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ORIGINAL PAPER

Appraisal of climate change and cyclone trends in Indian coastal states: a systematic approach towards climate action

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Abstract

Indian coastal regions have often been affected by frequent climate-induced natural disasters such as cyclones, floods, droughts and other related hazards in recent decades. Existing literature was not sufficient to fully understand these event trends from diverse perspectives in a systematised manner at current scenarios. Therefore, a systematic approach has been employed to assess the climate change and cyclone trends of nine Indian coastal states by using various geographical information system (GIS) tools for 2006–2020. The results showed that 61 cyclones occurred in nine coastal states from 2006 to 2020; the highest numbers were recorded in Odisha (20), West Bengal (14) and Andhra Pradesh (11). Accordingly, these three coastal states emerged as the most vulnerable for high-intensity cyclones. The results also identified that the highest average temperature (29.3 °C) was recorded at Tamil Nadu and Gujarat, and the lowest temperature (26.7 °C) was recorded in West Bengal and Odisha. Most of the coastal states showed fluctuations in temperatures during the study period. At the same time, Kerala and Karnataka states recorded the highest average rainfall (2341 mm and 2261 mm) and highest relative humidity (78.11% and 76.57%). Conversely, the Gujarat and West Bengal states recorded the lowest relative humidity at 59.65% and 70.78%. Based on these results, the current study generated GIS vulnerability maps for climate change and cyclone activity, allowing one to rank each state's vulnerability. Cumulatively, these results and maps assist in understanding the driving mechanisms of climate change, cyclones and will contribute towards more effective and efficient sustainable disaster management in the future.

Keywords Climate change · Cyclones · Indian coastal states · GIS maps · Systematic approach

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Introduction

Coastal states of India are often affected by frequent climate induced natural disasters such as cyclones, floods, droughts and other related hazards in recent years (Mirza 2003; Patel et al. 2020; Thomalla and Schmuck 2004; Yadav and Barve 2017). Climate change is having a significant impact in tropical and subtropical countries, especially coastal regions. Coastal areas in some countries particularly in the global south are highly susceptible to the various impacts of climate change due to anthropogenic and natural climatic factors (Bouwer 2011; DasGupta and Shaw 2013; Nath and Behera 2011; Sivakumar and Stefanski 2010). Severe changes in climatic and weather conditions, rapid sea-level rise (SLR), storm surge, temperature fluctuations and irregular rainfall trends have increased coastal vulnerability problems in the majority of coastal regions across the globe, resulting in huge losses of coastlines, properties and damage to coastal communities (Burkett 2012; Gupta et al. 2019; Lal 2003; Mimura 2013; Sánchez-Arcilla et al. 2011). Likewise, many coastal states of India suffer severe cyclonic storms leading to flooding. Furthermore, some of these coastal states are particularly highly populated: Maharashtra, West Bengal, Tamil Nadu, Karnataka, Andhra Pradesh, and Gujarat states' coastal communities have been highly impacted by climate change and cyclones (Baig et al. 2020; Kantamaneni et al. 2019; Mazumdar and Paul 2016; Rao et al. 2020a; Rehman et al. 2020). The rapid urbanisation increases the risk of pluvial floods in the coastal areas (Zhang et al. 2018; Zhu et al. 2021, 2015), and the impact of climate change on coastal states is a serious concern.

Tropical cyclones are one of the greatest threats to human life and property even during the initial stages of cyclonic development. In the last 50 years, 1, 942 disasters have been identified as tropical cyclones, killing 77,9324 people and causing $1,407.6 billion fiscal destruction across the world (World Meteorological Organisation 2021). Nearly, 630 million people will live below estimated annual flood levels for 2100; 1 hundred million people live below high tide areas globally (Kulp and Strauss 2019), and the number of high intensity global tropical cyclones will likely rise due to anthropogenic global warming in the twenty-first century (GFDL - Geophysical Fluid Dynamics Laboratory 2021). The different downscaling and Multiple Earth System Models (Emanuel 2017, 2021; Irvine et al. 2019; Knutson et al. 2020; Michaelis and Lackmann 2019; Patricola and Wehner 2018; Wehner et al. 2014) forecast that anthropogenic climate change will increase the frequency and intensity of the most intense tropical cyclones and amount of rainfall (Irvine et al. 2019). The warmer sea surface temperature has resulted in large stocks of moisture and the intensification of cyclones which hit land. Over the past 50 years, the number of landfalling hurricanes in the North Atlantic has increased by 94% (Michaelis and Lackmann 2019), and East Asia and North West Pacific have experienced an increasing trend in rapid intensification of tropical cyclones with an escalated cost of destructions (Basconcillo and Moon 2022; Chan et al. 2021; Liu and Chan 2022).

The changes in global sectoral interactions in several countries due to tropical cyclones over the period of 1990–2015 show that tropical cyclones have a substantial adverse effect on the yearly growth rate of almost all sectors. Damage to productive capital, infrastructure, or buildings can have direct negative consequences and lead to a negative income shock for the entire economy (Kousky 2012). The intensification of tropical cyclones due to global warming exposes more people to it and also intensifies the future cost of climate change (Kunze 2021). The extreme weather events in 2020 caused significant damage to the economies in several countries across the globe particularly in Asian Countries such as China (USS238), India (USS87), and Japan (USS83) (WMO-World Meterological Organisation 2021).

The Indian Ocean area is one of the 6 most prone cyclone areas in the world with five to six cyclones on average per year (Sahoo and Bhaskaran 2018). Indian coastal regions with low-lying terrain, high population density, frequent cyclones and storms, and a high rate of coastal environmental degradation lead to many disasters and extreme vulnerability for the coastal states. In the Indian region, more cyclones occur in the Bay of Bengal than in the Arabian Sea at a ratio of 4:1(Rao et al. 2020b). Many different types of coastal ecosystems can be found along the Indian coastline, i.e. coastal wetlands, major estuaries, lagoons, and mangroves. Total coastal wetland covers 43, 230 km^2 of the coastal states; 97 major estuaries and 34 major lagoons are found throughout the study area; 31 mangrove areas are located on the coastline and total mangrove areas covered 6740 km^2, where 57% of mangrove areas are situated the East coast, and 23% of the area covered along the West coast and 20% of the mangroves area is located at the Andaman and Nicobar Islands (Central Marine Fisheries Research Institute 2021). The coastal states have tropical climates and monsoons with a dry and rainy season. The rains are more or less intense and long-lasting depending on the area (Nandargi and Mulye 2012).

