score indicating highest level of proneness to floods, followed by Andhra Pradesh. At the same time, the Union Territories (UTs) of Goa and Puducherry had lowest FHI value (Figure 3 *a* and

Table 2. Normalized hazard indices showing relative positioning for coastal states and union territories

State/Union Territory	Cyclone	Flood	Heatwave	Shoreline change	Sea level rise	Multi-hazard
Gujarat	0.26	0.60	0.09	0.39	0.93	0.42
Daman and Diu	0.00	0.00	0.00	0.44	1.00	0.08
Maharashtra	0.31	0.71	0.03	0.48	0.54	0.29
Goa	0.33	0.00	0.02	0.32	0.49	0.00
Karnataka	0.33	0.55	0.02	0.34	0.70	0.27
Kerala	0.22	1.00	0.01	0.60	0.52	0.38
Tamil Nadu	0.67	0.31	0.02	0.52	0.38	0.25
Puducherry and Karaikal	0.56	0.00	0.00	0.74	0.91	0.33
Andhra Pradesh	0.83	0.79	1.00	0.12	0.48	1.00
Odisha	1.00	0.41	0.41	0.00	0.30	0.48
West Bengal	0.96	0.30	0.09	1.00	0.00	0.39

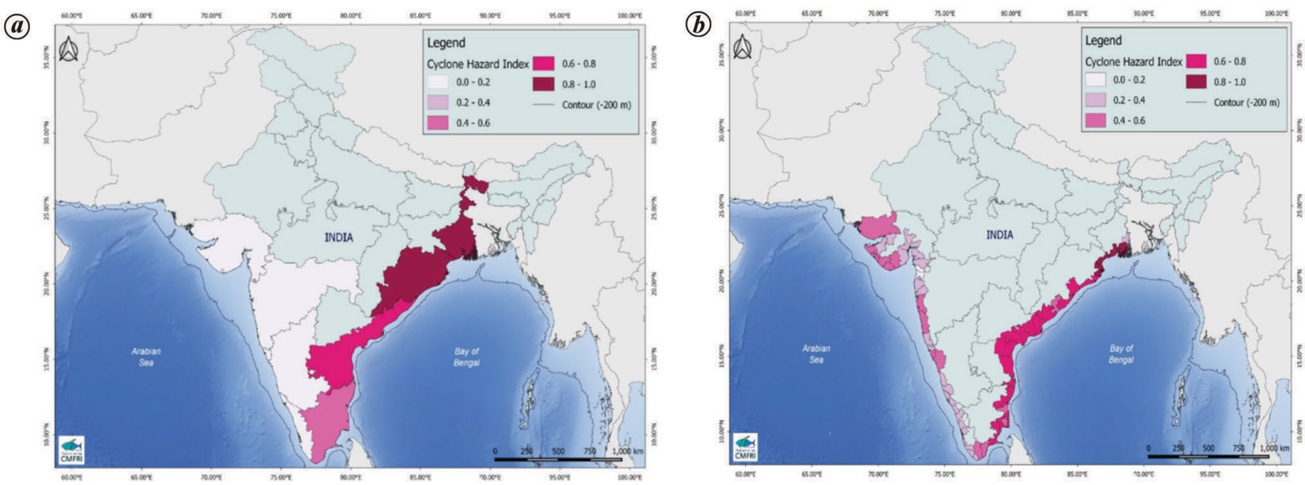

Figure 2. Maritime state-level (***a***) and coastal district-level (***b***) cyclone hazard index map.

Table 2). The district-level calculation showed that the Mumbai (city) district of Maharashtra state had highest FHI among the coastal districts and UTs. In contrast, Diu and Daman, North Goa, South Goa, Puducherry and Karaikal had lowest FHI (Figure 3 *b* and Table 3).

Shoreline change hazard: West Bengal had highest SLCHI value, indicating high level of susceptibility to shoreline changes. It was followed by Puducherry, while Odisha had the lowest value for SLCHI (Figure 4 *a* and Table 2). Among the coastal districts, highest SLCHI was observed for the North 24 Parganas district of West Bengal, and the lowest was for the Bhadrak district of Odisha, and Guntur district of Andhra Pradesh (Figure 4 *b* and Table 3).

Heatwave hazard: The quotient-based metric (heatwave hazard index – HWHI), derived from the data of heatwave events with at least one human death reported in media[52], showed highest value for Andhra Pradesh, followed by Odisha (Figure 5 *a* and Table 2). Among the coastal districts and UTs, highest HWHI was calculated for Vizhianagaram and West Godavari districts of Andhra Pradesh and the lowest for Diu and Daman, Puducherry and Karaikal (Figure 5 *b* and Table 3).

