

# Storm Surge Hazard Assessment Along the East Coast of India Using Geospatial Techniques

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## Research

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# Abstract

The present study is to estimate the inundation extent and depth to estimate the extent of damage using geospatial technique caused due to a storm surge. This is achieved by selecting a worst-case cyclone track (Super Cyclonic Storm) scenario for three Indian states, Andhra Pradesh, Odisha and West Bengal based on the historic data. Over 1300 cyclones are observed to have hit the east coast of India in the past 173 years, which is about an average of more than 7 cyclones per year. Geospatial model results for Orissa cyclone (1999) suggests that over 2,150 km<sup>2</sup> of land is submerged due to storm surge. The inundation was observed up to an extent of 45 km inland upright to the shoreline with over 1,100 km<sup>2</sup> area submerged 1-2m from ground level. This is the worst cyclone (with peak speed 140 knots) of the country known so far to have caused maximum damage. The storm surge model of Andhra cyclone (1996) suggests that about 450 km<sup>2</sup> of area inundated due to storm surge where majority of the area is submerged up to 1m of water pile. The most affected place is Mummidavaram. Whereas, the results of storm surge model for the state of West Bengal is carried out using a synthetic track passing through West Bengal coast with wind speed of 155 knots (worst case). The model result shows 5,400 km<sup>2</sup> of land submerged up to 1m of water and about 2,700 km<sup>2</sup> of area submerged under 1-2m of water. The most affected area is South 24 Parganas and parts of Bangladesh. The results of the current study are useful for the coastal cyclone disaster management in order to make decisions on preparedness and disaster risk reduction. These results can also be used for the coastal future development purposes.

## 1. Introduction

Indian subcontinent is one of the most cyclone-affected regions on the globe. The strong winds from the cyclone does considerable damage to the coastal structures and heavy precipitation from the cyclone can cause flooding in the rivers (NASA Space Place, 2018). Although, 80% of the cyclones affected in India made its history in the eastern coast alone (Fitchett and Grab 2014) and are already stressed with extreme habitants. Its need to study about frequent but intensive cyclones and its impact on socioeconomic condition of the living population (Cutter et al. 2000; Nicholls et al. 2008; Hinkel et al. 2014). The east coast of India was experienced nearly 308 cyclones and affected in the past between 1891 and 2000; among them, 103 cyclones were severe (Rao et al. 2007; Mohapatra 2015; Suchitra 2015). Climate change and its resultant sea-level rises can significantly increase the vulnerability of coastal population (Ravishankar et al. 2004; Mukhopadhyay et al. 2011; Kumar and Kunte 2012). Hence it is essential to assess the impact of storm surges based on the historical trend for the preparedness and resilience.

The present study was focused to measures the inundation extent as well as inundation depth to assess the probability and vulnerability of the cyclonic surge for the selected locations by examining the historical cyclone tracks (Fig. 1b), identify the most frequent cyclone hit along the east coast and simulation of storm surge at coast. Also modeling result can be further enhanced by use of synthetic worst-case scenarios generated based on the historical tracks. Geospatial technique helps to prepare

multi-layer information, management action plans and spatial relationships between natural hazards and exposure (Basheer Ahammed and Pandey 2019). Studies showed that satellite remote sensing offered high temporal resolution for monitoring of land-use change at lower costs than those associated with the use of traditional methods (Mahendra et al. 2011; Fang et al. 2014; Basheer Ahammed and Pandey 2019). GIS-based decision support system will work effectively even in the worst situations. This study assessed the cyclone density for entire mainland coast of India and selected high density area to run storm surge models in order to estimate coastal inundation. This facilitates the coastal managers at each state to manage the disaster.