Frequent occurrence of cyclones is very common in the Indian coast and causes heavy damage resulting from the effects of storm surges and high tides (Rao et al. 2020b; Shaji et al. 2014; Unnikrishnan et al. 2006). Estimated sea-level projections for future years and centuries indicate the potential exposure of the coastal population to the various hazards; coastal planning is vital for further improvement of adaption strategies. Additionally, three megacities are located on the Indian coastline, i.e. Mumbai, Kolkata, and Chennai, and some growing cities with millions of inhabitants are at high risk. Furthermore, the impact of climate change is reflected in sea surface temperatures and tropical storm characteristics which are increasing every year. India (coastal cities) has been chosen as a research area as one of the tropical countries in South Asia; however, the existing literature was not sufficient to fully understand these events' trends in coastal areas from diverse perspectives. Therefore, the current study examines climate change and cyclone trends in 9 coastal states. Also, this research address the UN-SDG (United Nations Sustainability Goal) 13 (climate change) by doing the above mentioned assessments in diverse ways. Consequently, this research explains how climate change will be a barrier to achieve SDG 13 in coastal states of India and offer some guidelines to overcome the problem. The changing environment and climatic conditions and the increasing number of extreme events (such as frequent floods, droughts, cyclones and other related disasters) push millions of people into chronic poverty worldwide. This increases the imbalances in physical, social and economic systems and affects sustainable development. It disturbs various economic activities, including agriculture, food safety and tourism. It threatens the very existence of island counties and coastal cities. Different research findings proved the effects of climate vulnerability on vector-borne diseases. Increasing sea surface temperature raises coastal vulnerability. Overall, it has a significant impact on the Sustainable Development Goals (SDGs), which we plan to achieve by 2030. Though SDG 13 focuses on combating climate change and its impacts, and national governments are taking various steps to build climate-change-resilient communities, climate change is still a great challenge and an impediment to achieving all the other SDGs. These results will help for future planning and policy making and efficient sustainable coastal management.

Study area

India is the seventh-largest country in the world by area (3.28 million sq. km) and the second-largest by population (1.3 billion), with 28 states and 8 union territories (Government of India 2022). It occupies a significant portion of the South Asian subcontinent, which has nine coastal states and two coastal union territories. These states' boundaries occupy the Bay of Bengal, the Arabian Sea and the Indian Ocean as shown in Fig. 1. The total length of the coastline is 7, 516.6 km, comprising the mainland with 5, 422.6 km and island territories of 2094 km (Table 1). The exclusive economic zone (the areas identified as economically beneficial) is an identified 2.02 × 106 million km2, and three states include megacities with the largest population pressure, i.e. Maharashtra, West Bengal and Tamil Nadu. The total population of coastal states and union territories is 560 million, and it comprises 46.2% of the total population (Kumar et al. 2006; Singh 2003). The inland consists of four areas called the plains of the Ganga and the Indus (1), the great mountain zone (2), the desert region (3) and the southern peninsula (4). India is a tropical country with hot to extremely hot weather in summers and dry winters with four main periods per year called winter (December–February), summer (March–June), pre-monsoon season (June–September) and post-monsoon season (October–November) (Government of India 2022). However, significant changes have been recorded in these four seasons — extended hot summers and shortened winters.

According to the NDMA (National Disaster Management Authority), in 2022, 75% of the Indian coastline is susceptible to cyclones and related hazards. More than 60 districts and > 14% of the coastal states and the population of the union territories are frequently exposed to different levels of cyclones. Though 7% of global cyclones originate in the Arabian Sea and the Bay of Bengal, the impact of cyclones on Indian coastal states is enormous. The geography of India and the fluctuations in climatic conditions (temperature, rainfall trends, humidity, etc.) are vital factors that lead to an increase in the intensity and frequency of cyclones and in the damage inflicted on the coastal areas of India. Among all natural disasters, cyclones contributed to 15% of the total number of natural disasters that occurred in India between 1999 and 2020, and they rank third after floods and earthquakes (Government of India 2022). Based on these reasons, nine Indian coastal states (excluding two union territories) have been selected for the assessment to offer updated knowledge on climate changes and cyclone trends.

Methodology

Data

The current study adopted the Donnadieu et al. (2017)'s systematic approach to assess climate change and the cyclone trends in Indian coastal states. This systematic approach accumulates all the empirical evidence that is related to corresponding research, and it has been considered the answer to an explicit research question. Besides, the systematic approach method reduces bias and leads to more trustworthy findings for decision-making. Accordingly, a systematic approach has been used to assess the trends of climate change and cyclones in a logical order to offer updated knowledge. The present research is an appraisal of historical climatic data (temperature, rainfall

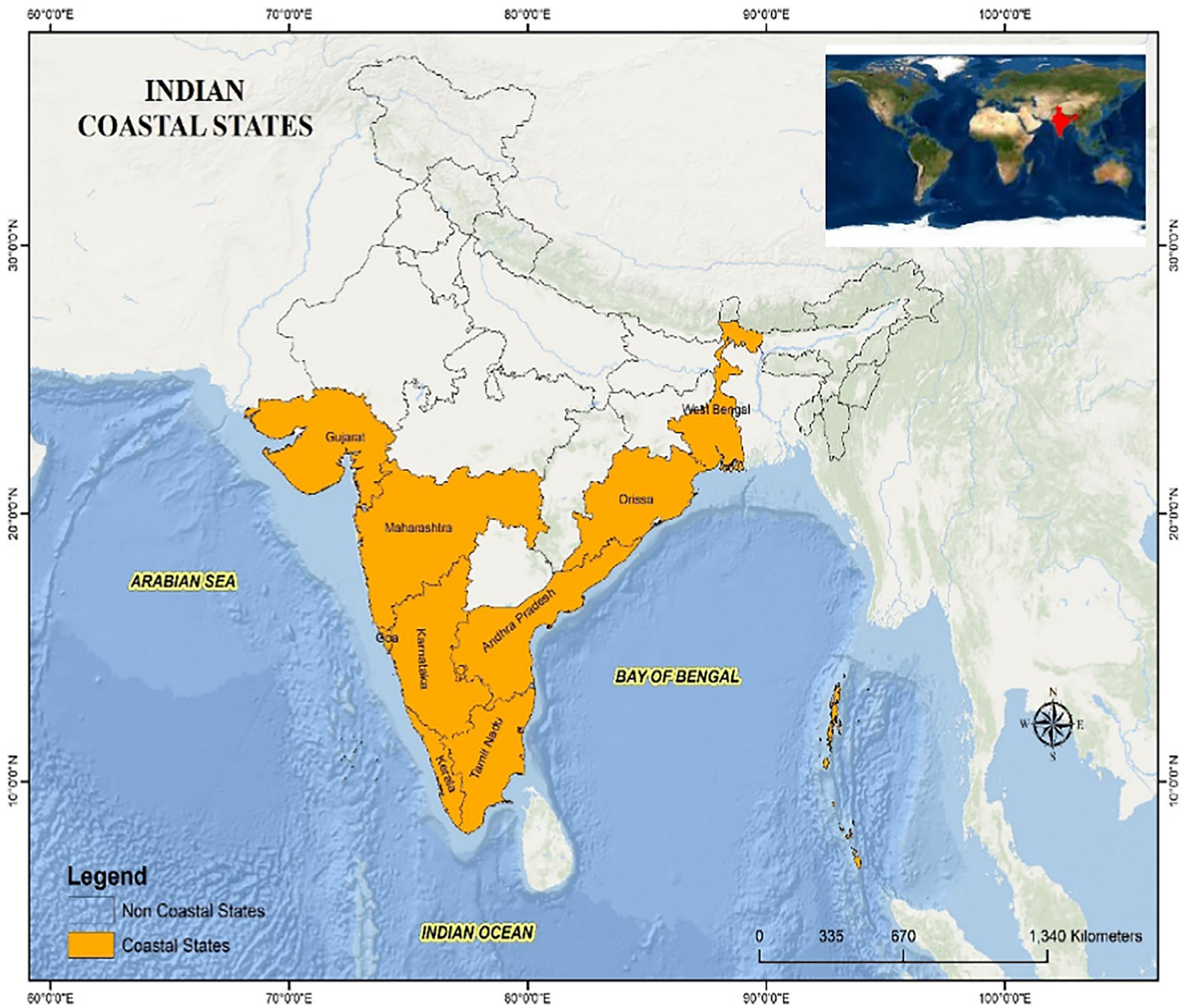

Fig. 1 Map of the case study area: Indian coastal states

and relative humidity) in relation to cyclone intensity. The data was acquired from NASA Power Data Access (https://power.larc.nasa.gov/data-access-viewer/) and NASA Langley Research Center. Temperature and humidity were measured 2 m above the surface. Correspondingly, the data about cyclones (Table 1) was gathered from IMD E-atlas, the Indian Meteorological Department, and was divided into three categories based on the intensity (i.e. depressions [D], cyclonic storms [CS] and severe cyclonic storms [SCS]). The current study analysed the spatial exhibitions of the cyclone-prone areas and the spatial exhibitions of the cyclonic paths using the 'Display XY Data' GIS tools – ArcGIS 10.6. Temperature, rainfall, and humidity data were constructed annually to reveal the in-depth climatic changes of Indian coastal states (Table 2).