Sea level rise hazard: The quotient-based index, SLRHI built using the sea level anomaly dataset from the Copernicus database captured the highest value for Daman and Diu, followed by Gujarat (Table 2), and West Bengal reported the lowest SLRHI (Figure 6 *a*). SLRHI was highest for Bhavnagar, Ahmedabad, Surat, Anand, Vadodara, Bharuch, Navsari, Valsad and Daman among the coastal districts and UTs, and lowest for Pudukkottai district of Tamil Nadu (Figure 6 *b* and Table 3).

District-level analysis of the severity of physical hazards within the different maritime states

Gujarat, and Daman and Diu: In Gujarat, SLRHI is one of the hazard indices that is extremely high (Table 2), especially in the vast coastal areas that reach south Gujarat's districts, up to Bhavnagar on the Saurashtra coast, and to Diu, where the SLRHI was 1.0 (Figure 6 *b* and Table 3). Gujarat is observed to have low cyclone and shoreline change hazards (Figures 2 *a* and 4 *a*). The two districts in Gujarat with highest HWHI value (0.10) are Gir Somnath and Devbhumi Dwarka. Compared to the other coastal districts of Gujarat, Gir Somnath likewise suffers a high

Table 3. Normalized hazard indices showing relative positioning for coastal districts

State/Union Territory	District	Heatwave	Shoreline change	Flood	Cyclone	Sea level rise	Multi-hazard index
Gujarat	Valsad	0.08	0.52	0.36	0.12	1.00	0.39
	Navsari	0.08	0.45	0.30	0.04	1.00	0.29
	Surat	0.08	0.29	0.43	0.22	1.00	0.37
	Bharuch	0.08	0.46	0.43	0.32	1.00	0.50
	Anand	0.07	0.47	0.27	0.32	1.00	0.42
	Ahmedabad	0.08	0.39	0.44	0.38	1.00	0.50
	Bhavnagar	0.09	0.39	0.33	0.39	1.00	0.46
	Amreli	0.08	0.51	0.28	0.47	0.56	0.30
	Gir Somnath	0.10	0.56	0.26	0.51	0.61	0.37
	Junagadh	0.09	0.68	0.38	0.42	0.62	0.45
	Porbandar	0.08	0.60	0.28	0.48	0.47	0.30
	Devbhumi Dwarka	0.10	0.54	0.26	0.44	0.56	0.31
	Jamnagar	0.09	0.45	0.31	0.32	0.56	0.22
	Kachchh	0.09	0.42	0.31	0.49	0.56	0.29
	Morbi	0.08	–	0.26	0.26	0.56	***