## 2. Study Area

The study area lies between India's Eastern Ghats and the Bay of Bengal, extends from the Ganga delta to Kanniyakumari (Fig. 1a). It is about 3500 km long and stretches covering four maritime states namely Tamil Nadu, Andhra Pradesh, Orissa and the state of West Bengal in the North and also covers 32 coastal districts (10 in Tamil Nadu, 9 in Andhra Pradesh, 9 in Orissa and 3 in West Bengal). The coastal length of Tamil Nadu 906.9 km, Andhra Pradesh 973.7 km, Odisha 476.4 km and West Bengal 157.5 km (<http://www.quickgs.com/coastal-length-of-indian-states>). It is an important region for agriculture and economic activities. It is fed by four major rivers; Cauvery, Godavari, Krishna and Mahanadi and receives good rainfall. The area has experienced rapid growth due to migration and accelerated urbanization with its four major ports, fueled by industrialization and economic activity over the past decades (Kadarpeta et al., 2015).

## 3. Data Used And Methodology

There are four broad aspects dealt in the present study such as: (1) construction of historical cyclone tracks of Bay of Bengal from 1842 to 2016 (Fig. 1b) by using International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp et al. 2010) data, (2) A fishnet grid of size  $1^0 \times 1^0$  was generated using ArcMap in order to estimate the distribution of frequency, (3) Cyclone track was selected at each state pertaining to high cyclone vulnerable location and a worst case scenario was assumed at these locations. This means the high intensity cyclone scenario was considered for storm surge modeling using the Advanced Circulation (ADCIRC) model to estimate inundation in each state of major cyclone which helps in determining the area affected and (4) Also generated spatial distribution map by kriging interpolation method in ArcGIS 10.3 version in order to get storm surge inundation depth on continuous images on regular surface.

## 4. Results And Discussion

The results of the current study on the cyclone frequency and density highlighting the highly vulnerable areas and storm surge model results pertaining to these areas pertaining to West Bengal, Odisha and Andhra Pradesh were detailed in the following sections.

#### ***4.1 Analysis of historical cyclone tracks***

The historical cyclone tracks recorded during 1842-2016 were assessed to calculate the cyclone density and frequency. The results reveal the varying density and the frequency of the cyclones along the east coast at grid levels (fig.2a&b) and at district level (fig.1a). It was observed that majority of cyclones enter India via Orissa – West Bengal coast and move ahead. The grid which is formed at the border of Orissa- West Bengal and extends towards the sea is seen to have highest cyclone count of 297. Which means about 297 cyclones have occurred in an area of 13,200 km<sup>2</sup> (1×1degree) in the past 173 years. The highest density was recorded at Bhaleshwar district of Odisha (Fig.1a).

The map represents the distribution of frequency of cyclones (fig.2a) that has occurred in the past. The highest frequency observed was 1.8 per year in the northern Orissa at Bhaleshwar district and West Bengal covering Midnapore and South 24 Paraganas coasts. The grids with red color are the areas which experience more than one cyclone per year on an average (fig.2b). The orange colored grids experience up to one cyclone per year on an average. Some parts of Andhra Pradesh experience a cyclone in 2-4 years. This analysis clearly highlights Orissa and West Bengal coasts are experiencing the most frequent as well as dense cyclones.

The assessment of total cyclones recorded at each district along the east coast (fig.1 a), Baleshwar district of the state of Orissa and few coastal districts of West Bengal (East Midnapur; South 24 Parganas and North 24 Parganas districts) was recorded more than 145, the highest number of cyclones in the past. Bhadrak; Kendrapara; Puri and Ganjam district of Orissa state were recorded number of cyclones between 90 to 144. Whereas, all Andhra Pradesh districts recorded cyclones count between 49 to 89.