Analysis

The study categorised the cyclones into three types based upon the intensity derived from the criteria-based classification, Indian Meteorological Department, such as cyclonic storms and severe cyclonic storms (Fig. 2). Moreover, the climatic data was calculated year-wise from 2006 to 2020, which was considered an average for each year. In addition, spatial and temporal analysis was accomplished using the choropleth method using ArcGIS 10.6 software. Spatial representations into four categories based on numerical values on the chronological order using the natural breaking tool in ArcGIS 10.6 were created; the units of measurement of the climatic data includes rainfall (mm), temperature (°C) and humidity (%). The study reveals the impacts of climate

Table 1 Indian coastal states and key statistics. Adapted from census of India 2011(Ministry of Home Affairs and Government of India 2011). *Andhra Pradesh was separated from the Telangana state in 2014. The population statistics were taken from the 2022 Andhra Pradesh Aadhar Card (Indian Identification Card) database

Sl. No	Coastal state	Population (millions)	Density	Coastal stretch (km)
1	*Andhra Pradesh	52	308	975
2	Kerala	34	859	580
3	Tamil Nadu	72	555	1076
4	Goa	1.4	394	160
5	Karnataka	61	319	320
6	Maharashtra	112	365	720
7	Odisha	41	269	485
8	Gujarat	60	308	1600
9	West Bengal	91	1029	157

change per state. This study considered 15 years of climatic data for an appraisal of climate changes.

Results and discussion

State-wise paths of cyclones

There were 61 cyclonic disturbances across the Indian coastline during 2006–2020. The maximum number of cyclonic disturbances occurred in Odisha (20), and the second highest cyclonic turbulences traversed West Bengal (14) followed by Andhra Pradesh (11) and Tamil Nadu (11) during 2006–2020. The maximum cyclonic disturbances were crossed at Gujarat (2) and Goa (3). However, Karnataka, Kerala and Maharashtra coastlines had no cyclones during 2006–2020 (Fig. 2). The identification and tracking of cyclonic turbulences assist in facilitation of the necessary precautions and warnings for vulnerable coastal communities. The study considered the starting location of each cyclone which are the Bay of Bengal, Arabian Sea, Indian Ocean and Inland. The results show the state-wise cyclonic paths for the selected study period.

State-wise cyclonic data consists of the data/m/year (which is shown in Table 3) contains the data of the depression, cyclonic storm and severe cyclonic storm. Furthermore, the Southwest monsoon played a major role in producing 29 cyclonic disturbances near the coastal region and 27 cyclonic turbulences associated with the Northeast monsoon, whereas 5 cyclones occurred during the non-monsoon season. Consequently, the study has evaluated three cyclones seasons, i.e. Southwest monsoon (June to September), Northeast monsoon (October to December) and non-monsoon season (January to May), and these were assessed for climate change appraisal.

In-depth analysis: state wise of cyclones

Eastern coastal India

Andhra Pradesh Andhra Pradesh is one of the Indian coastal states located in the south-eastern India, where cyclones frequently pass during the monsoon season every year. Consequently, the study has identified that most of the cyclones cross the state during the Northeast monsoon. Andhra Pradesh is a vulnerable coastal zone, experiencing 11 cyclonic turbulences (Fig. 3), 5 depressions (D) were documented during the years 2007, 2008, 2010, 2013 and 2018; although 2 cyclonic storms occurred during years 2006 and 2018, and 4 severe cyclonic storms (SCS) were measured in 2010, 2013, 2014 and 2020. These severe Cyclonic Storms resulted in 95 fatalities and resulted in the displacement of 4,93,732 people in Andhra Pradesh (Chapman et al. 2020; Dhara 2019; NASA Power Data Access 2020). Depressions would typically initiate heavy rainfall in the coastal districts: namely Nellore, East Godavari and Krishna, which are very highly prone cyclonic areas, whereas Srikakulam, Guntur, Visakhapatnam, West Godavari, Prakasam, and Vizianagaram districts are the highly prone areas as classified by the Indian Meteorological Department, Government of India.

Table 2 Criteria for classification of cyclones. Source: Adopted from the India Meteorological Department (India Meteorological Department 2021)

Sl. No	Types	Maximum sustained wind
1	Low pressure area	Not exceeding 17 knots (< 31 kmph)
2	Depression	17 to 27 knots (31–49 kmph)
3	Deep depression	28 to 33 knots (50–61 kmph)
4	Cyclonic storm	34 to 47 knots (62–88 kmph)
5	Severe cyclonic storm	48 to 63 knots (89–117 kmph)
6	Very severe cyclonic storm	64 to 90 knots (118–167 kmph)
7	Extremely severe cyclonic storm	91 to 119 knots (168–221 kmph)
8	Super cyclonic storm	120 knots and above (≥ 222 kmph)

