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ORIGINAL PAPER

Tropical cyclone vulnerability assessment for India

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Abstract
Tropical cyclones affect millions of lives in the Indian subcontinent which makes the region highly vulnerable to cyclones. Classifying the region's vulnerability greatly helps the stakeholders involved in the disaster management associated with tropical cyclones. This study is a comprehensive assessment of India's vulnerability to cyclones of different categories prepared at district level. It is based on recently updated cyclone track data, and considers both meteorological parameters such as surface-level winds, daily rainfall, storm surge height and socioeconomic parameters like population and household densities. Statistical tools like the cyclone return period as well as the landfall frequency count are also calculated for cyclones of varied intensities. A normalized cyclone vulnerability index is defined as a combination of above parameters that provides an overall vulnerability of each district to cyclonic, severe cyclonic and the total cyclonic storm categories. Results show that coastal districts of the northern most states of the east coast consisting of West Bengal and Odisha are most vulnerable to tropical cyclones followed by districts of Andhra Pradesh and Tamil Nadu on longer timescale. However, a southward shift in the cyclone activity as well as vulnerability is observed for the recent period. Along the West Coast, coastal districts of Gujarat show an increased vulnerability in the recent times than before. In terms of percentage of districts extremely vulnerable to cyclones, Andhra Pradesh dominates the list with 40–50% followed by Odisha (29–34%), West Bengal (13–14%) and Tamil Nadu (7–13%).

Keywords Tropical cyclones · Vulnerability · Cyclone return periods · NCVI

1 Introduction

Indian subcontinent has a long coastal belt covering nine of its states and several union territories. Tropical cyclones (TCs here onwards) frequently form in the north Indian Ocean particularly over the Bay of Bengal (BOB) causing enormous damage to the coastal districts due to the landfall and affect many other districts as the cyclone passes through. Intense TCs are destructive in nature due to the strong surface-level winds, heavy rainfall and the associated storm surge and carry the potential to damage

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agriculture, properties and livelihood worth billions of dollars every year. TCs including hurricanes stand only second to earthquakes in terms of number of deaths (233,000 deaths, 17% of the total) during 1998–2017 globally (CRED, 2018). They contribute to the most damage with almost half (46%) of the total economic losses (about $1330 billion) during the same period with low- to middle-income countries being the most affected. While the millennium declaration in 2000 urged the global community to intensify efforts to reduce the number of both natural and man-made disasters, the Sendai framework on disaster risk reduction adopted in 2015 has set targets and defined indicators for measuring the progress in reducing the disasters. In India, widespread improvement in predicting the TCs (track and intensity) that formed over the Bay of Bengal and Arabian Sea during the last decade reflects the growing expertise in this field. However, better preparedness measures would always help us in coping with the damage caused by the TCs. Thus, it is essential to understand the vulnerability of each and every corner of the country using latest datasets and advanced tools like GIS.

According to McCarthy et al. 2001, the term vulnerability is defined as the result of interaction between hazard, exposure and adaptive capacity. However, recent reports define it as the "propensity and predisposition to be adversely affected or susceptibility to harm and lack of capacity to cope and adapt" (Field et al. 2014, Portner et al. 2022). The term vulnerability specifically regarding the storms/cyclones can be referred to the sensitivity of human habitats and their resilient capacity to minimize the damage occurred. Cyclone vulnerability of a community or an individual is defined as its sensitivity character to be exposed or degree of loss due to lack of capabilities (coping and adaptive). Here, we refer the term vulnerability to identify the sensitivity of the system (districts) to potential meteorological characteristics of the TCs.

Different approaches have been followed to assess the cyclone vulnerability in the past. Chu and Wang (1998) estimated it through return periods from deriving a dimensionless quantity called relative intensity and performing Monte-Carlo simulations on it. Sharma and Patwardhan (2008) studied the tropical cyclone vulnerability in India (using number of cyclones, and maximum windspeed as hazard characteristics; coastline length and population density for exposure and cumulative human mortality as a representative factor of impact) for the period 1971–2003. They also compared the index-based vulnerability assessment and the one based on a cluster analysis. Mohapatra et al. 2012, 2015 identified the hazard proneness for coastal districts of India by rating different cyclone characteristics collected from the observed data. Hussain et al. 2019 estimated the cyclone vulnerability over Bangladesh using various factors including cyclone frequencies, total number of cyclone-related deaths, etc., and GIS techniques.

Previously, the vulnerability atlas of India has been prepared at state level by Building Materials and Technology Promotion Council (BMTPC) in collaboration with several government organizations like India Meteorological Department (IMD), National Institute of Disaster Management (NIDM) etc. (BMTPC (2006)). Nevertheless, it is necessary to make a comprehensive analysis of cyclone vulnerability considering both meteorological aspects of cyclones and socioeconomic aspects of the affected areas. Therefore, this study aims to prepare a comprehensive district-level vulnerability assessment for India using latest datasets of cyclone tracks as well as meteorological parameters such as surface-level windspeed, daily maximum rainfall, storm surge height, etc., which are combined with the population and household densities. GIS techniques such as buffering to get the best coverage of TCs around a district segregate the data of all the chosen parameters with the help of a buffer distance.

2 Data and methodology

2.1 Datasets used

The following datasets are used in this analysis.

(a) IMD digital cyclone track data from Cyclone e-Atlas for the period 1871–2020 provided by RMC Chennai
(b) Probable maximum sustainable winds (MSW) data is from MD Best Track Cyclone data for the period 1981–2020
(c) Daily rainfall data for more than 9000 rain gauge stations for the period 1901–2020.
(d) Storm surge data from reports of RSMC, New Delhi
(e) Population and Housing Density data is from Census 2011 data.

[Note: In case of non-availability of data for new districts, information from publicly available sources and government agencies has been utilized].

We have considered IMD Cyclone data from Cyclone e-Atlas for the period 1961–2020 for computation of several parameters. Since, in Cyclone e-Atlas information on cyclone is combined for severe cyclonic storms, very severe cyclonic storms and super cyclonic storms and termed as SCS, in our analysis we have produced the information on cyclonic storm (CS) and severe cyclonic storm (SCS) and all the cyclonic storms (ALL).

2.2 Estimation of cyclone return periods

TC return period refers to the average time period (in years*)* it would take a category of system to pass through the system. Probability of a system is calculated first and the inverse of which gives the return period. Cyclone return periods (CS, SCS and ALL) are computed for the coastal districts on annual scale. The methodology for computing the return periods is based on the computation of the Hurricane return period by NOAA (Neumann 1987) which considers a 50 nautical mile (92.6 km) buffer zone around a chosen location to compute it. Return periods are calculated as the average time at which a certain intensity of cyclone can be expected within that buffer zone of a chosen location, and in this study, it refers to a district. Cyclone return periods maps are prepared for CS, SCS and ALL categories.

2.3 Estimation of probable maximum sustainable winds

For the computation of maximum sustained winds in each district, IMD Best Track Cyclone data for the period 1981–2020 is used for the analysis. We have first created a 5-degree buffer zone from all the track points over India. This would exclude the winds that are not related to the TCs and are caused by different other weather phenomena. A buffer zone of 1 degree is considered for extracting the windspeeds for each district, and then, the district-wise probable maximum sustainable winds are estimated for each category of cyclones.