#### ***4.2 Storm surge modeling Results of Orissa:***

The cyclone track selected for Orissa to study was super cyclone of 1999 which was known worst event in the area. cyclonic rainfall spread throughout the coastal districts of Odisha state, and effectively covering the area more than 200 km<sup>2</sup>. The maximum intensity of cyclonic rainfall more than 200 mm was observed and as a result, these were more prone to floods and damages (Patel & Sahoo 2018). At least 13 million people, including 3.3 million children, 5 million women and nearly 3.5 million elderly people were affected and 23,129 houses washed away, (Source: UNDP, Odisha Disaster Management Authority) with each other (Fig. 4). The results depict that the cyclonic rainfall spread throughout the coastal districts of Odisha state, and effectively covering the area up to > 200 km from the location of landfall 'Paradip' (Jagatsinghpur district) during Super–cyclone 1999 (Fig. 4a). The cyclonic rainfall of > 100 mm over these 3 days (29–31 October 1999) was observed along the coast line comprising several coastal districts of Odisha including the landfall location. Due to cyclonic activities, the maximum intensity of cyclonic rainfall of >200 mm was observed in those districts, which were located near to the landfall. As a result, these districts (i.e., Baleshwar, Bhadrak, Ken- drapara, Jajpur, and Jagatsinghpur) were more prone to floods and damages (Fig S2), wherein these districts also received surplus water

from reservoirs/dams and river basins. The spatial distribution of cyclonic rainfall during Phailin 2013 showed that lesser magnitude of rainfall amount was received during this period, compared to that of Super-cyclone 1999 (Fig. 4b). The spread-out of rainfall due to Phailin 2013 was more profound than 1999 event, and effectively spread up with each other (Fig. 4). The results depict that the cyclonic rainfall spread throughout the coastal districts of Odisha state, and effectively covering the area up to > 200 km from the location of landfall 'Paradip (Jagatsinghpur district) during Super-cyclone 1999 (Fig. 4a). The cyclonic rainfall of > 100 mm over these 3 days (29–31 October 1999) was observed along the coast line comprising several coastal districts of Odisha including the landfall location. Due to cyclonic activities, the maximum intensity of cyclonic rainfall of >200 mm was observed in those districts, which were located near to the landfall. As a result, these districts (i.e., Baleshwar, Bhadrak, Kendrapara, Jajpur, and Jagatsinghpur) were more prone to floods and damages (Fig S2), wherein these districts also received surplus water from reservoirs/dams and river basins. The spatial distribution of cyclonic rainfall during Phailin 2013 showed that lesser magnitude of rainfall amount was received during this period, compared to that of Super-cyclone 1999 (Fig. 4b). The spread-out of rainfall due to Phailin 2013 was more profound than 1999 event, and effectively spread up istrict) along the coast.

The cyclone track of 1999 Orissa Super Cyclone was made landfall near Paradeep coast (Fig.3a). The resultant different inundation depth (water level above ground) was estimated using the storm surge modelling depicts maximum surge inundation up to 4m (fig.3b). Inundation level of 3-4m was covered an area of 5.9 km<sup>2</sup> in a patch near the coast was recorded and 2-3m inundation level covered 143.3 km<sup>2</sup> were extended up to hinterlands in the vicinity of river and creeks. However, majority class was 1-2m inundation level covered 1,146.3 km<sup>2</sup>. There are few areas of 833.2 km<sup>2</sup> slightly elevated areas were recorded up to 1m inundation. It was also observed there are some areas not inundated but surrounded by inundation were also in vulnerable as these areas will get stranded during an event of cyclone.

Totally the large area of 2128.7 km<sup>2</sup> was depicted under inundation end extended up to 45 km hinterland from the coast (fig. 3b). Jagatsinghpur district is observed to be affected the most among two other districts, Kendrapara and Cuttack. The larger inundation was observed at the cyclone landfall area and the river systems act as corridors for inundation and carried inundation deep into hinterlands.

#### ***4.3 Storm surge modeling Results of Andhra Pradesh:***

Andhra Pradesh coast experienced more than 62 cyclones including depression, cyclone surge, and severe cyclone surges in the past 40 years. Among these 32 cyclones were affected the Krishna–Godavari region, comprising four districts and around 7% of the area observed high vulnerability (Basheer et al., 2019). The cyclone track selected for the Andhra Pradesh coast was the Very Severe Cyclone of 1996 made landfall near Mummidivaram of East Godavari District (Fig.4a).

