Estimating Cyclone Vulnerability and Its Linkages With Child Mortality Trajectories Along the Bay of Bengal Coast in India: a Geospatial Approach

Arup Jana
International Institute for Population Sciences  https://orcid.org/0000-0001-5377-4614

Subhojit Shaw
International Institute for Population Sciences

Aparajita Chattopadhyay  (aparajita@iipsindia.ac.in)
International Institute for Population Sciences (IIPS)  https://orcid.org/0000-0002-1722-4268

Research

Keywords: BoB, Neonatal and under-5 mortality, Cyclone, Vulnerability, India, East Coast

Posted Date: August 31st, 2021

DOI: https://doi.org/10.21203/rs.3.rs-840847/v1

License: Creative Commons Attribution 4.0 International License.  Read Full License
Abstract

Background

The coastal population of Indian subcontinent experience variety of coastal hazards of which cyclone is the most destructive one. Most recently, on 20th May 2020, the super cyclone *Amphan* lashed with 155 km/h, as tall as a two-story building on the Eastern coast and state of West Bengal in India. In the following year 2021, another cyclonic storm, named *Yaas*, intensified in the Bay of Bengal in May, and it has ravaged many parts of the apex of the BoB coast. Over the decades, the devastating tropical cyclones of the Bay of Bengal (BoB) have thrashed thousands of lives and properties.

Methods

An empirical study to assess the coastal population's vulnerability and mortality along the east coastal districts of India is the need of the hour. Using a set of data the paper estimates the hazard exposure, sensitivity, and adaptability. Further, to understand the association between vulnerability and neonatal and under-5 mortality, regressions are applied.

Results

A very high coastal vulnerability risk for poor socio-economic status and lack of infrastructure was observed in certain districts of the BoB coast. Women, children, elderly and agrarian population are more sensitive to the cyclone; while lack of accessibility and infrastructure and poor health care system impact the population's adaptive capacity. A strong association of child mortality with coastal vulnerability is observed in the study area. Other factors that also play marked role in child mortality are prevalence of diarrhoea, lack of improved water and sanitation.

Conclusion

The study, first of its kind in India, has identified vulnerable districts of the east coast to help policymakers take measures for disaster planning and improving the basic facilities for a resilient society.

1. Introduction

The global sea surface temperature (SST) has increased throughout the past half-century due to the global greenhouse gas emission, leading to the intensification of cyclones over time [1]. Globally, 40% of the world population resides within 60 km from the coast, a driver for the coastal vulnerability [2]. The Intergovernmental Panel on Climate Change (IPCC) has identified several hotspots of climate change sensitive region where livelihood depends on subsistence agriculture, fishing, aquaculture [3]. Vulnerable places experience damage of property, lives, and displacements. Aside from the direct losses, insecurity of food, lacking opportunity of employment, and health impairments are exacerbated by coastal hazards. Additional socio-economic impact is mainly accrued by developing nations due to low challenges to adaptation and high mitigations strategies [4]. Over the decades, South Asia has experienced recurrent hazards related to tropical cyclones. The area is identified as a hotspot characterized by high population density, poverty, low development level, and exclusion [5]. In the north Indian Ocean region, Bay of Bengal (BoB) alone accounts for 7% of all global cyclones of the world [6]. Historically, coastal zones of India have attracted people due to port facilities, prosperity in agriculture,
tourism, industries, trades, transport benefits, and habitable ecology [7, 8]. However, these regions are vulnerable zones due to the coincidence of low elevation, storm surges, floods, saline intrusion, coastal erosion [9], and other environmental challenges leading to infectious diseases and mortality [10, 11].

The coastal population of Indian subcontinent experience variety of coastal hazards of which cyclone is the most destructive one. With nearly 137 million populations [12] residing along with the BoB coastal districts and higher frequencies of depression-cyclonic storms, the coast is quite vulnerable as compared to the Arabian Sea coast in India due to higher frequency of cyclone (4:1 ratio of cyclones in Bay of Bengal than the Arabian Sea cyclone), low flat coastal terrain, high population density, poor knowledge of community, inadequate response and preparedness and absence of any hedging mechanism [13]. Most recently, on 20th May 2020, the super cyclone *Amphan* lashed with 155 km/h, as tall as a two-story building on the Eastern coast and state of West Bengal in India [14]. The devastation was amplified with strong winds, tidal waves, and heavy rains that caused flooding across the deltaic regions, with an estimated economic loss of US$13.5 billion [15]. In the following year 2021, another cyclonic storm, named *Yaas*, intensified in the Bay of Bengal in May, and it has ravaged many parts of the apex of the BoB coast. India has witnessed severe to very severe cyclones: Laila, Helen, *Phailin, Hudhud, Vardah, Ockhi, Titli, Gaja, Amphan* and *Yaas* from 2010–2021 [16] As a result of cyclone hazard proneness, the Indian Coastal Zone (CRZ) has demarcated 500 m from the shoreline as coastal vulnerability zones. However, a buffer of 100 km perpendicular from the shoreline is measured for coastal vulnerability assessments considering the coastal geomorphology [17]. Literature suggests that, to escape from subsistence livelihood and poverty, aquaculture and industrialization have been introduced in these coastal regions, which had been the prime loop to coastal vulnerability [18].