2.4 Estimation of probable maximum rainfall

The daily maximum rainfall as a result of a tropical cyclone passing through or nearby a selected district has been an important parameter in the study of cyclone vulnerability. The probable maximum rainfall is calculated as the maximum of all such daily maximum rainfall values for the selected period of time for example 1981–2020. In order to get this value, first the e-Atlas data is categorized into the three main categories of CS, SCS and ALL. Considering the horizontal scales of the cyclone and their effect in producing rainfall in the broader area, a 500 km (approx.) buffer zone is created in GIS for monthly cyclone data and the same is used to filter out any rainfall values beyond the cyclone limits. Only the cyclone track without depressions is used for all the calculations. Then, a 1-degree buffer zone is created for all the districts of India and the daily maximum rainfall values have been collected for all the track points passing through the respective buffer zone of a district. A point of note is that only one point from a day is considered out of multiple 3/6 hourly tracks points to avoid repetition (although it would not affect the maximum value). Finally, the maximum of all the daily maximum values is estimated to get the PMRF values.

2.5 Estimation of normalization cyclone vulnerability index

Normalized cyclone vulnerability index (NCVI) is the final expected output from this entire analysis and an efficient indicator of the level of vulnerability a particular district has regarding the TCs. The NCVI is defined as a product of all of the normalized values of population density, household density, maximum sustainable windspeed, max storm surge height, daily max rainfall and the probability of TCs in the following ratio (Wu et al. 2002, Karmakar et al. 2010, Raskar-Phule and Choudhury 2015).

$$\mathrm{NCVI} = \frac{0.25(\mathrm{NPD} + \mathrm{NHD}) + 1(\mathrm{NMSW} + \mathrm{NMRF}) + 1.5(\mathrm{NTCP} + \mathrm{NMSS})}{0.25 + 0.25 + 1 + 1 + 1.5 + 1.5}$$

where the values NPD, NHD, NMSW, NMRF, NTCP and NMSS refer to the normalized values of population density, household density, max sustainable winds, TC probability and max storm surge height, respectively.

Normalized values are categorized in four parts by using four quartiles as shown in Table 1. Also, the methodology followed in Sects. 2.2, 2.3, 2.4, 2.5 is provided as flowchart in Fig. 1.

Table 1 Normalized values are categorized in four parts by using four quartiles

Normalized vulnerability index value	Category
0.0	Nil
0.0 < VI < 0.25	Low
0.25 < VI < 0.50	Moderate
0.50 < VI < 0.75	High
0.75 < VI < 1	Very high

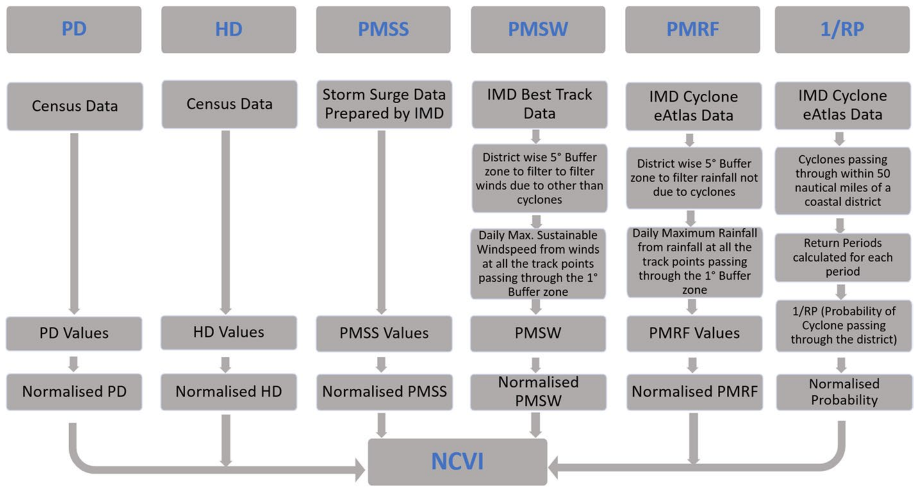


Fig. 1 Methodology followed in this study

2.6 Landfall frequency count calculation

Landfall of a TC causes maximum damage as the intense storm suddenly hits an area in general a coastal region or an island. High frequency of cyclone landfall over a district indicates its high vulnerability. Cyclone landfall count for each district gives the total number of cyclones (of any intensities) that made landfall over the district during the period 1961–2020. These maps are also made on the monthly and as well as on annual scale.

3 Results and discussion

3.1 Cyclone climatology (frequency and tracks)

The north Indian Ocean is a hotspot for tropical cyclones and experiences different intensity of cyclones annually. We have analyzed the cyclone vulnerability for a total of six decades starting from 1961 and also for the more recent period starting 1981. The TC tracks (Fig. 2) for both the above periods clearly show how densely these intense storms are distributed near Indian coasts particularly the Bay of Bengal side. When the TCs affecting Indian region is concerned, there is a declining decadal trend in all categories of cyclones (ALL, CS and SCS) during the total period (1961–2020) (Table 2). However, it does not confirm the same since 1981 as it shows a clear increase. Moreover, the growing sea surface temperatures due to global warming and the land use/land cover changes due to human occupancies, tropical cyclones will remain affecting the socioeconomic conditions of the region particularly making the coastal region vulnerable.

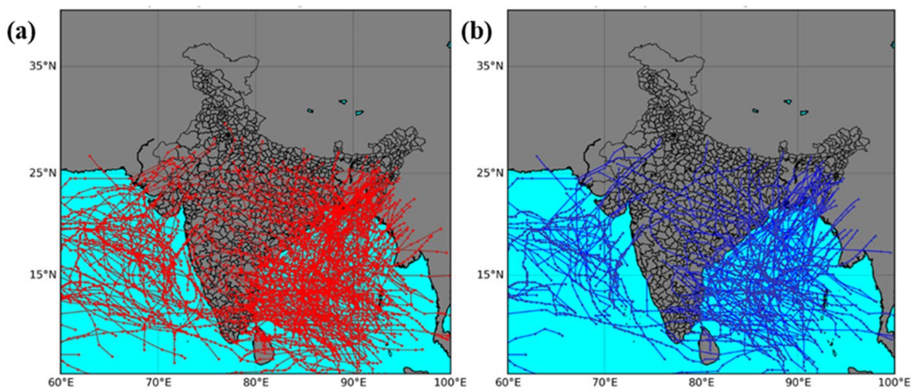


Fig. 2 Tropical cyclone tracks over North Indian Ocean during **a** 1961–2020 and **b** 1981–2020 periods

Table 2 Decadal cyclone frequency of each category of cyclones affecting India

Decade	All	CS	SCS
1961–1970	63	25	38
1971–1980	62	21	41
1981–1990	38	14	24
1991–2000	40	13	27
2001–2010	39	20	19
2011–2020	45	17	28

3.2 Return periods

3.2.1 1961–2020

The return period maps show the average time period (in years) it takes for selected category storm to return to each coastal district for the period 1961–2020 (Fig. 3). When cyclonic storms of ALL categories are considered, the return period of any category cyclone is minimum (0–5 years) all along the east coast which is from the South 24 Parganas of West Bengal to the Ramanathapuram of Tamil Nadu. On the west coast, only the Kachchh district of Gujarat, Malappuram and Thrissur of Kerala experience such very high frequency of cyclones. The island districts of North and Middle as well as the South Andaman also experience such frequency. When cyclonic storms of CS category are considered, the Kendrapara and Jagatsinghpur of Odisha along with the Nellore of AP and Tiruvallur of TN experience high frequency of storms. As far as the SCS (severe cyclones) are concerned, the pattern remains almost same as the ALL category except the Visakhapatnam district of AP, Tiruvarur, Pudukkottai and Ramanathapuram of TN on the east coast and Kachchh district of Gujarat on the west coast which have relatively less frequency (5–12 years) of severe cyclones compared to ALL category for the same period (Tables 3 and 4).