The storm surge simulation results of Very Severe Cyclone of 1996 hit Andhra coast reveal a maximum inundation depth of 2-3m covering up to an area 12 km<sup>2</sup>, 48.9 km<sup>2</sup> area was experienced an inundation depth of 1-2m and Majority of the area of 376.1 km<sup>2</sup> is was inundated up to 1m of water from the ground

(Fig.4b). A total of 437.6 km<sup>2</sup> of coastal area is inundated by storm surge and Mummidivaram is the most affected taluk followed by Kakinada and some parts of Ramachandrapuram (Fig4b). Even Razole and Amalapuram taluks in the south also recorded coastal inundation.

#### ***4.4 Storm surge modeling Results of West Bengal:***

The synthetic track with hypothetical wind speed value of 155 knots was used to run a storm surge model for parts of West Bengal (Fig.5a). The maximum inundation depth due to storm surge depicted was 5.5 m and maximum extent was up to 145 km inland (Fig.5b) from the coast. Large inundation was observed in the West Bengal and Bangladesh in the Sunderban area (Fig.5b).

Inundation was carried deep inland up to 145 km due to the strong event and creek systems of Ganga-Brahmaputra. The large amplitude of surge heights was observed along the coasts of Bangladesh. Maximum area inundated in the eastern parts of south 24 Parganas district and southern parts of North 24 Parganas district (Fig. 5b). Maximum level of inundation depth of 3-4m was observed in the vicinity of creeks in West Bengal. The maximum area (5439.67 km<sup>2</sup>) was under one meters of inundation. Followed by 1-2m inundation recorded 2674.79 km<sup>2</sup>. Inundation more than 4m was recorded 25 km<sup>2</sup> is constrained along the banks of the major creeks and small islands at the distal parts A total 9036.92 km<sup>2</sup> area was inundated due to this storm surge event (Fig.5b).

The analysis of the historical cyclones revealed the Orissa and West Bengal states are highly vulnerable to cyclones with high count and frequency. The storm surge modeling was carried out at each state considering worst event in the past for Orissa and Andhra Pradesh. In case of West Bengal synthetic worst case was considered. The results of these storm surge simulations suggest the large inundation in the Orissa and West Bengal. A moderate inundation was recorded in the Andhra Pradesh coast. This may be due to the strength of the event and the large low-lying coastal areas exposed to the cyclones in the Orissa and West Bengal whereas the strength of the cyclone that occurred in Andhra Coast was not as great as the ones that occurred at West Bengal and Orissa coast. And also, the presence of low-lying large delta in West Bengal coast may have facilitated inundation extent and inundation levels. The large parts of coastal zones in West Bengal and Odisha are highly exposed to inundation due to low lying areas resulted in high vulnerability due to storm surges.

## **5. Conclusions**

The current study is an attempt to demonstrate the geospatial techniques to assess the probability (based on historical tracks), intensity and vulnerability (based on the modeling) of the cyclonic surge and their impact on the coastal environment. The results of the current study reveal Orissa and West Bengal coasts are highly vulnerable to cyclonic surge that hit these coasts. The study further highlights the role of the large river/creek systems of major deltas in Orissa and West Bengal in carrying inundation into much higher and hinterlands. These areas are highly exposed to cyclonic induced storm surges due to large low-lying coastal areas. Whereas, Andhra Pradesh coast is moderately vulnerable when compared

to above areas. The modeling result can be further enhanced by use of synthetic worst-case scenarios generated based on the historical tracks. The use of the very high-resolution bathymetry and topography can also improve the modeling results to assess the storm surge risk and vulnerability.

Coastal residents can scale back the harm done by a storm surge by protecting native wetlands. Wetlands, such as swamps, estuaries, and mud flats, act as sponges for tropical cyclones. As the cyclone makes landfall, the marshy land and plants absorb the water and the energy of the storm surge. Silt and swamp vegetation hinder the intensive part of the storm surge from striking homes and businesses. The results of the current study are useful for the coastal cyclone disaster management in order to make decisions on preparedness and disaster risk reduction. These results can also be used for the coastal future development purposes.

## List Of Abbreviations

NASA: National Aeronautics and Space Administration

GIS: Geographical Information System

IBTrACS: International Best Track Archive for Climate Stewardship

ADCIRC Model: Advanced Circulation Model

UNDP: United National Development Program

## Declarations

### Availability of data and materials

The datasets generated and/or analysed during the current study are provided by the first author Harshith C. Prince and can be accessed on reasonable request from corresponding author Ms. R.Nirmala by writing at [nirmala.agara@gmail.com](mailto:nirmala.agara@gmail.com).