Daman and Diu	Diu	0.00	0.63	0.00	0.38	0.61	0.16
	Daman	0.00	0.38	0.00	0.00	1.00	0.04
Maharashtra	Sindhudurg	0.03	0.35	0.23	0.36	0.34	0.00
	Ratnagiri	0.03	0.49	0.30	0.45	0.44	0.20
	Raigad	0.02	0.56	0.23	0.44	0.54	0.25
	Mumbai City	0.03	0.47	1.00	0.33	0.62	0.58
	Mumbai Suburban	–	0.54	–	–	0.62	***
	Palghar	0.02	0.61	0.11	0.28	0.63	0.18
	Thane	0.02	–	0.44	0.38	0.63	0.09
Goa	North Goa	0.02	0.51	0.00	0.36	0.47	0.02
	South Goa	0.02	0.40	0.00	0.41	0.57	0.05
Karanataka	Dakshinna Kannada	0.02	0.53	0.40	0.36	0.70	0.36
	Udupi	0.03	0.47	0.16	0.36	0.65	0.18
	Uttara Kannada	0.02	0.39	0.34	0.42	0.57	0.22
Kerala	Kasargode	0.01	0.53	0.41	0.38	0.75	0.40
	Kannur	0.01	0.57	0.50	0.39	0.76	0.47
	Kozhikkode	0.01	0.84	0.63	0.36	0.80	0.68
	Malappuram	0.01	0.70	0.56	0.37	0.69	0.52
	Thrissur	0.01	0.11	0.43	0.31	0.48	0.03
	Ernakulam	0.01	0.56	0.43	0.30	0.29	0.15
	Alappuzha	0.01	0.66	0.54	0.27	0.24	0.21
	Kollam	0.01	0.64	0.54	0.21	0.36	0.23
	Thiruvananthapuram	0.01	0.47	0.85	0.26	0.47	0.39
Tamil Nadu	Thiruvallur	0.03	0.49	0.16	0.62	0.36	0.18
	Chennai	0.04	0.39	0.38	0.50	0.48	0.26
	Kancheepuram	0.01	0.65	0.11	0.63	0.70	0.41
	Villupuram	0.02	0.69	0.16	0.60	0.95	0.57
	Cuddalore	0.02	0.49	0.17	0.59	0.82	0.40
	Nagapattinam	0.02	0.51	0.19	0.70	0.56	0.34
	Thiruvarur	0.02	0.72	0.12	0.60	0.10	0.13
	Thanjavur	0.02	0.48	0.24	0.70	0.10	0.12
	Pudukkottai	0.02	0.59	0.15	0.66	0.00	0.06
	Ramanathapuram	0.02	0.53	0.15	0.76	0.40	0.28
	Thothukudi	0.02	0.35	0.10	0.53	0.52	0.11
	Thirunelveli	0.01	0.37	0.14	0.47	0.51	0.10
	Kanyakumari	0.02	0.65	0.17	0.23	0.47	0.12
Puducherry and Karaikal	Puducherry	0.00	0.54	0.00	0.48	0.96	0.34
	Karaikal	0.00	0.70	0.00	0.56	0.56	0.26
Andhra Pradesh	Nellore	0.94	0.42	0.51	0.75	0.42	0.88
	Prakasam	0.93	0.31	0.43	0.79	0.49	0.84
	Guntur	0.86	0.00	0.43	0.74	0.69	0.72
	Krishna	0.96	0.48	0.48	0.78	0.58	1.00
	West Godavari	1.00	0.40	0.54	0.63	0.58	0.94
	East Godavari	0.95	0.47	0.56	0.69	0.49	0.94
	Vishakhapatnam	0.97	0.45	0.37	0.61	0.43	0.78