Natural hazard vulnerability has a detrimental impact on human health, especially at conception and ending at the start of the third postnatal year (first 1000 days of life) [19–23]. Progressively, with the availability of satellite images and radar data, coastal hazard vulnerability assessments have soared [9, 17, 24–27]. However, a handful of scientists has conducted vulnerability assessment as a function of geomorphological, socio-economic, infrastructures, and other vectors [28, 29] The use of convoluted indices to understand the vulnerability has been adopted by many scholars like Cutter et al., 2006, who measured Social Vulnerability Index (SVI) using socio-economic and infrastructural indicators. Kim and Gim (2020) measured flood vulnerability and adaption along the Java coast, integrating the spatial regression model [31]. In India, Mazumdar and Paul (2016) and Sharma and Patwardhan (2008) measured the SVI due to cyclone with the principal component method. Scientists have studied the extreme effect of climate variability on health and mortality trajectories [34, 35]. Maternal exposure to cyclone increases the risk of having preterm [36–38] birth and consequently plays critical role in neonatal mortality [39, 40]. Past study observed that tropical storm increases the risk of illness, injuries and health needs [41]. The risk of disease transmission tends to heighten in developing countries due to population density, inadequate sanitation, and poor health facilities. The outbreak of gastroenteritis and diarrhoeal disease has been documented in the parts of West Bengal, India, after Cyclone Aila, 2008 [42, 43]. Other morbidities like acute respiratory diseases, leptospirosis have been reported following a cyclone in Orissa, India, in 1991 [44]. The extreme weather events have a significant impact on the health of a child [45, 46]. Female infant mortality was 15.1 times higher than males in a natural disaster as observed in Philippines [47]. Furthermore, a cross-country analysis of 12 developing countries indicated an increase in infant mortality due to the cyclone's long-term effect [48]. As cyclones have the potential to cause infant and under 5 mortality, empirical studies suggest that natural hazard-induced child mortality positively responds to higher fertility rates [49, 50].
The rich body of literature in this field mainly focused on different natural hazard vulnerability assessments or aftermath of extreme events. Studies in India are rare in this field, especially highlighting aggregate measurement of vulnerability based on public data and revealing the associations of vulnerability and child health. The present study, unique in its approach, aims to estimate vulnerability at coastal districts of the Bay of Bengal, consisting of 45 districts within a 100 km buffer zone along the coastline. We made progress on integrating the vulnerability and its effects on health by considering two crucial health indicators, i.e. neonatal and under-5 mortality. The study adds to the literature by providing additional evidence of socio-economic vulnerability as a function of exposure, adaptation, and sensitivity due to cyclones and its linkages to child mortality in India.

2. Methods

2.1 Study area

Districts less than 100 km from the coast line were considered coastal districts according to the definition of MDI [51]. A total of 45 districts were selected for this study (Fig. 1). The temperature of the study area exceeds 30º C and the region experience a high level of humidity. Annual rainfall ranges from 1,000 to 3,000 mm. Most of the cyclones here are developed either in the month of April to May (pre-monsoon season in the apex of BoB coast) or October to November (pre-winter season in the southern part of BoB coast).