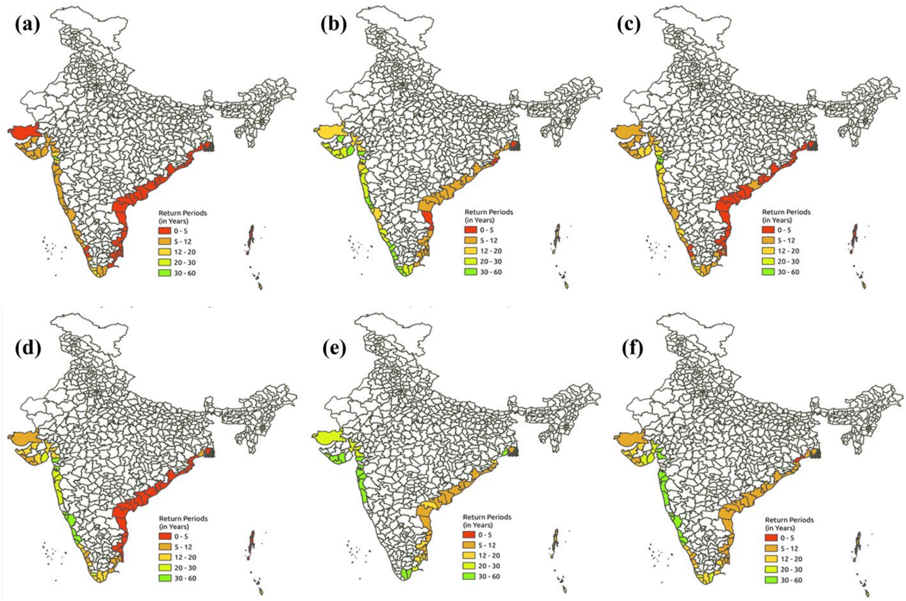


Fig. 3 Cyclone return periods of ALL, CS and SCS categories for **a**–**c** 1961–2020 and **d**, **e** 1981–2020 periods

3.2.2 1981–2020

The return period maps show the average time period (in years) it takes for selected category storm to return to each coastal district for the period 1981–2020 (Fig. 3). When storms of ALL categories are considered, the return period of any category cyclone is minimum (0–5 years) all along the east coast which is from the South 24 Parganas of West Bengal to the Ramanathapuram of Tamil Nadu except the East Mednipur. The island districts of North and Middle as well as the South Andaman also experience such frequency. It takes about 5–12 years for many districts of Gujarat, Kerala and South TN. When cyclonic storms of CS category are considered, majority of the districts on the east coast take about 5 to 12 years or even more time to face a cyclonic storm. As far as the SCS (severe cyclones) are concerned, for the above period only Balasore district of Odisha has the experience of facing high frequency of severe cyclonic storms.

3.3 Vulnerability to cyclonic winds (1981–2020)

The PMSW maps above provide an idea about the district-wise count of the cyclone PMSW for (a) All, (b) Cs and (c) Scs categories for the period 1981–2020 (Fig. 4). When storms of ALL categories are considered, high to very high PMSW values ranging between 76 and 127 knots can occur over the coastal districts along with the interior districts near to the coast from West Bengal, Odisha, Andhra Pradesh, Tamil Nadu and Gujarat including the southern districts of Tripura and Mizoram. Moderate PMSW values ranging between 51 and 76knots can occur over the coastal districts of Maharashtra,

Table 3 List of vulnerable districts under each category of cyclones for the period 1961–2020

Category	All	CS	SCS
Very high	South 24 Parganas, East Mednipur, Balasore, Bhadrak, Kendrapara, Jagatsinghpur, Puri East and West Godavari districts, Krishna, Guntur, Prakasam & Nellore Tiruvallur	South 24 Parganas, East Mednipur, Balasore, Bhadrak, Kendrapara, Jagatsinghpur East and West Godavari districts, Krishna, Guntur, Prakasam & Nellore Tiruvallur, Chennai and Kancheepuram	South 24 Parganas All the coastal districts of Odisha and Andhra Pradesh
High	North 24 Parganas Ganjam Srikakulam, Vizianagaram, Visakhapatnam Chennai, Kancheepuram, Villupuram, Cuddalore, Nagapattinam, Tiruvarur, Thanjavur, Pudukkottai, Ramanathapuram Puducherry South Andaman	North 24 Parganas Puri, Ganjam Srikakulam, Vizianagaram, Visakhapatnam Chennai, Kancheepuram, Villupuram, Cuddalore, Nagapattinam, Tiruvarur, Thanjavur, Pudukkottai, Ramanathapuram Puducherry Ratnagiri, Mumbai	Almost all the coastal districts of Tamil Nadu, Puducherry Mumbai
Moderate	The complete west coast Two levels of Interior districts of Odisha and Tamil Nadu, one level interior districts of Andhra Pradesh North and Middle Andaman	North and Middle as well as South Andaman One to two levels of interior districts of Odisha, Andhra Pradesh and Tamil Nadu All the coastal districts of Gujarat, Maharashtra, Goa and Northwest districts of Karnataka	North and Middle as well as South Andaman One to two levels of interior districts of Odisha, Andhra Pradesh and some interior districts of Tamil Nadu Almost all the coastal districts of Gujarat, Maharashtra

Table 4 List of vulnerable districts under each category of cyclones for the period 1981–2020

Category	All	CS	SCS
Very high	South 24 Parganas, East Mednipur Balasore, Bhadrak, Kendrapara, Jagatsinghpur Srikakulam, East and West Godavari districts, Krishna, Guntur, Prakasam & Nellore Tiruvallur	South 24 Parganas All the Coastal districts of Odisha, Andhra Pradesh	South 24 Parganas, East Mednipur Balasore, Bhadrak, Kendrapara, Jagatsinghpur Prakasam
High	North 24 Parganas Puri, Ganjam Vizianagaram, Visakhapatnam Almost all the coastal districts of Tamil Nadu and Puducherry Bhuj, Porbandar, Junagadh, Amreli and Gir Somnath North and Middle as well as South Andaman	North 24 Parganas, East Mednipur All the coastal districts of Tamil Nadu Mumbai	North 24 Parganas, Puri Srikakulam, Vizianagaram, Visakhapatnam, East and West Godavari, Krishna, Guntur, Nellore Tiruvallur, Chennai, Kancheepuram, Villupuram, Nagapattinam, Thanjavur Puducherry
Moderate	Lakshadweep One to two levels of interior districts of Odisha, West Bengal, Andhra Pradesh and North Tamil Nadu Almost all the remaining coastal districts of India	One to two levels of interior districts of Odisha, Andhra Pradesh and Central Tamil Nadu Almost all the coastal districts of Gujarat and Maharashtra North, Middle and South Andaman districts	North and Middle as well as South Andaman and Lakshadweep One to two levels of coastal and interior districts of West Bengal, Gujarat, Southern Andhra Pradesh and Northern Tamil Nadu All the coastal districts of Kerala, Maharashtra, Goa and Karnataka