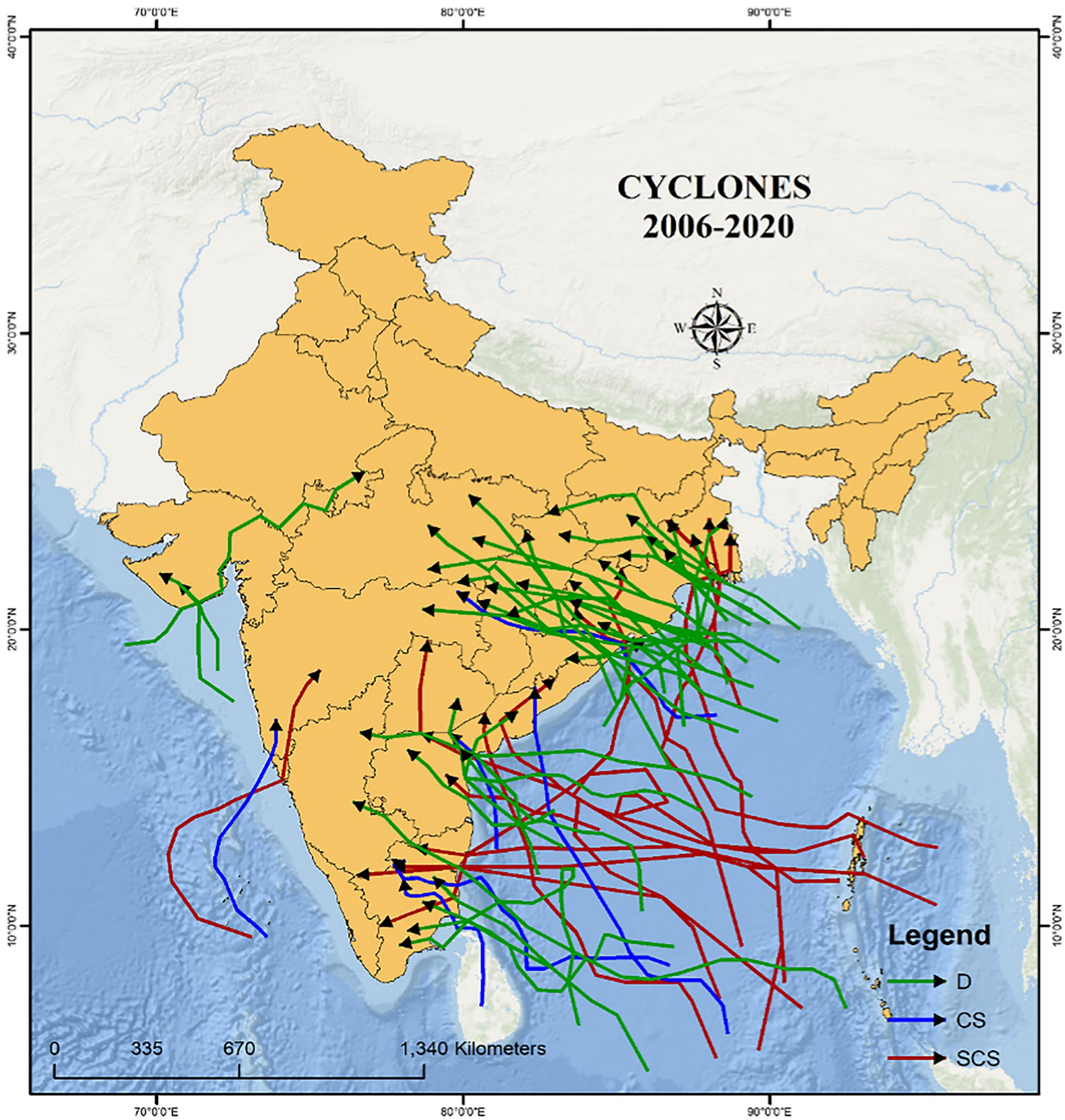

Fig. 2 Number of crossed cyclones thorough the coastal states for 2006–2020

West Bengal The coastline of West Bengal consists of two coastal districts, i.e. Midnapur and South Parganas district, and it encompasses the Sundarbans mangrove ecosystem (Zhang et al. 2021). Fourteen cyclones traversed through West Bengal (Fig. 3); 9 cyclonic disturbances provided the lowest impacts on coastal districts, and 3 cyclonic turbulences created the largest impacts. In addition, 2 cyclonic storms traversed through West Bengal, and 3 severe cyclonic storms crossed, which created a high impact on humans and the environment as these cyclones lead to torrential rain. The resulted in a total of 138 fatalities and displacement of 8,38,000 people in the state (Ehrnsten et al. 2019; Serpetti et al. 2017). These cyclonic turbulences had major impacts on Kolkata and several districts, Sabang, North and South 24 Parganas, East and West Midnapore, Bankura, Howrah, Burdwan, Hoogly,

Table 3 List of coastal cyclones 2006–2020. Analysed from eAtlas, India Meteorological Data (Cyclone eAtlas - IMD 2021)

Odisha		West Bengal		Andhra Pradesh		Tamil Nadu		Gujarat		Goa	
Year	Intensity	Year	Intensity	Year	Intensity	Year	Intensity	Year	Intensity	Year	Intensity
02.07.2006	D	12.08.2006	D	29.10.2006	CS	25.11.2008	CS	23.06.2009	D	09.11.2009	CS
02.08.2006	D	03.09.2006	D	21.06.2007	D	04.11.2010	D	11.06.2011	D	01.06.2020	SCS
16.08.2006	D	23.05.2009	SCS	13.11.2008	D	25.12.2011	SCS	22.06.2015	D	–	–
12.08.2006	D	05.09.2009	D	17.05.2010	SCS	28.10.2012	CS	–	–	–	- -
28.06.2007	D	07.10.2010	D	07.12.2010	D	13.11.2013	D	–	–	–	–
05.08.2007	D	16.06.2011	D	19.11.2013	D	06.12.2013	D	–	–	–	–
21.09.2007	D	29.05.2013	D	23.11.2013	SCS	08.11.2015	D	–	–	–	–
09.08.2008	D	16.08.2016	CS	07.10.2014	SCS	29.11.2016	D	–	–	–	–
15.09.2008	D	21.07.2018	D	08.10.2018	D	06.12.2016	SCS	–	–	–	–
20.07.2009	D	06.09.2018	D	13.12.2018	CS	10.11.2018	SCS	–	–	–	–
13.10.2010	D	06.09.2018	CS	11.10.2020	SCS	22.11.2020	SCS	–	–	–	–
22.09.2011	D	05.11.2019	SCS	–	–	–	–	–	–	–	–
30.07.2013	D	16.05.2020	SCS	–	–	–	–	–	–	–	–
08.10.2013	SCS	22.10.2020	D	–	–	–	–	–	–	–	–
20.06.2015	D	–	–	–	–	–	–	–	–	–	–
18.07.2017	D	–	–	–	–	–	–	–	–	–	–
19.10.2017	D	–	–	–	–	–	–	–	–	–	–
19.09.2018	CS	–	–	–	–	–	–	–	–	–	–
26.04.2019	SCS	–	–	–	–	–	–	–	–	–	–
06.08.2019	D	–	–	–	–	–	–	–	–	–	–

Key: *D* depression; *CS* cyclonic storm; *SCS* severe cyclonic storm; – no cyclonic storm

Purulia, Ghatal, Darjeeling, Sabang, Pingla, Cooch Behar, Datan and Jhargra and Cooch Behar districts, were severely affected.

Odisha Based on the appraisal of historical cyclonic data, Odisha state was defined as a highly cyclone-prone area. In total, 20 cyclones crossed throughout the period 2006–2020: 17 cyclonic depressions (Fig. 3) formed on the Bay of Bengal, which resulted in heavy rainfall to the entire coastal district; 1 cyclonic storm came across the Odisha coastline; and 2 severe cyclonic storms (SCS) occurred during the Northeast monsoon. These cyclonic turbulences directly impacted the Balasore, Kendrapara, Jagatsinghpur, Bhadrak, Ganjam, Puri and Khordha districts leading to water-based disasters (floods), with 2007 and 2014 chronicling extreme floods in Odisha. The districts Balasore, Bhadrak, Jagatsinghpur, Jaipur, Keonjhar, and Mayurbhanj, Balikuda and Naugaon experienced 94 deaths, and 90,000 people were displaced during the study period. It is noteworthy that tropical monsoons impacted on one-third of the entire state.

Tamil Nadu Tamil Nadu comprises 14 coastal districts, i.e. Chennai, Kancheepuram, Thiruvallur, Villupuram, Cuddalore, Mayiladuthurai, Nagapattinam, Thiruvarur, Thanjavur, Pudukkottai, Ramanathapuram, Thoothukudi, Thirunelveli and Kanyakumari (organised from north to south), and is one of the most prone to cyclones. According to the Indian Meteorological Department (IMD), 11 cyclones were caused by the northeast monsoon and 5 depressions traversed Tamil Nadu (Fig. 3). The state was predominantly affected by severe cyclonic storms during the northeast monsoon; these were accompanied by various losses such as human life, environment and habitats. Furthermore, two major floods occurred in 2014 and 2015, caused by a tropical cyclone crossing the east coast of India; and low-pressure systems caused flooding in Tamil Nadu. These resulted in the loss of 360 human lives in the Chennai and Cuddalore districts.