### Competing interests

The authors declare that they have no competing interests.

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### Authors' contributions

The first author Mr. Harshith collected and interpreted the data at INCOIS facilities. The co-author Ms. Nirmala preformed interpretation of the data and contributed in writing the manuscript. Mr. Mahendra

conceptualised the study and worked for analysis and write-up. Dr. Murthy analyses and interpreted the storm surge inundation.

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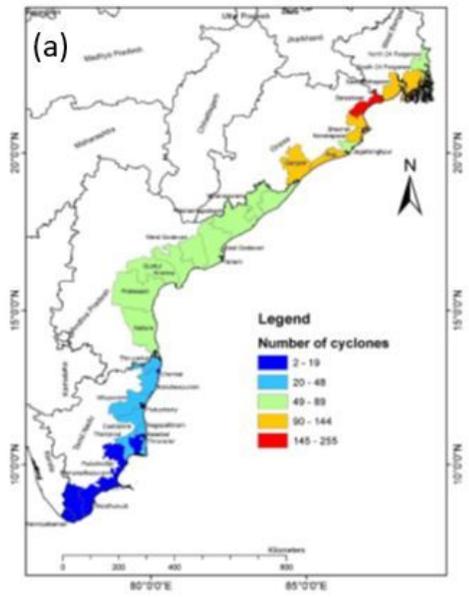
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## Figures

Cyclone Landfalls on Districts of East Coast (1842-2016)



Cyclones originating and passing through Bay of Bengal towards Indian mainland (1842-2016)

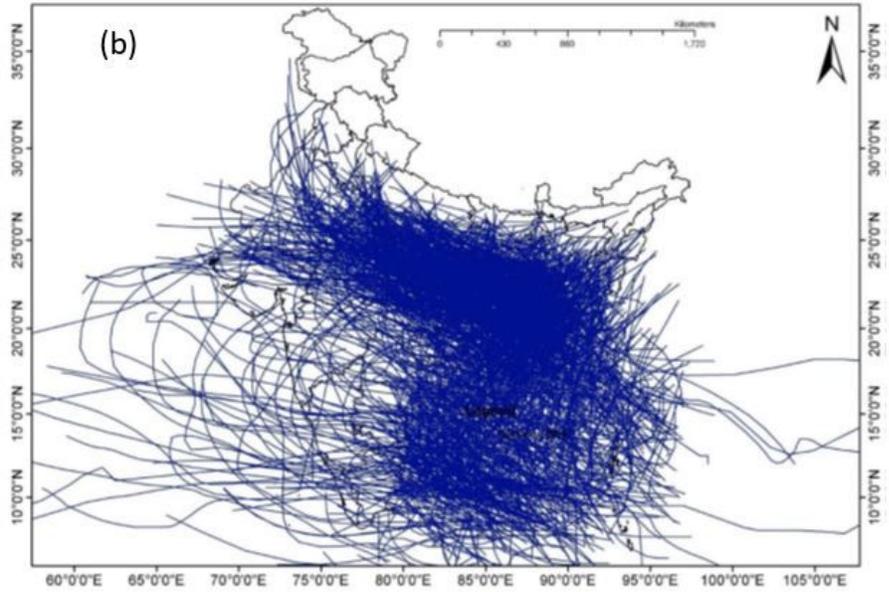
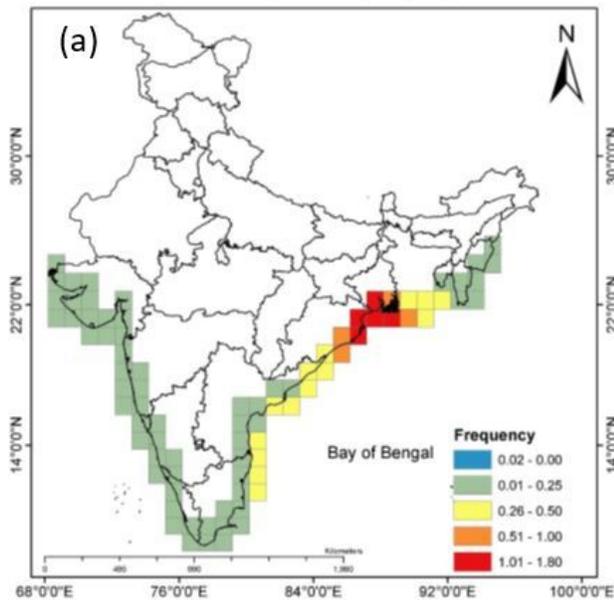