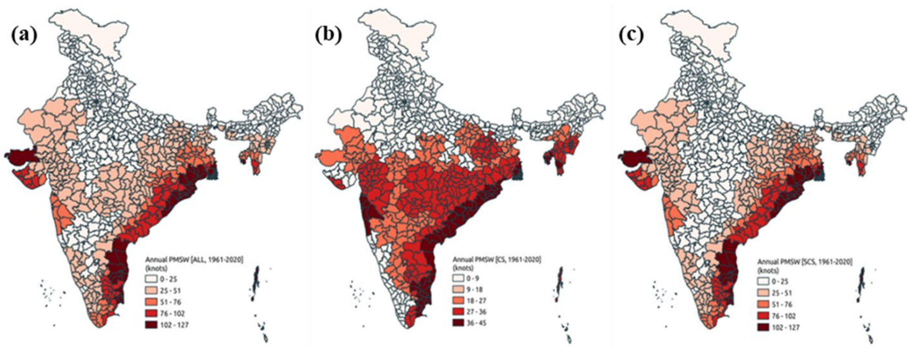


Fig. 4 Probable maximum sustainable winds for 1981–2020 periods

southern Kerala and Tamil Nadu, interior districts of Jharkhand. In case of storms of CS category, the maximum values of PMSW remain relatively less than other categories but are high over all the coastal districts on east coast and Maharashtra on the west coast. Majority of the interior districts of Peninsular and Central India have moderate PMSW values. When storms of SCS category are considered, the pattern remains same as the ALL category.

3.4 Vulnerability due to rainfall

Probable maximum daily rainfall (PMR) values indicate the maximum of the daily rainfall during active days of all the cyclonic storms. Thus, PMR values refer to the maximum possible rainfall due to TCs. These PMR values are normalized to get the vulnerability index of TCs due to the resultant rainfall.

3.4.1 1961–2020

The PMRF maps above provide an idea about the district-wise probable maximum rainfall associated with the (a) All, (b) Cs and (c) Scs categories for the period 1961–2020 (Fig. 5). When cyclonic storms of ALL categories are considered, very high PMRF values ranging between 412 and 630 mm/day can occur over the South 24 Parganas (West Bengal), central coastal districts of Odisha, central and southern districts of coastal Andhra Pradesh (except Nellore), north Tamil Nadu, central and South Maharashtra, Goa and NW Karnataka including many of the interior districts next to them. Moderate-to-high values (145–412 mm/day) can occur over many districts of Telangana, north Kerala, West Bengal, Gujarat and Jharkhand, southern TN and northeastern states of Meghalaya, Tripura and Mizoram.

In case of storms of CS category, the pattern remains almost same except the districts of Odisha which show relatively low values. When storms of SCS category are considered, only coastal districts of Odisha and South 24 Parganas of West Bengal experience very high rainfall (412–630 mm/day) and remaining districts on both the east and west coast show moderate values of 252–412 mm/day.

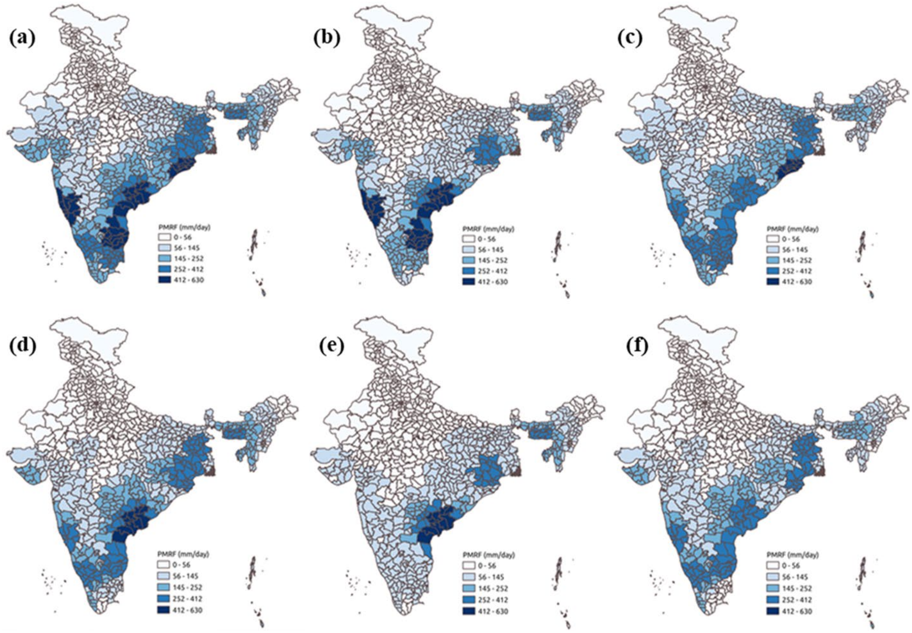


Fig. 5 Probable maximum daily maximum rainfall of ALL, CS and SCS categories for **a**–**c** 1961–2020 and **d**, **e** 1981–2020 periods

3.4.2 1981–2020

The PMRF maps above provide an idea about the district-wise probable maximum rainfall associated with the (a) All, (b) Cs and (c) Scs categories for the period 1981–2020 (Fig. 5). When cyclonic storms of ALL categories are considered, very high PMRF values ranging between 412 and 630 mm/day can occur over the coastal and interior districts of the central Andhra Pradesh. Remaining coastal and interior districts of Andhra Pradesh, Tamil Nadu, Karnataka and Goa show moderate values of PMRF ranging between 145 and 412 mm/day. Districts of interior states like Jharkhand, Telangana and Meghalaya also show moderate values of PMRF. Some districts of Maharashtra and Gujarat also show moderate values. When storms of CS category are considered, very high PMRF values in the range of 412–630 mm/day occur over the coastal and interior districts of Andhra Pradesh similar to the ALL category. On the other hand, moderate-to-high values of PMRF (252–412 mm/day) occur over the interior districts of Jharkhand, Telangana, Odisha and Meghalaya. When storms of SCS category are considered, relatively high values of PMRF (252–412 mm/day) occur over the coastal districts of Andhra Pradesh, Odisha, north Tamil Nadu and north Kerala, south Maharashtra and Goa. Some districts of Gujarat, Meghalaya and Maharashtra also show moderate-to-high values (145–412 mm/day) of PMRF.