Western coastal India

Kerala, Karnataka and Maharashtra The Kerala, Karnataka and Maharashtra coastal states are located in the west India coastal area, lying vertically from north to south sharing boundaries with the Arabian Sea. No cyclones hit during 2006–2020; the Southwest monsoon generated continuous rainfall for the period of June to September causing heavy rainfall and floods near the coastal districts. In 2010 monsoon rain caused floods and landslides in both southern parts (Kerala and Assam) where 50 people were killed and approximately 500,000 people were relocated (ReliefWeb

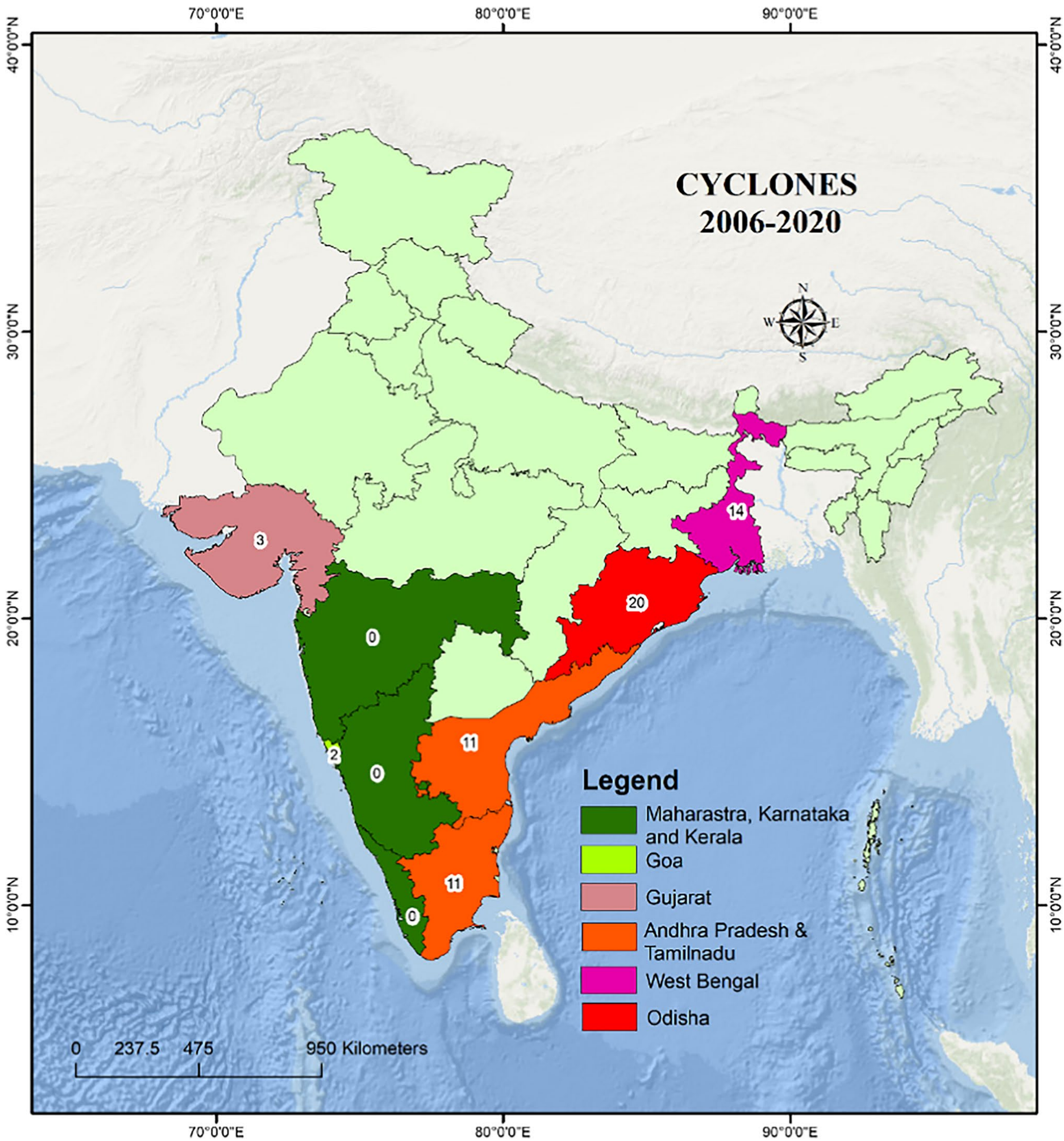

Fig. 3 The number of cyclones occurring in nine Indian coastal states for 2006–2020

2021). In 2018, Kerala was severely affected by high rainfall for all of its 14 districts, namely Alappuzha, Kasaragod, Wayanad, Kannur, Kozhikode, Malappuram, Palakkad, Ernakulam, Thrissur, Idukki, Kottayam, Pathanamthitta, Kollam and Thiruvananthapuram. Moreover, water was released from multiple dam reservoirs, and deaths were documented at 359 with 7 people missing. In 2009, heavy monsoon rain caused flash floods, the states Andhra Pradesh, Karnataka and Kerala were severely affected by the floods, and many places saw exceptional monsoon rainfall, severe river flooding and landslides affecting west coast areas and southern provinces.

Goa and Gujarat The state of Goa is divided into north and south administrative districts. Goa suffered 2 cyclonic disturbances (Fig. 3), crossing the Goa and Konkan regions during 2006–2020. Bicholim, Sattari, Ponda, Canacona and Sanguem areas were affected by floods, and Pernem, Bardez, Tiswadi, Salcete, Mormugao and the Canacona regions were affected by coastal erosion. During this period, 3 depressions crossed Gujarat caused by the southwest monsoon (June), and most of the coastal districts were affected by heavy monsoon rainfall. In 2007, monsoon flooding harshly affected and/or damaged most of the regions, i.e. Saurashtra region, Surendranagar, Rajkot, Bhavnagar, Jamnagar, Junagadh and Amreli; in South Gujarat, Bharuch, Narmada, Surat, Junagarh, Patan, Mehsana, Gandhinagar and Sabarkantha; and in the Kutch region, Vadodara, Ahmedabad, Anand, Panchmahal, Daskroi, Dholka, Valsad and Kheda.

Climate change and data analysis

The research appraised the impacts of climate change on the coastal states from the east to west coast, i.e. West Bengal, Odisha, Andhra Pradesh, Tamil Nadu, Kerala, Karnataka, Goa, Maharashtra and Gujarat using the empirical climate data. These states measured climate change aspects from 2006 to 2020. The study revealed average temperature, average rainfall and average humidity for the selected study period. The result identified that Tamil Nadu and Gujarat had the highest temperatures 29.3 and 29.0 °C, and the lowest temperatures were in West Bengal and Odisha 26.7 and 27.5 °C. Kerala and Karnataka states recorded the highest average rainfall of 2341 and 2261 mm. Conversely, Odisha and Tamil Nadu states had the lowest rainfall levels of 994 and 1075 mm from 2006 to 2020. Kerala and Karnataka states had the highest humidity of 78.11 and 76.57 percent, whilst Gujarat and West Bengal states recorded the lowest humidity of approximately 59.65 and 70.78°. The overall appraisal of climatic data identifies the Kerala and Karnataka states as being highly affected by climate change (Table 4).