Figure 1

(a) Study area of Indian east coast with cyclone density at district level (b) based on the cyclone track data recorded during 1842-2016 [Source: International Best Track Archive for Climate Stewardship (IBTrACS)].

Distribution of cyclone frequency at grid level



Distribution of cyclone count at grid level

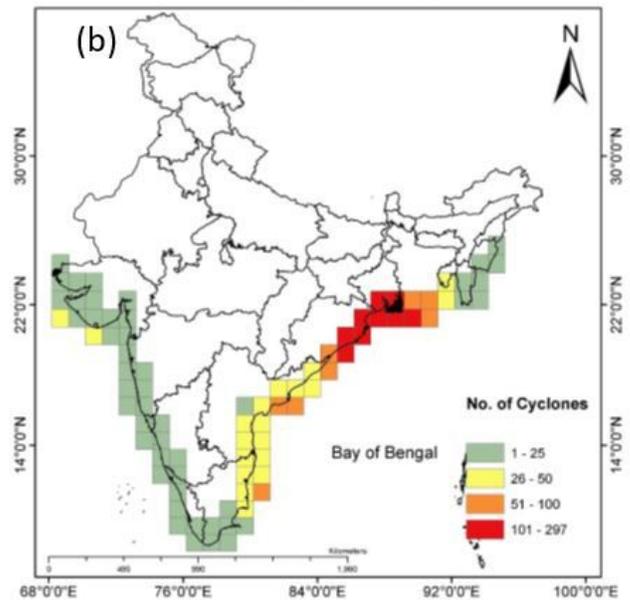
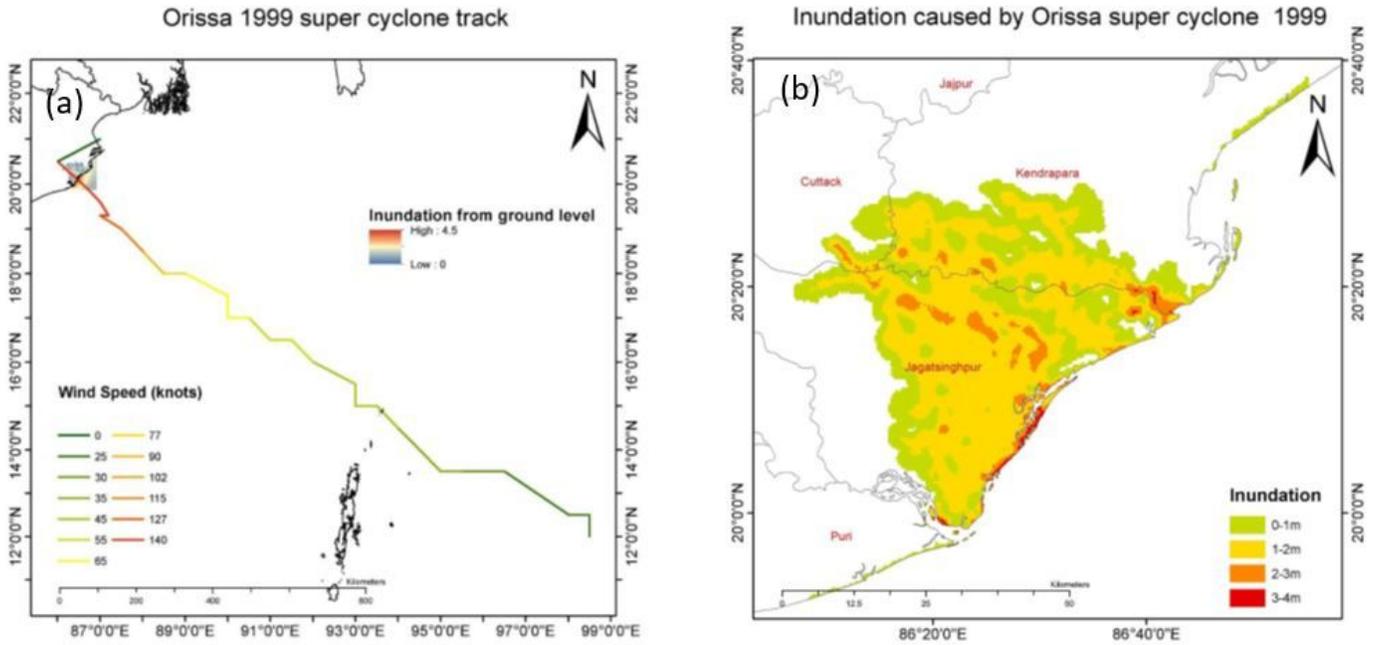