3.5 Vulnerability from storm surge

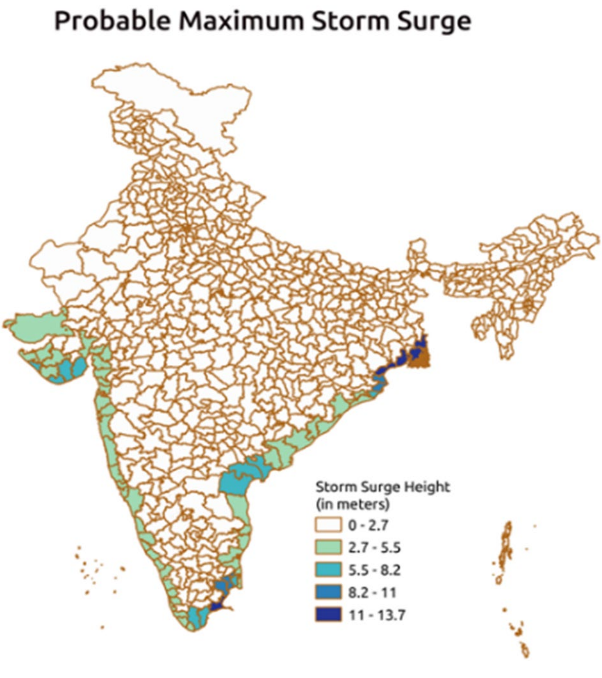
Storm surge can be as damaging as the intense winds does and most of the time it adds to the problem by damaging not just the crops, but uprooting the trees and inundating the coastal region. Increased salinity in the soil can be another problem due to storm surge. As per the analysis, the storm surge is highest for Balasore and Bhadrak districts of Odisha with a 13.1 m and 10.3 m, respectively (Fig. 6). It is followed by all the coastal districts of Andhra Pradesh with the surge height ranging from 4.4 to 8.2 m. High surges are also recorded at Porbandar (4.6 m) of Gujarat and Puri district (4.3 m) of Odisha among the top. Nagapattinam has the highest record of SS among the districts of Tamil Nadu.

Based on the available data (with IMD) and earlier documentation of storm surge heights (m), the PMSS has been determined. The map shows the vulnerability of the Indian coastal districts to storm surges. It can be seen here that the intense storm surge can occur at the West Bengal and Tamil Nadu coasts with a height ranging up to about 14 m. Northern districts of districts of Odisha, Central districts of Andhra Pradesh, South Gujarat along with much of the coastal districts of Tamil Nadu experience moderate levels of storm surge due to cyclones. Remaining coastal districts of low PMSS value are observed.

3.6 Population and housing densities

Population density is highest in metropolitan cities like Delhi, Mumbai, Kolkata, Chennai, Chandigarh as well as in the semi-urban districts of Bihar and Uttar Pradesh (Fig. 7). This is followed by districts in the Indo-Gangetic Plains, Kerala, West Bengal and Tamil Nadu.

Fig. 6 Probable maximum storm surge height for 1961–2020



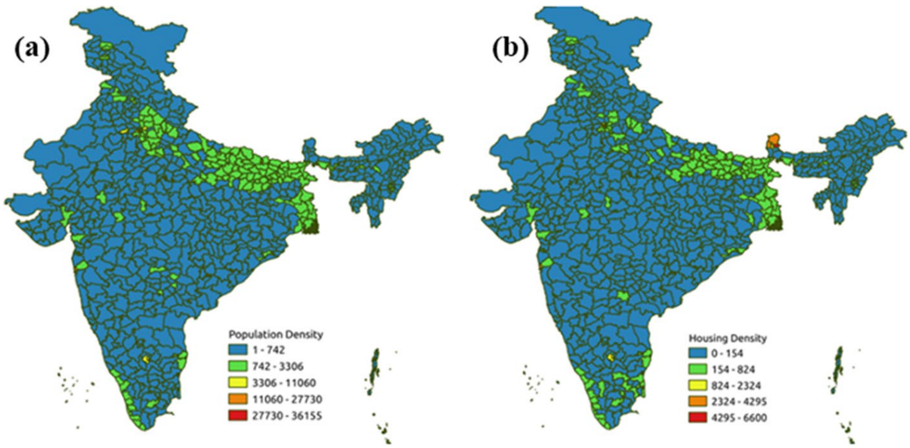


Fig. 7 Population and Household densities

The household density is proportional to the population density, and therefore, the distribution of household density follows a pattern similar to population density.

4 Normalized cyclone vulnerability index

Vulnerable categories are defined for ALL, CS and SCS categories.

4.1 NCVI for the period 1961–2020

The NCVI maps above provide an idea about the district-wise vulnerability of the cyclone landfall for (a) All, (b) Cs and (c) Scs categories for the period 1961–2020 (Fig. 8). When cyclonic storms of ALL categories are considered, the most vulnerable districts include almost all the coastal districts on the east coast from West Bengal to Ramanathapuram of TN. The vulnerability is high in all the districts along the West coast and over many interior districts just next to the coastal districts falling under moderate vulnerability. When cyclonic storms of CS category are considered, severely vulnerable districts include the northern coastal districts of Odisha and West Bengal, the coastal districts of Andhra Pradesh from East Godavari to the Kancheepuram district of Tamil Nadu, whereas the remaining coastal districts of east coast and Ratnagiri and Sindhudurg districts of Maharashtra are highly vulnerable. When storms of SCS category are considered, vulnerability is same as that of the ALL category except the Visakhapatnam and Vizianagaram districts which fall under highly vulnerable rather than severely vulnerable districts.

4.2 NCVI for the period 1981–2020

The NCVI maps above provide an idea about the district-wise vulnerability of the cyclone landfall for (a) All, (b) Cs and (c) Scs categories for the period 1981–2020 (Fig. 8). When storms of ALL categories are considered, the severely vulnerable districts include all the coastal districts of West Bengal, Odisha (except Puri and Ganjam), Andhra Pradesh (except

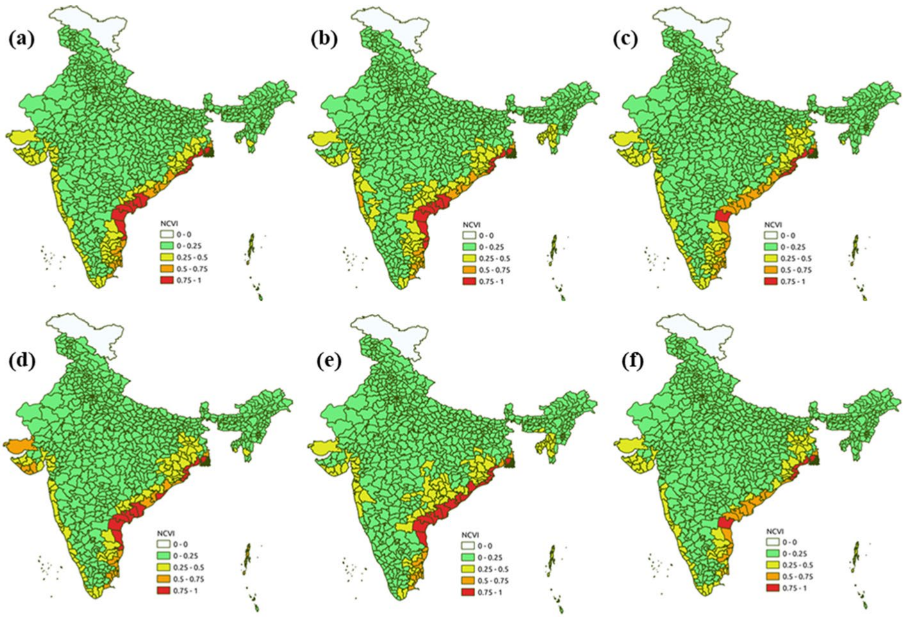


Fig. 8 Normalized cyclone vulnerability index of ALL, CS and SCS categories for the **a**–**c** 1961–2020 and **d**, **e** 1981–2020 periods