Temperature

The study considered climatic parameters such as temperature, rainfall and humidity which was calculated as an average for each year from 2006 to 2020 (Fig. 4). West Bengal experienced the highest average temperature documented at 25.96 °C in 2015, and the lowest average temperature identified at 25.32 °C in 2008. Odisha's average temperature was recorded at 27.17 °C in 2009, whereas the lowest temperature noted at 26.10 °C in the year 2020. Andhra Pradesh's highest average temperature was recorded at 27.83 °C in 2009, and the lowest average temperature documented as 27.05 °C in 2007. Tamil Nadu highest average temperature was 35.62 °C in 2019, and their lowest average temperature was documented at 27.27 °C in 2020. Kerala's highest average temperature was 27.41 °C in 2019, while the lowest average temperature measured 26.50 °C in 2008. Karnataka's maximum average temperature of 27.06 °C was in 2019, and their minimum average temperature measured 25.35 °C in 2007. The smallest state of Goa recorded their maximum average temperature of 27.58 °C in 2020 and lowest average temperature of 27.10 °C in 2011. Maharashtra's highest average temperature hit 27.66 °C in 2011, and their lowest average temperature measured 27.26 °C in 2007. The maximum temperature of Gujarat was 28.30 °C in 2015, and their lowest average temperature was 27.4 °C in 2013. However, whilst the distribution of average temperatures varies throughout the study period, the maximum average temperature overall was found in Tamil Nadu. Tropical cyclones form based upon intensifying temperatures in oceanic regions. This is also related to greenhouse gas

Table 4 Climatic data appraisal 2006–2020. Analysed from NASA Power Data Access (NASA Power Data Access 2020)

Sl. No	Coastal states	Average			Changes 2006–2020		
		Temperature (°C)	Precipitation (mm)	Relative humidity (%)	Temperature (°C)	Precipitation (mm 2006–2020)	Relative humidity (%)
1	West Bengal	26.7	1597	70.78	−0.60	330	4.7
2	Odisha	27.5	1593	72.05	−0.34	−145	2.5
3	Andhra Pradesh	28.4	1191	71.87	0.14	226	1.7
4	Tamil Nadu	29.3	1075	75.35	0.71	−285	-2.0
5	Kerala	27.9	2341	78.11	0.78	−556	-1.2
6	Karnataka	27.7	2261	76.57	−0.64	1072	-1.6
7	Goa	28.4	1383	75.14	0.43	602	0.7
8	Maharashtra	28.0	2210	70.28	0.22	−111	1.0
9	Gujarat	29.0	994	59.65	−0.29	188	2.8

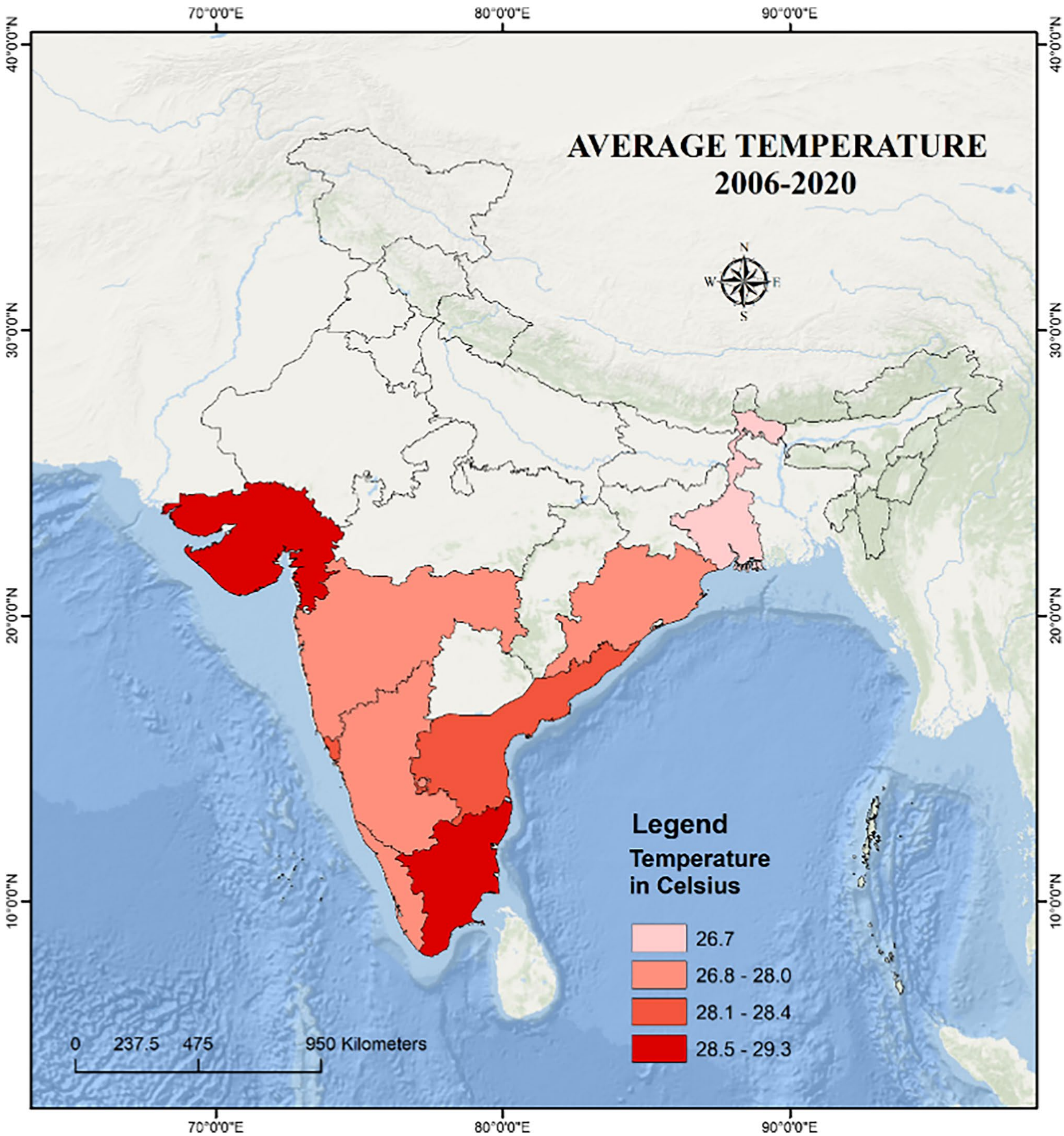

Fig. 4 Average temperatures 2006–2020

(GHG)-induced surface temperature increase. Furthermore, the world meteorological organization (WMO) global level appraisal (Knutson et al., 2020) concluded that tropical cyclones are extremely unusual compared with other natural causes.