(*Contd*)

Table 3. (*Contd*)

State/Union Territory	District	Heatwave	Shoreline change	Flood	Cyclone	Sea level rise	Multi-hazard index
	Vizhianagaram	1.00	0.48	0.26	0.53	0.31	0.65
	Srikakulam	0.95	0.35	0.30	0.62	0.62	0.78
Odisha	Ganjam	0.41	0.34	0.25	0.67	0.63	0.50
	Puri	0.41	0.16	0.26	0.66	0.54	0.37
	Jagatsinghpur	0.38	0.66	0.14	0.70	0.54	0.56
	Kendrapara	0.37	0.58	0.17	0.80	0.43	0.53
	Bhadrak	0.35	0.00	0.20	0.86	0.18	0.14
	Baleshwar	0.42	0.20	0.31	1.00	0.18	0.41
West Bengal	East Midnapore	0.06	0.50	0.08	0.97	0.24	0.28
	South 24 Parganas	0.11	0.68	0.18	0.96	0.24	0.44
	North 24 Parganas	0.10	1.00	0.23	0.35	0.24	0.32

–, No data; ***Not included in the calculation as data for all five-hazard index are not available.

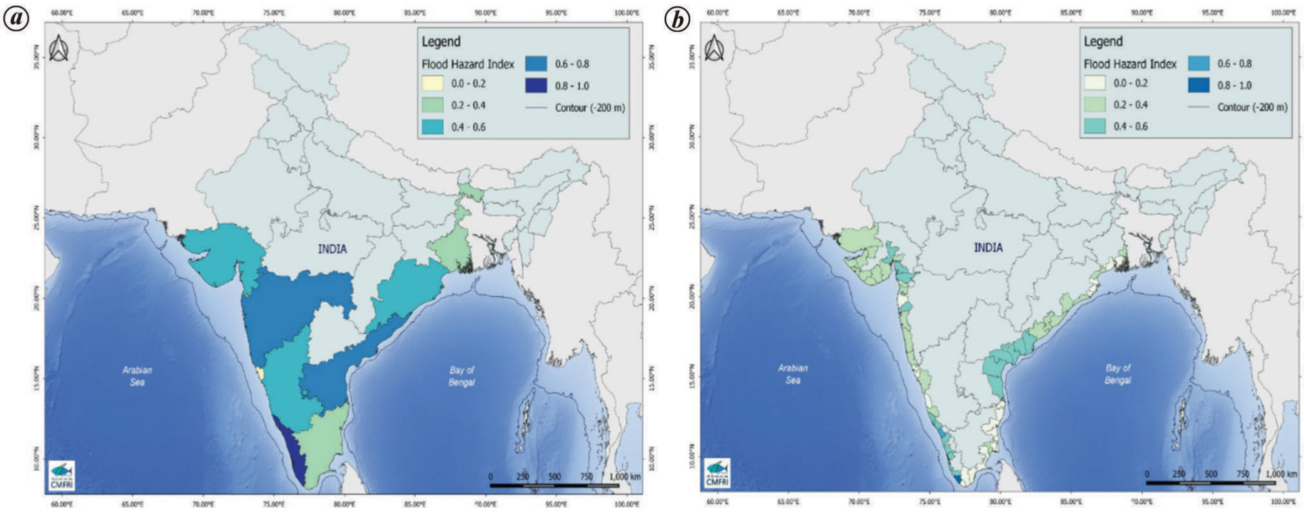

Figure 3. Maritime state-level (***a***) and coastal district-level (***b***) flood hazard index map.

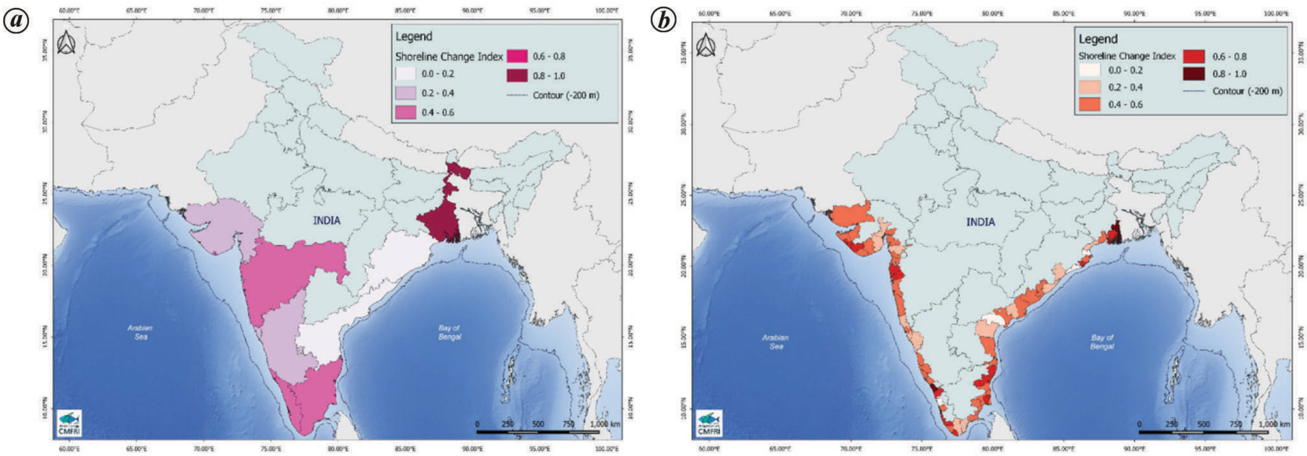

Figure 4. Maritime state-level (***a***) and coastal district-level (***b***) shoreline change hazard index map.

cyclone hazard severity (Table 3). Compared to other hazards considered in the present study, Gujarat witnessed least heatwave hazard severity (Figure 5 *a* and Table 3). Due to this region's extremely high diurnal tidal ranges, the potential for enhanced flood hazards is immense[53]. To determine the flood level and to mitigate its impacts, it is crucial to consider the synergistic effects of tides and sea level rise.