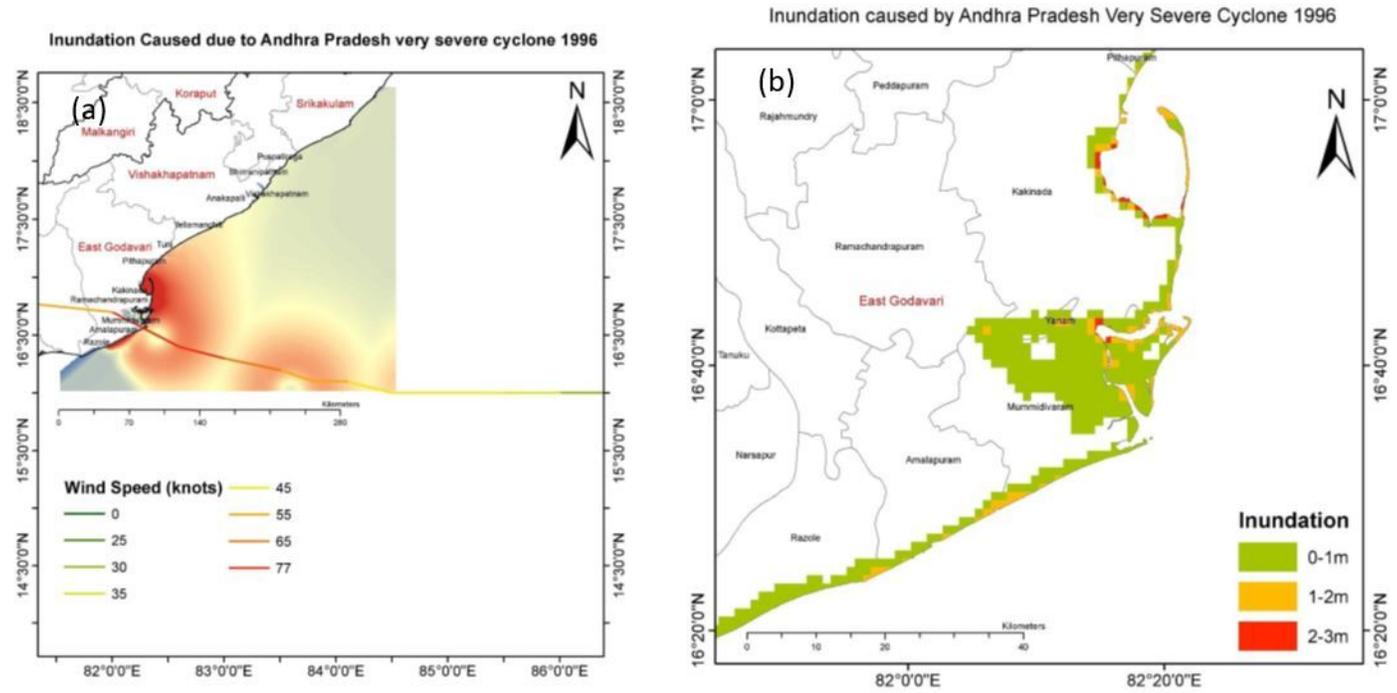
Figure 2

(a) Frequency and (b) density of cyclones along the Indian mainland coast estimated based on the historical cyclones recorded during 1842-2016