Srikakulam, Vizianagaram and Visakhapatnam). The vulnerability is high in all the remaining coastal districts of east coast and Amreli, Gir Somnath, Junagadh, Porbandar and Kutch of Gujarat. Andaman Islands also highly vulnerable. When storms of CS category are considered, the complete coastal belt of east coast is severely vulnerable to this category storms during the above period. The highly vulnerable districts include the Tirunelveli and Kanyakumari districts of Tamil Nadu, many of the interior districts of Andhra Pradesh and Odisha (up to 2 levels) and almost all the coastal districts of Maharashtra and Gujarat and the Andaman Islands. When storms of SCS category are considered, vulnerability is same as that of the ALL category except that some interior districts of Odisha next to the coastal region, all the coastal districts of Gujarat and Kannur, Kozhikode and Malappuram districts of Kerala are also highly vulnerable.

4.3 Percentage of contribution from different states

When compared with other areas, the coastal districts and hence the coastal states fall under the more vulnerable categories. Based on the NCVI values, the percentage of districts from the top states contributing to moderate, high and extreme cyclone vulnerability has been calculated for each selected category of cyclonic storms (ALL, CS and SCS) and for both the study periods, viz., 1961–2020 and 1981–2020. Based on our analysis that consists of many important parameters contributing to vulnerability, coastal states are most affected by cyclonic storms and thus more likely to fall under the high and very high (extreme).

Considering the extreme or very high vulnerability and for all the cyclones (Fig. 9), the states Andhra Pradesh, Odisha, West Bengal and Tamil Nadu have the maximum number

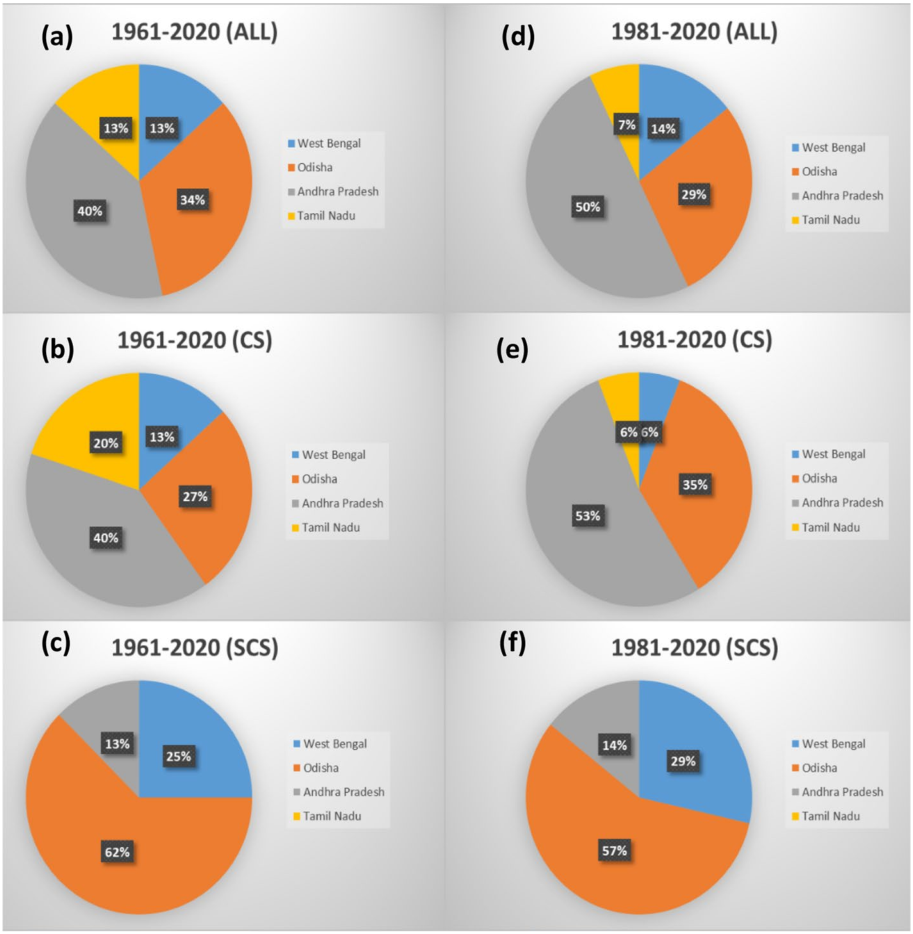


Fig. 9 States with highest number of extremely vulnerable districts under each category of cyclones during **a**–**c** 1961–2020 and **d**, **e** 1981–2020 periods

of districts covering 40 (50), 34(29), 13(14) and 13(7) percentage of districts, respectively, for the period 1961–2020 (1981–2020). For only cyclonic storms, again the same states having different percentages, i.e., 40(53), 27(35), 13(6), 20(6), respectively, are extremely vulnerable. Similarly, for the severe cyclonic storms, the states Odisha, West Bengal and Andhra Pradesh face maximum vulnerability in the percentages of 62(57), 25(29), 13(14), respectively.

There is a completely different scenario when considered high vulnerability of cyclones (Fig. 10). During the total period and for the recent periods, Tamil Nadu has maximum number of highly vulnerable districts with almost 50 (39) percentage out of total highly vulnerable districts of India. It is followed by Andhra Pradesh, West Bengal, Andaman and Nicobar Islands and Odisha. For the CS, it is again Tamil Nadu with 47–63% followed by West Bengal, Puducherry, Andhra Pradesh and Maharashtra with highest percentage. Similarly, in case of severe cyclonic storms, Tamil Nadu remains with maximum number of districts falling under highly vulnerable category it is followed by Andhra Pradesh, West