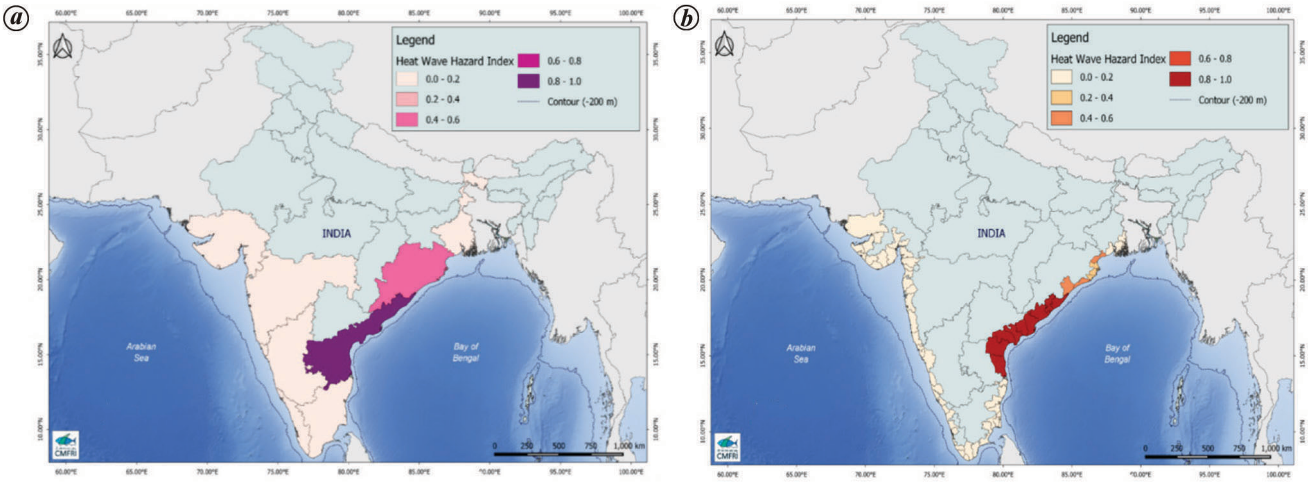

Figure 5. Maritime state-level (***a***) and coastal district-level (***b***) heatwave hazard index map.

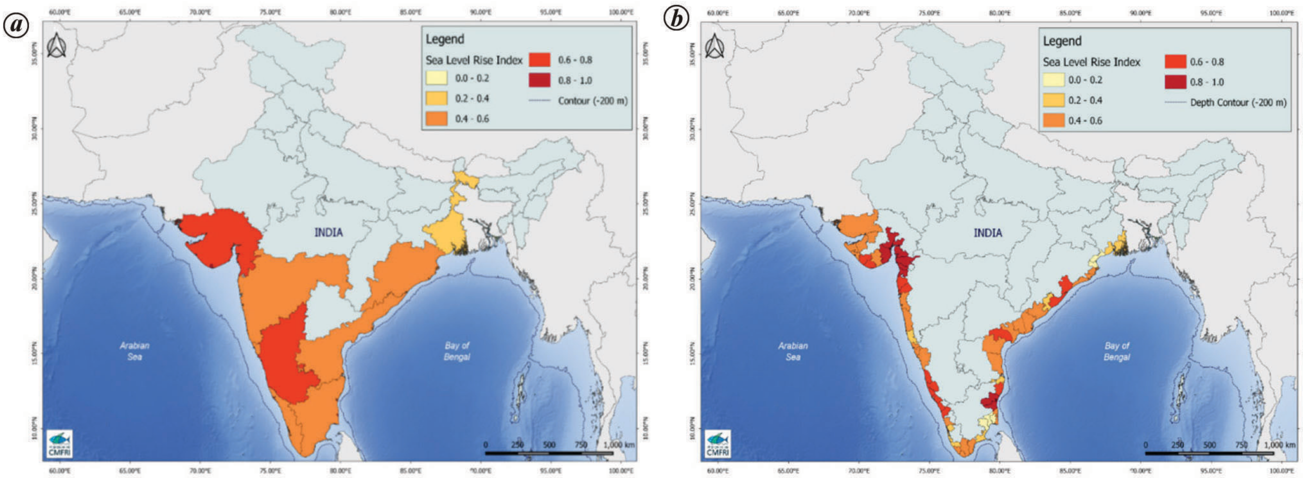

Figure 6. Maritime state-level (***a***) and coastal district-level (***b***) sea level rise hazard index map.

Maharashtra: The maritime state of Maharashtra reports highest severity (0.7) for the flood hazard compared to other hazards in the present study (Figure 3 *a* and Table 2). The extreme flood event reports in the Konkan coast of Maharashtra point to a six-fold increase along the coastal districts in the past 50 years. Mumbai City, Thane and Ratnagiri districts are the major hotspots of the flood hazards (Table 3). Hazards like sea level rise and shoreline change in Maharashtra are clubbed under the moderate severity category. Palghar, Thane, Mumbai City and Mumbai Suburban are the coastal districts with highest severity for the sea level rise hazard (Figure 6 *b* and Table 3). According to a recent study[54], Mumbai and Thane districts saw micro-climatic changes, which indicated an increase in cyclonic disturbances such as larger storm surges, persistent rain, and flooding. The strong cyclonic storms can cause an abnormal rise in water levels above the astronomical tide, eventually penetrating the inlands[55]. The shoreline configuration may change due to such catastrophes in the short term[56,57]. Palghar reported a maximum value for the SLCHI compared to other coastal districts of Maharashtra. Ratnagiri, Raigad, Mumbai City and Mumbai Suburban showed moderate severity for the shoreline change hazard (Figure 4 *b* and Table 3).