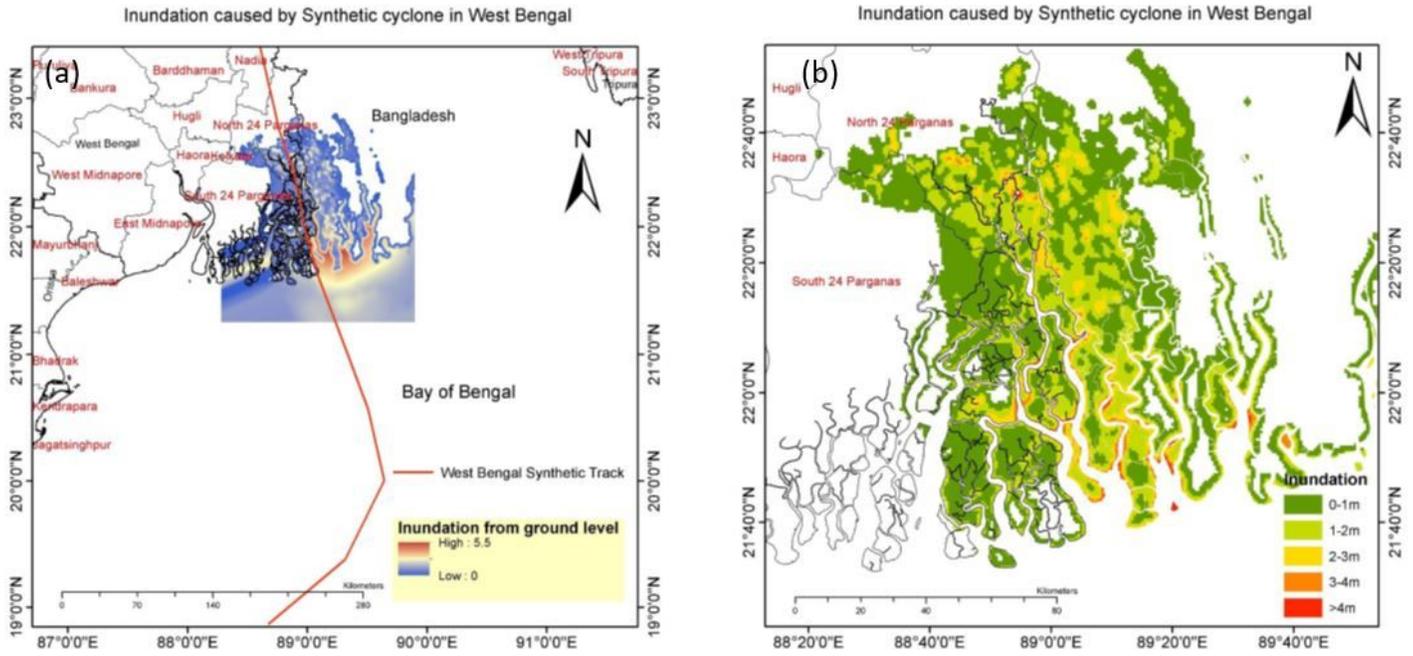
**Figure 3**

(a) 1999 Orissa Super Cyclone track with different wind speeds overlaid on storm surge model results and (b) estimated Inundation depth based on the storm surge model results.



**Figure 4**

(a) Andhra Pradesh Very Severe Cyclone track of 1996 with different wind speeds overlaid on storm surge inundation and (b) Inundation recorded on the land.



**Figure 5**

(a) West Bengal Synthetic Super Cyclone Track used for storm surge modeling and (b) resultant inundation depth.