Rainfall

The appraisal of average rainfall in Indian coastal states dates from 2006 to 2020 (Fig. 5), and the study describes the maximum and minimum rainfall for each state. West Bengal's maximum average rainfall observed 2080 mm in the year

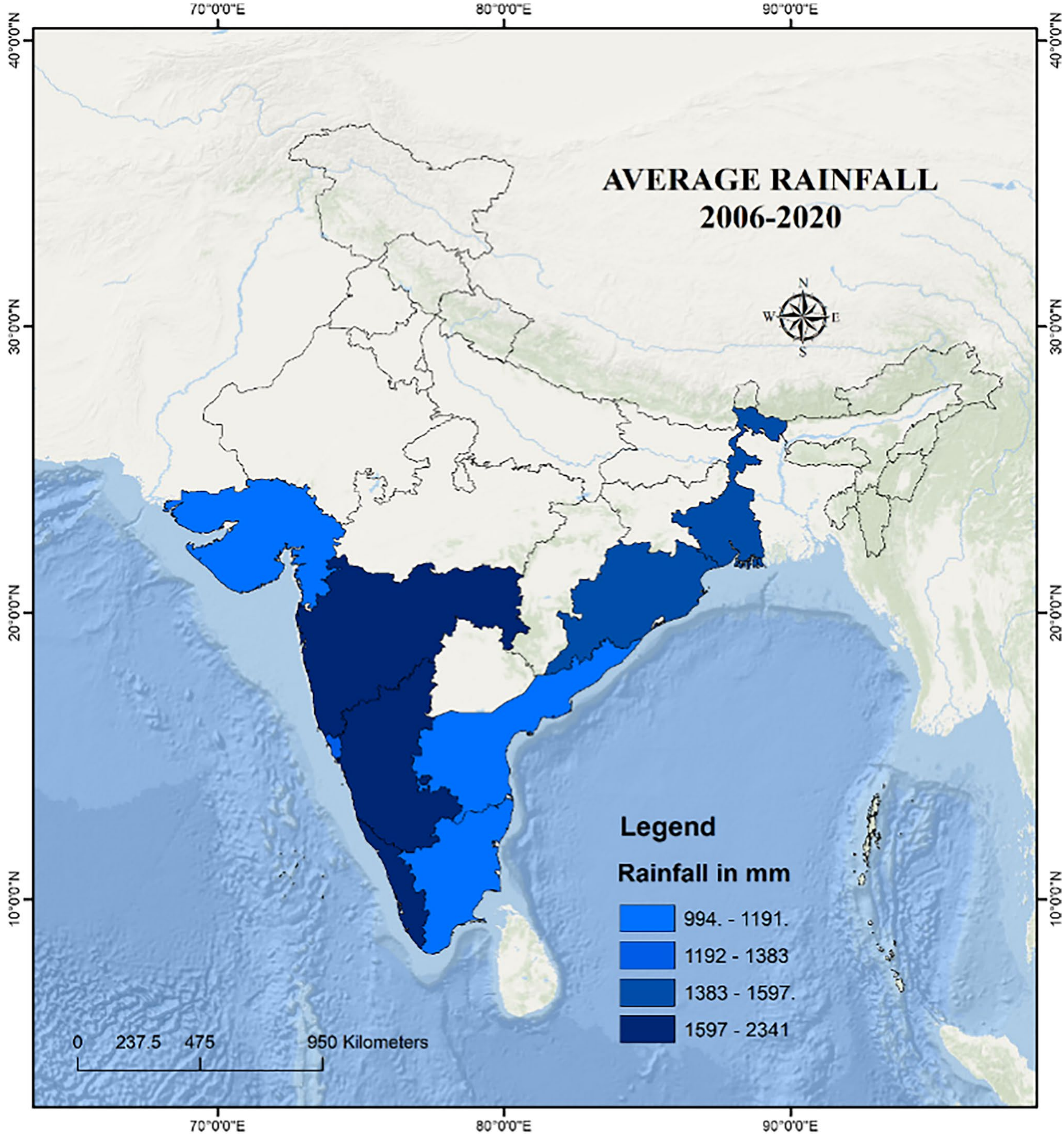

Fig. 5 Average rainfall 2006–2020

2017 and minimum average rainfall measured at 1197 mm in 2012. Odisha's maximum average rainfall was 1913 mm in 2018, with a minimum average rainfall of 1317 mm in 2009. Andhra Pradesh recorded their highest average rainfall of 1682 mm in 2010 and lowest rainfall of 865 mm in 2009. Tamil Nadu observed their highest average rainfall of 1515 mm in 2015 and lowest average rainfall of 796 mm in 2012. Kerala measured their highest rainfall of 2960 mm in 2006 and lowest rainfall of 1691 mm in 2012. Karnataka observed their highest average rainfall of 3044 mm in 2020 and in 2008 their lowest rainfall of 1848 mm. Goa measured their maximum average rainfall of 1915 mm in 2019 and minimum average rainfall of 1131 mm in 2008. A highest average rainfall for Maharashtra was 2713 mm in 2006 and lowest average rainfall of 1464 mm in 2015. Gujarat received their highest average rainfall of 1349 mm in 2007 and their lowest average rainfall of 693 mm in 2018. The highest distribution of average rainfall was dispersed across the states. Most of the states, i.e. Odisha, Tamil Nadu and Kerala states, received the lowest average rainfalls, particularly in the year 2012, when the monsoon failed to arrive.

Humidity

The humidity is recorded during the study period as a statewide quantity representing the amount of water vapour in the atmosphere as an average distribution. The highest average humidity was measured in West Bengal at 75.04% in 2020 (Fig. 6), and their lowest humidity was measured