Goa: Sea level rise hazard is of moderate severity in case of Goa, while cyclone and shoreline modification hazards are of medium severity (Figure 6 *a* and Table 2). Compared with the North Goa district, the South Goa district shows relatively more severity regarding sea level rise and cyclone hazards. In contrast, the SLCHI calculated is more for the North Goa district (0.51; Table 3).

Kerala: Compared to other coastal states in India, Kerala's FHI score displays a curiously high severity and takes the top spot (Figure 3 *a* and Table 2). HWHI and CHI fall under very low and low severity classes in Kerala, whereas shoreline change and sea level rise hazards are relatively higher in severity. Kasargod, Kannur, Kozhikode and Malappuram, the northern districts of Kerala, displayed high severity for the sea level rise hazard, with Kozhikode being in the extremely high severity class. The CHI also displays a similar pattern, with the northward districts showing more severity than the central and southern coastal districts, where Kannur displayed highest CHI value of 0.39 (Figure 2 *a* and Table 3). However, the southernmost district of Kerala, Thiruvananthapuram, displayed a maximum value for the FHI (0.85), suggesting an extremely high severity of flood hazard. Regarding the severity of flooding, all other districts in Kerala – aside from the coastal districts of Kozhikode and Thiruvananthapuram – fall under the moderate severity category. Shoreline change hazard is more severe in Kozhikode, followed by Malappuram district. Alappuzha district exhibited a low value for the SLRHI among the coastal districts of Kerala, whereas Thrissur showed less severity towards shoreline change hazard (Table 3).

Tamil Nadu: The southern state on the east coast of India, Tamil Nadu, showed a high proneness (0.67) to the cyclone hazard compared with the other hazards in the present study (Figure 2 *a*). A digitalized record of the past cyclonic track (1891–2013) showed that Tamil Nadu experienced a total of 98 tracks, of which 29 were severe cyclonic storms, 25 were cyclonic storms, and 44 were depressions[58]. Similarly, the northern Tamil Nadu coast was more prone to cyclones when compared to the southern coast[58]. The CHI estimated in the present study also showed that Ramanathapuram district (0.76) was extremely susceptible to cyclone hazards, whereas Kanyakumari district (0.21) was less susceptible than other coastal districts. SLCHI was classified as having moderate severity, whilst SLRHI and FHI were classified as having low severity in Tamil Nadu (Table 2). The sea level rise risk was extremely severe in the Cuddalore and Villupuram districts. In comparison to other districts in Tamil Nadu, the coastal district of Chennai had high FHI (Figure 3 *b* and Table 3) and HWHI (Figure 5 *b* and Table 3), indicating more susceptibility towards both the hazards. Thiruvarur district has the most severe shoreline shift, followed by Villupuram district. The risk from sea level rise is especially severe around the coasts of Puducherry and Karaikal. Thus, SLCHI is classified as being extremely severe. Previous studies[48] pointed out that littoral drift and coastal development are the two leading causes of the altered shorelines. However, as the sea surface warms, the ensuing wave action accelerates the rate of erosion[59]. Additionally, the coast's geomorphology, typically low-lying with a gentle slope, exposes it to inundation[60]. Puducherry and Karaikal are least susceptible to flood and heatwave hazards among the coastal states of India (Figures 3 *a*, 5 *a* and Table 2).

Andhra Pradesh: The two hazards identified as most severe in Andhra Pradesh are heatwaves and cyclones followed by flood hazards, which fall under the highly severe category. HWHI showed the highest value for Andhra Pradesh among all other coastal states. This extremely severe heatwave hazard effect[61,62] is ascribed to the high condensation of hot and dehydrated wind from the west and northwest, and the weakening sea breeze alongside the coast, which result in the accumulation of heat, thus escalating the heatwave ailments[63]. Regarding HWHI, West Godavari and Vizhianagaram districts hold the top position among India's coastal districts (Figure 5 *b* and Table 3). Except for Vizhianagaram, all other coastal districts are classified as having high CHI severity, rendering the state extremely vulnerable to cyclone hazards (Table 2). Compared to other hazards considered in the present study, Andhra Pradesh appears less susceptible to shoreline change (Figure 4 *a* and Table 2) and sea level rise hazards (Figure 6 *a* and Table 2).

Odisha: Cyclones pose an extremely high severity (1.0) along the coast of Odisha (Figure 2 *a*)[62]. Over the past century, the coast of Odisha has faced 260 cyclonic storms, of which 180 were depressions, 57 were cyclones, and 23 were severe cyclones[64]. Odisha experiences moderate to extremely severe cyclones in every district (Table 3). The effects of high-speed wind, tidal surge, and severe rainfall caused by cyclones can physically devastate low-lying areas and cause floods and salinization[64]. The most susceptible coastal district in India to cyclonic hazards is Odisha's Baleshwar district (Figure 2 *b* and Table 3). Odisha is rated as having a very low severity for SLCHI and ranks last among the other coastal states in terms of shoreline change. Of all the coastal districts in India, Bhadrak[65] in Odisha is the least prone to shoreline change (Figure 4 *b*). All the six coastal districts of Odisha fall either under very low or low severity category with regards to HWHI (Table 3).