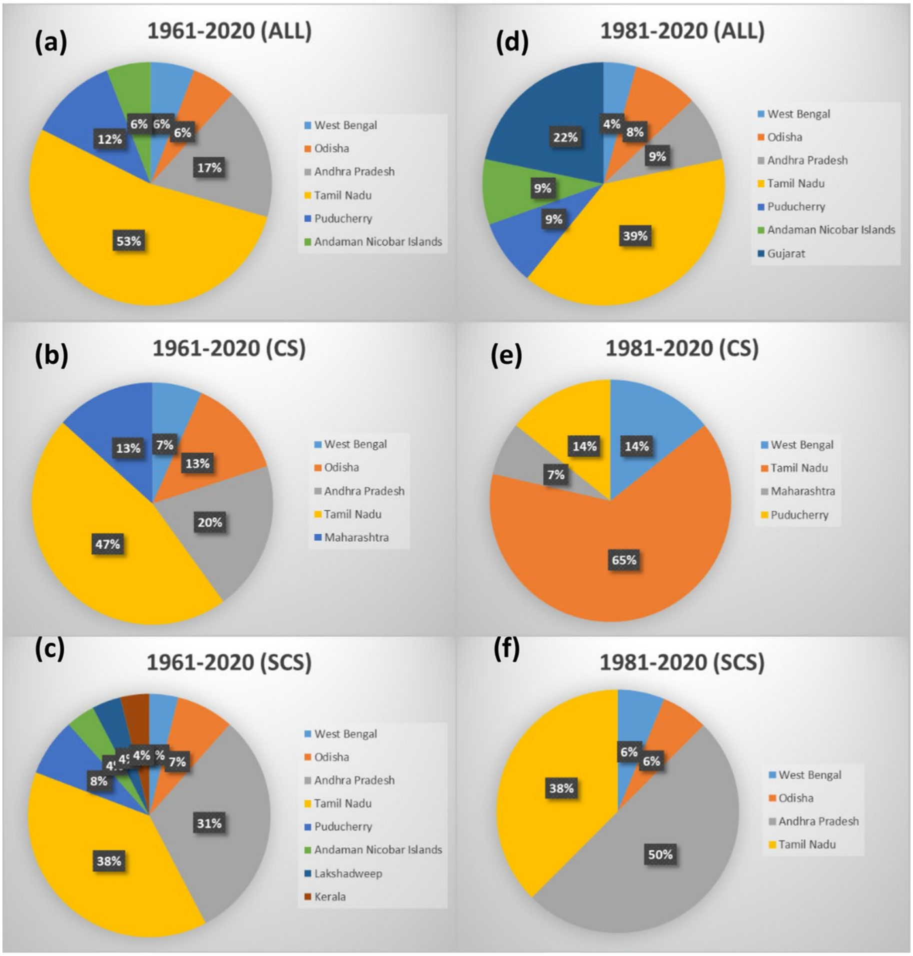


Fig. 10 Percentage of districts with high vulnerability to each category of cyclones during **a**–**c** 1961–2020 and **d**, **e** 1981–2020 periods

Bengal and Odisha with remaining states contributing to highest percentage of highly vulnerable districts.

When considering the moderate cyclone vulnerability (Fig. 11), West Bengal, Odisha, Tamil Nadu, Telangana, Kerala, Jharkhand, Maharashtra, Gujarat, etc., consist majority of the vulnerable districts. These states are either costal or close to the coastal line and mostly affected by the cyclone winds and rainfall unlike those states experiencing the landfall and the associated storm surge. A few northeastern states like Tripura and Mizoram which are close to the head Bay of Bengal can also be seen falling in this category.

5 Landfall frequency of cyclones (LFC)

Maximum damage due to the TCs take place at the time of landing and thus information about the landfall frequency over any particular district is of significant important.

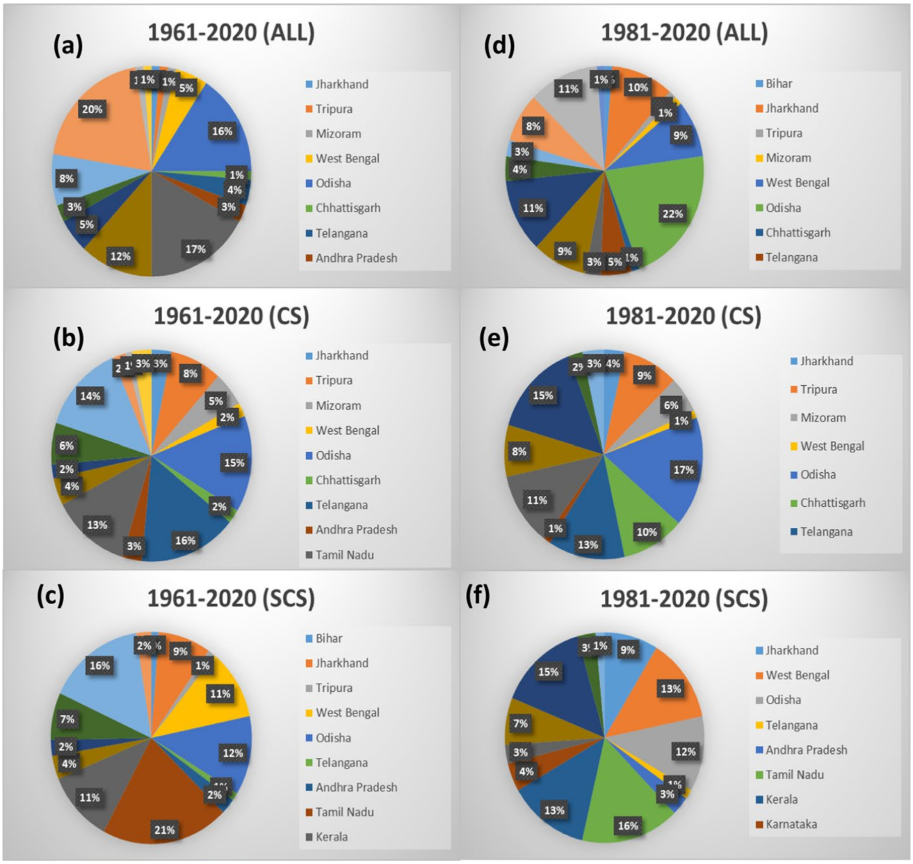


Fig. 11 Percentage of districts moderately vulnerable to each category of cyclones during **a**–**c** 1961–2020 and **d**, **e** 1981–2020 periods

5.1 LFC during 1961–2020

The LFC maps above provide an idea about the district-wise count of the cyclone landfall for (a) All, (b) Cs and (c) Scs categories for the period 1961–2020 (Fig. 12). When cyclonic storms of ALL categories are considered, the count is maximum of 6–9 storms over the South 24 Parganas district of West Bengal, whereas districts like Kendrapara, Ganjam of Odisha, Srikakulam, East Godavari, Krishna, Prakasam and Nellore districts of AP, Villupuram, Nagapattinam and Ramanathapuram of TN on the east coast and Devbhoomi Dwarka on the west coast, and Andaman Islands also experience high number of storms (3–6). When cyclonic storms of CS category are considered, the count is maximum of 3–5 storms over the South 24 Parganas (West Bengal), Puri (Odisha) and Nellore (AP), whereas districts like Balasore (Odisha) and Nagapattinam (TN) on the east coast also experience high number of storms (2–3). When cyclonic storms of SCS category are considered, the count is maximum of 6–9 storms over the South 24 Parganas district of West Bengal, whereas districts like Kendrapara, Ganjam of Odisha, Srikakulam, East Godavari, Krishna, Prakasam and Nellore districts of AP, Villupuram, Nagapattinam and