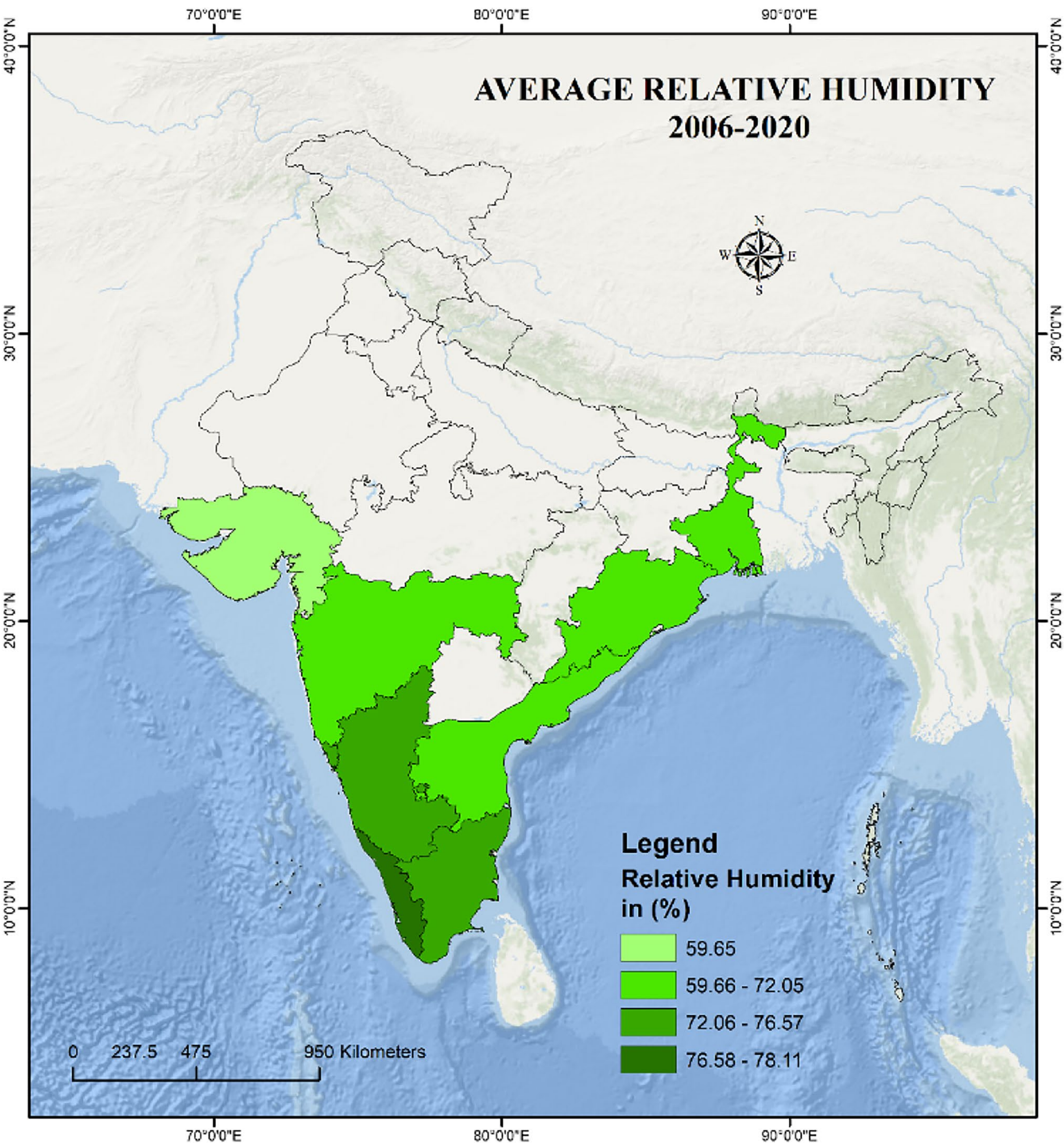

Fig. 6 Average relative humidity 2006–2020

at 68.06% in 2012. Odisha's highest average humidity was recorded at 75.4% in 2020 and their lowest humidity measured 69.0% in 2009. Andhra Pradesh's extreme humidity was 74.3% in 2020, while their lowest humidity was 69.3 in 2009. The highest average humidity measured at Tamil Nadu was 76.9% in 2006, and their lowest was 72.0% in 2016. Kerala recorded their highest value of humidity at 79.2% in 2006 and lowest value of 76.8 in 2019. The highest humidity measured in Karnataka was 79.7% in 2006, and the lowest was 74.6 in 2007. Goa's maximum humidity was 76.9% in 2010, and the lowest was 74.1% in 2015. Maharashtra's highest humidity at 72.7% in 2010 and lowest humidity was 67.5% in 2018. Gujarat's highest humidity was 64.0% in 2020, and the lowest was 54.7% in 2018. The study revealed the West Bengal, Odisha, Andhra Pradesh and Gujarat states experienced the highest humidity, particularly the year 2020.

In the overall assessment of temperatures, rainfall and humidity, the study identified that the temperature increased in Kerala (0.78 °C) and Tamil Nadu (0.71 °C), whereas in Karnataka (− 0.64 °C) and West Bengal (− 0.60 °C) the temperature decreased. Karnataka (1072 mm) and Goa (605 mm) states received the highest rainfall. Kerala (− 556 mm) and Tamil Nadu (− 285 mm) states rainfall decreased from 2006 to 2020. West Bengal's (4.7%) and Gujarat's (2.8%) humidity increased; Tamil Nadu (− 2.0%) and Karnataka (− 1.6%) observed decreased humidity from 2006 to 2020. Therefore, the overall appraisal noted that the highest changes were documented in Karnataka and Kerala, and the results indicate these states are acquiring rapid climatic changes, with the rest of the coastal states experiencing no change, based on the appraisal of climatic data.

Overall trends of climate change and cyclones in Indian coastal states

Climate change and fluctuations in the climate are the major challenges for sustainable coastal zone management across India and also barriers to achieving the UN SDG 13. This study evaluated the climatic data for the past 15 years, identifying the impacts of climate change on coastal states and revealing that the climate is changing for most of the coastal states with Karnataka, Goa, Kerala, Tamil Nadu, West Bengal and Andhra Pradesh experiencing increasing or decreasing temperatures, abnormal rainfall and humid conditions. As a result of these climate changes, increasing sea level rises (1.7 mm/year) is contributing to other challenges including habitat loss, degradation of coastlines and coastal ecosystems and shoreline changes. Furthermore, climate change is exacerbating coastal erosion within this short time period, leading to coastal area flooding and seawater intrusion. West Bengal suffered the largest proportion of erosion between 1989 and 2001, with alteration along 70% of its coast, followed by Kerala (65%), Gujarat (60%) and Odisha (50%). Sea-level rise and floods may cause greater evacuation in major coastal cities, in addition to the displacement of people along the eastern coast (Dhara 2019). These aforementioned issues are impacting on the Indian coastal states. Cyclones are a natural disaster that strike India almost every year, claiming many lives and wreaking havoc on property. Based upon historic cyclonic data from 2006 to 2020, the study reveals that Tamil Nadu, Andhra Pradesh, Odisha and West Bengal states are severely affected by cyclones during the northeast monsoon. The state of Gujarat is highly vulnerable to tropical cyclones every year by the southwest monsoon. In recent years, cyclonic intensity has been very high and damaged the human and coastal environment.

The direct impact of climate change to the coastal area is also from heavy rains, unbearably high temperatures, humidity, etc. (Chapman et al. 2020; Zhang et al. 2021). These studies have demonstrated the vulnerability of the coastal area and reveal the impacts of climate change on coastal states (Serpetti et al. 2017). A large number of drivers, such as cyclones and floods, are closely associated with climate change (Ehrnsten et al. 2019). This study has been undertaken in coastal states affected by climatic factors such as cyclone, temperature, rainfall and humidity. The study shows the influence of climate change to the coastal states of India. In addition, this should identify the natural hazards determined by climate change and associated human stress in these coastal states. Adaptation to climate change must be implemented for resilience to future disasters as well as to achieve UN-SDG 13.

The study limitations

This study focused on the appraisal of climate change in Indian coastal states where the climatic data was available from 2006 to 2020. Consequently, the analysis is limited to the study duration, and it is not focused on the wider trends of climate change and water-based disasters such as flood and landslide. Furthermore, due to time constraints, the study did not evaluate the impacts of climate change on human health. While the researchers took this into consideration during the conception of the present study, it was not possible to achieve that goal on time.

Conclusions

Climate change (temperature, rainfall and humidity) and cyclones are some of the world's most destructive issues and often lead to destruction in South Asia, particularly India. The regular occurrence of cyclones is widespread in the Indian coastal states and causes significant damage resulting from the effect of storm surges and high tides. To improve information regarding these issues, the current study has assessed the climate change and cyclone trends in nine coastal states of India from 2006 to 2020 by using GIS tools, NASA and the IMD E-atlas and Indian Meteorological Data. The study identified that there has been a rise in high-intensity cyclones during the study period. Odisha and West Bengal are the most cyclone-prone states, and Maharashtra, Kerala and Karnataka are the least prone states, though Kerala and Karnataka states recorded the highest average rainfall and highest humidity. The highest average temperature was recorded in Tamil Nadu and Gujarat, and the lowest temperature was recorded in West Bengal and Odisha, although these two states have the highest cyclone vulnerability. These trends once again raise the urgency of further investigations on the relationship between climate change and cyclone activities. The GIS maps, generated from the study results, help to identify the intensity of climate change and cyclones state-wise. The study results also help policy and decision-makers to progress and improve effective strategies for sustainable coastal management. Also, these results help towards achieving one of the goals of the UN-SDG 13 (climate change), which further helps to improve the sustainability of coastal management in Indian coastal regions and also people's lives.

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Declarations

Conflict of interest The authors declare competing interests.

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