West Bengal: The hazards of cyclones and shoreline change are extremely severe in West Bengal (Table 2). Though the Bengal coast shows an alarming trend for the sea level rise[66], the state showed least susceptibility to the physical hazards of sea level rise, according to the SLRHI, compared to the other hazards in the present study (Figure 6 *a* and Table 2). East Midnapore, South 24 Parganas and North 24 Parganas, the three coastal districts of West Bengal exhibit the same level of susceptibility to the sea level rise hazard (Figure 6 *b*). The North 24 Parganas is the most vulnerable coastal district in India and falls under the extremely high severity category for the shoreline change hazard due to high level of erosion than the accretion and stable coastal line[67].

Impact of multi-hazards along the coastal regions

The maritime state of Andhra Pradesh recorded maximum severity for MHI, making it the most susceptible state to

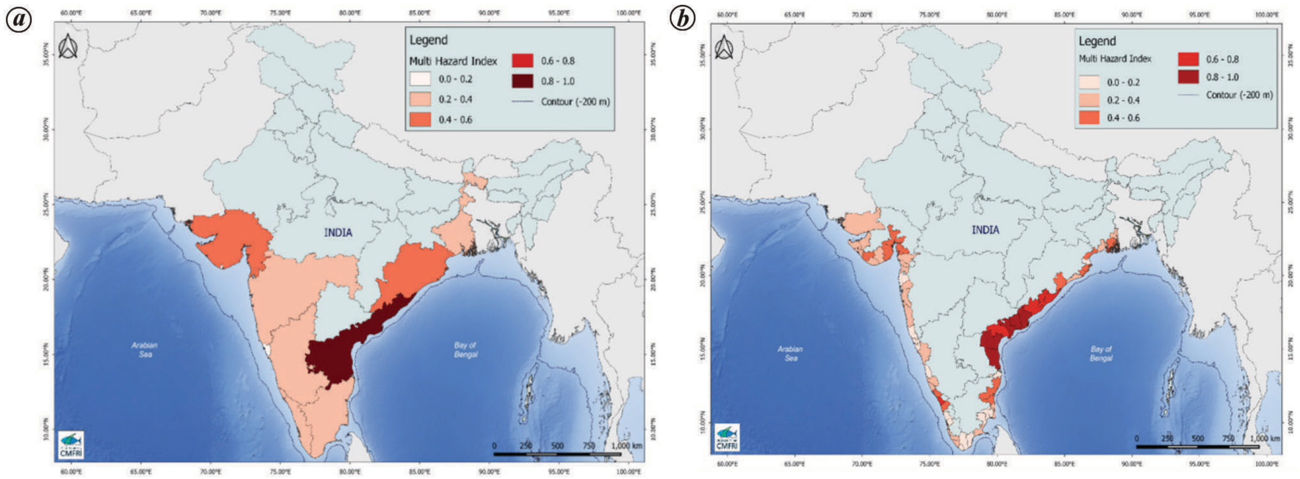

Figure 7. Maritime state-level (***a***) and coastal district-level (***b***) multi hazards index map.

the cumulative effect of physical hazards due to climate change (Figure 7 *a* and Table 2). The MHI indicated that all the districts in the states fall either under high or extremely high severity category (Table 3). However, Goa showed least proneness to climate change-induced physical hazards as evidenced by the index value (Figure 7 *b* and Table 2). Similarly, the relative positions of the coastal districts in the hazard atlas based on the MHI indicated lowest value for Sindhudurg district of Maharashtra and highest value for Krishna district of Andhra Pradesh (Figure 7 *b* and Table 3). The MHI value for the maritime state of Gujarat (0.42) falls under the moderate proneness category, making it the highest among west coast maritime states. Gujarat's multi-hazard profile could be mostly caused by its coastal terrain, strong seismicity due to its proximity to an inter-plate boundary and riverine environment[68]. Maharashtra and Karnataka come under the low multi-hazard severity category, as evidenced by the index value of 0.29 and 0.27 respectively (Figure 7 *a* and Table 2). In terms of the intensity of multi-hazards, Kerala comes in second place after Gujarat among the southern coastal states (Figure 7 *a* and Table 2). West Bengal, and Puducherry and Karaikal come under low severity category based on the MHI calculated (Figure 7 *a*), whereas Odisha is in the high severity category mainly attributed by extreme cyclonic incidence and high severity of fold and heatwave hazards (Table 2).