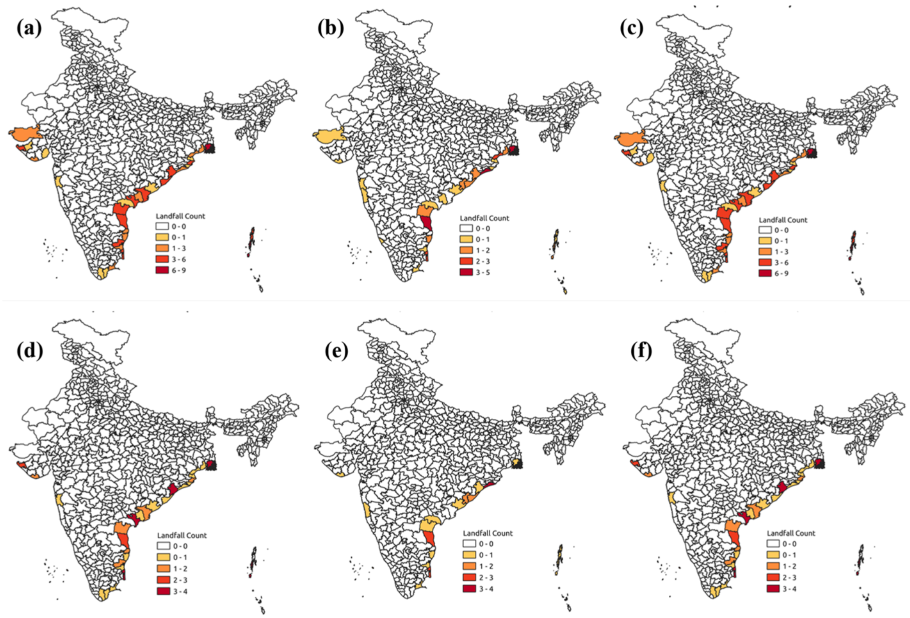


Fig. 12 Cyclone landfall frequency of ALL, CS and SCS categories for **a**–**c** 1961–2020 and **d**, **e** 1981–2020 periods

Ramanathapuram of TN on the east coast and Devbhoomi Dwarka on the west coast and Andaman Islands also experience high number of storms (3–6).

5.2 LFC during 1981–2020

The LFC maps above provide an idea about the district-wise count of the cyclone landfall for (a) All, (b) Cs and (c) Scs categories for the period 1981–2020 (Fig. 2). When cyclonic storms of ALL categories are considered, the count is maximum of 3–4 storms over the South 24 Parganas (West Bengal), Ganjam (Odisha), Krishna (AP) and Nagapattinam (TN), while Nellore district of AP and Devbhoomi Dwarka (Gujarat) on the west coast experience high number of storms (2–3). When cyclonic storms of CS category are considered, only Puri district of Odisha has experienced 3–4 storms for the period, whereas Nellore (AP) and Nagapattinam (TN) districts faced high number of storms (2–3). When cyclonic storms of SCS category are considered, the count is maximum of 3–4 storms over the South 24 Parganas (West Bengal), Ganjam (Odisha), Krishna (AP) and Nagapattinam (TN), while Nellore district of AP and Devbhoomi Dwarka (Gujarat) on the west coast experience high number of storms (2–3).

6 Recent versus longtime cyclone vulnerability

All the analysis in study has been carried out for the total (1961–2020) as well as for the recent periods (1981–2020). A comparison of results from both the periods highlights some important aspects of the cyclone activity and the associated vulnerability over India.

(a) A maximum of PMRF values with over 400 mm/day (Fig. 5) was observed at different locations over the west coast and that seem to be limited in the recent period especially after1981.
(b) Although there is no much difference in the NCVI pattern of all the cyclonic storms during both the periods, there is a clear rise in the spread of very high (extreme) values along the east coast in case of the cyclone storms of modest intensity (Fig. 8) in the recent period.
(c) At the same time, some districts of Gujarat also join the high vulnerability category in the recent period which highlights the increasing cyclonic vulnerability on the west coast as well.

7 Summary and conclusions

Tropical cyclone vulnerability assessment has been carried out for the Indian subcontinent at district level for two different periods, i.e., 1961–2020 (longtime) and 1981–2020 (recent period). All the cyclonic storms are categorized into cyclonic storms of relatively less intensity (CS), severe cyclonic storms (SCS) and all cyclonic storms (ALL). The assessment considers different meteorological characteristics of cyclones such as probable maximum sustainable windspeeds, probable maximum daily rainfall and probable maximum storm surge height from longtime cyclone datasets as well as socioeconomic parameters like the population and household densities from the census data. Unlike the previous studies, it is prepared at district level and also uses GIS techniques. The inclusion of calculated statistical parameters such as the cyclone return periods makes this vulnerability assessment more robust. The final cyclone vulnerability is assessed through a normalized cyclone vulnerability index (NCVI) which is defined as a weighted average of all the above parameters.

The main conclusions of this study are as following.

(1) It concludes that the districts most vulnerable to the cyclonic winds are the coastal districts along with the districts that are near to the coast from West Bengal, Odisha, Andhra Pradesh, Tamil Nadu and Gujarat including the southern districts of Tripura and Mizoram.
(2) Regarding the daily maximum rainfall associated with the cyclones, the most vulnerable districts include South 24 Parganas (West Bengal), central coastal districts of Odisha, central and southern districts of coastal Andhra Pradesh (except Nellore), north Tamil Nadu, central and South Maharashtra, Goa and NW Karnataka including many of the interior districts next to them.
(3) As far as storm surges are concerned, West Bengal and Tamil Nadu coasts are most vulnerable and northern districts of Odisha, Central districts of Andhra Pradesh, South Gujarat along with much of the coastal districts of Tamil Nadu are moderately vulnerable.
(4) Since population density is highest in metropolitan cities like Delhi, Mumbai, Kolkata, Chennai, Chandigarh as well as in the semi-urban districts of Bihar and Uttar Pradesh, these are more vulnerable to cyclones if combined with other factors.
(5) From the return periods point of view, South 24 Parganas of West Bengal to the Ramanathapuram of Tamil Nadu on the east coast and Kachchh district of Gujarat, Malap-

puram and Thrissur of Kerala have low cyclone return periods and thus highly vulnerable to the cyclones.

(6) Landfall frequency or otherwise the cyclone strike rate is maximum over South 24 parganas with 6–9 storms in the 1961–2020 period, whereas districts like Kendrapara, Ganjam, Srikakulam, East Godavari, Krishna, Prakasam, Nellore, Villupuram, Nagapattinam and Ramanathapuram on the east coast and Devbhoomi Dwarka on the west coast and Andaman Islands are highly vulnerable with 3–6 storms during the above period.

(7) Overall, based on NCVI, the most vulnerable districts include the coastal districts on the east coast from South 24 Parganas in West Bengal to Ramanathapuram of Tamil Nadu. The vulnerability is high in all the districts along the West coast and over many interior districts next to the coastal districts are moderately vulnerable to cyclonic storms.

(8) An increase in cyclone vulnerability particularly to very cyclonic storms is observed. Hence, appropriate measures to mitigate the same are crucial.

(9) Also, increased vulnerability is observed along with the west coast of India, especially the coastal districts of Gujarat are more vulnerable in the recent times than before.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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