Causal factors of the spatial variability of the multi-hazard index

The susceptibility to climate change-induced hazards is more pronounced in the maritime states along the east coast compared to their west coast counterparts, as indicated by the MHI. These heightened hazards can be attributed to various factors beyond anthropogenic influences, including topographical diversity, regional climate patterns, monsoonal variability, geographical positioning and oceanic factors. The risk of several climatic hazards such as floods, cyclones, landslides, thunderstorms, etc. are generally correlated with the monsoonal patterns, and is sometimes difficult to distinguish because of the 'connected CIDs' which occur as compound, sequential or simultaneous events[69,70]. Compared to the east coast region, the MHI of the west coast region is more influenced by hazards like floods, shoreline changes and sea level rise (Table 2). Sea level rise attributed to climate change-induced thermal expansion of seawater and the melting of glaciers leads to an increased risk of coastal flooding, particularly during extreme weather events such as cyclones and monsoons on the west coast[71]. India's west coast has limited orographic lifting effects compared to east coast because of the smoother topography of the low-lying coast abutted by the mountains of the Western Ghats. But, the sediment flow from rivers leads to sea level rise. The combination of higher sea levels and heavy rainfall can lead to flooding and inundation of low-lying coastal areas. These alterations disrupt the natural coastal equilibrium, leading to erosion and coastline changes[72,73]. In contrast to the west coast states, the cyclone and heatwave hazards, often called as 'silent killers'[74] are the major contributors to the MHI of the east coast, except for West Bengal where shoreline change is also a very severe hazard (Table 2). There are four folds of cyclone landfalls on the Bay of Bengal in the east coast than on the Arabian Sea in the west coast[75], mainly attributed to the rising temperature[76]. The divergent Matsuno-Gill response to the anomalous cooling in the ocean[77], and El Niño Southern Oscillation (ENSO), as well as variations in the sea surface temperature across the Bay of Bengal[78] are the major causes of the elevated heatwave incidences on the east coast[79].

Conclusion

Since India has two extremely different coasts in the west and east, hazard mapping along the regions, sectors, and communities at the district level is essential for efficiently implementing the climate action frameworks along the coasts. The main goal of hazard assessment is to assess and pinpoint any physical occurrences or phenomena that can be harmful or destructive. Hence, the present study has aimed at hazard assessment of the Indian coastal districts to understand the type, magnitude, frequency, and severity of the five major natural catastrophes and climate-related hazards, viz. floods, cyclones, heatwaves, shoreline change and sea level rise by considering the selected hazard threshold CIDs.

Compared to India's west coast, the east coast recorded a higher value for the CHI with Odisha having the highest CHI value, followed by West Bengal. The coastal state of Kerala has the lowest CHI value, indicating that it is less prone to cyclones. The severity classification showed that only one state, i.e. Kerala, came in the extremely severe category with respect to the flood hazard. Among the coastal districts, the highest SLCHI was observed for the North 24 Parganas district of West Bengal, and the lowest was for the Bhadrak district of Odisha and Guntur district of Andhra Pradesh. The highest HWHI was calculated for the Vizhianagaram and West Godavari districts of Andhra Pradesh, and the lowest for Diu and Daman, and Puducherry and Karaikal. According to the MHI, the east coast states were more prone to hazards brought by climate change than the west coast states.

The present study's hazard assessment and mapping at the coastal district level can be used to successfully communicate the variations in the incidence of various hazards relative to a reference period. This would also be useful in creating a map of sensitivity towards climate change and estimating the risks in various coastal districts while planning development policies, and spatial climate adaptation and mitigation strategies. However, the hazards considered in the present study need not be mutually exclusive. It is difficult to precisely estimate complete and exclusive impacts of climate change hazards, because climate data used from secondary sources, particularly at the local level, may not be consistent or complete. Climate change-induced hazards might vary substantially over time and across different places depending on geomorphology, slope, etc. Similarly, micro-scale variations in climate change hazards are difficult to capture in a broad analysis at the state or district level. Hence, the present study projects some potential areas for future focus, like a possible improvement to consider the multicollinearity of the CIDs through enhancing the spatial resolution by ground truthing, making future projections, and continuously updating climate scenarios and models to reduce uncertainty in future hazard predictions.

Conflict of interest: The authors declare no potential conflicts of interest.

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