2.2 Operational definition and analysis

Vulnerability is defined as "A function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" [52]. Total cyclone frequency, severe cyclone frequency, wind speed and shoreline length were considered in the calculation of cyclone exposure. Additionally, we included three components: sensitivity, demographics, agriculture and health. The components that help to adjust with different shocks like economic capacity and skills & infrastructure were considered to calculate the adaptive capacity as better-off households are able to recover the damages of the cyclones in a short period of time [53, 54] (Table 1). The vulnerability index was calculated using the universal normalization technique:

\[
X_{ij} = \left[ \frac{(X_{ij} - \text{Min}X_{ij})}{\text{Max}X_{ij} - \text{Min}X_{ij}} \right]
\]

Where \(X_{ij}\) refers to the normalized index value of the indicator, \(i\) represents indicators, \(j\) is the coastal district and \(\text{Min}X_{ij}\) and \(\text{Min}X_{ij}\) indicates the maximum and minimum value of the \(i\)th indicator among all the coastal districts. The value of the index varies from 0 to 1. Then, the composite vulnerability index was calculated using the equal weighting approach [55]. After normalizing all the indicators, the vulnerability index was derived as:

\[
M_j = \left[ \frac{\sum_{i=1}^{n} \text{Index}X_{ij}}{n} \right]
\]

Where \(M_j\) is the vulnerability index \(X_{ij}\) is the index value of the \(i\)th indicator for district \(j\), and \(n\) is the number of indicators considered to represent the index.
Table 1
Description and data source to measure cyclone hazard exposure, sensitivity, adaptive capacity and vulnerability.

| Determinants of vulnerability | Components | Indicators | Data source |
|-------------------------------|------------|------------|-------------|
| Hazard and Exposure | Characteristics of cyclone | Frequency of total cyclone | IMD report of cyclone by Government of India |
| | | Frequency of severe cyclone | |
| | | Wind speed in Knots | |
| | Coast length | Coastal length in (km) | Measured by authors using GIS |
| Sensitivity | Demographic sensitivity | Share of district population to total population of the state | Census of India, 2011 |
| | | Growth rate of the population during 2001–2011 | |
| | | Population density | |
| | | Percentage of rural population | |
| | | Percentage of female population | |
| | | Percentage of children (less than 6 years) | |
| | | Percentage of old people (above 60 years) | |
| | Agricultural sensitivity | Percentage of cultivator | Census of India, 2011 |
| | | Percentage of labourer | |
| | | Percentage of gross sown area | Land use statistics |
| | Health sensitivity | Crude death rate | Districtsofindia.com |
| | | Percentage of stunting children | National Family Health Survey (NFHS), round 4 |
| Adaptive capacity | Economic capacity | Economic development Index | Mohanty, S. K., Dash, A., Mishra, R. S., & Dehury, B. (2019) |
| | Skills & Infrastructure | Hospital available per 100000 population | Data.gov.in |
| | | Road density | Brief Industrial Profile of different districts, Ministry of MSME |
| | | Average number of bank per 100000 population | |
| | | Total number of small scale industries in each district | |
| | | Electricity | Census of India, 2011 |
| | | Pucca house | |

Compiled by Authors
The fourth round of the National Family Health Survey (NFHS-4), the landmark Demographic Health Survey (DHS) in India, was used to estimate neonatal and under-5 mortality at the district level, considering the information of 69,971 children in the study area [56]. The mortality rate was calculated using the information of the date of birth of the child, their survival status and age at death of the deceased child. The synthetic cohort probability approach was applied to estimate the neonatal mortality rate (NMR) and under-5 mortality rate (U5MR) for the ten years preceding the survey using the full birth history information of women aged 15–49. The total population of the districts were taken from the Census of India, 2011.

Scatter plots were used to establish the association between coastal vulnerability and neonatal and under-5 mortality in coastal districts of BoB. Finally, linear regressions, Spatial Lag Model (SLM) and Spatial Error Model (SEM) were used to find out the empirical association between coastal vulnerability and neonatal and under-5 mortality. SLM and SEM helped to adjust the spatial endogeneity and provide a refined measure.

3. Results

3.1 Vulnerability

In India, the number of cyclones, especially severe cyclones, increased considerably over the last decade (Fig. 2b). Meanwhile, a large number of people were displaced as a result of these disasters, notably in 2012 (Fig. 2a), when more than 9 million people were displaced. More than 5 million people in India were displaced by natural catastrophes in 2019, accounting for the highest number of new internal movements in the world [57].

The districts located in the apex part of BoB were more prone to coastal cyclone vulnerability than the southern part (Table 2). The highest degree of exposure was observed in districts of West Bengal. A very high degree of sensitivity was noted in Kendrapara, followed by Gajapati, Thiruvarur and Baleswar because of the higher degree of demographic, agricultural and health sensitivity. Adaptability was higher in the districts of Chennai and Calcutta. This study demonstrated a high vulnerability index in South 24 Parganas district, followed by Baleswar, Purba Medinipur, Kendrapara, Srikakulam and Bhadrak. Chennai had the lowest vulnerability index due to its higher adaptive capacity.

Table 2. Vulnerability, exposure, sensitivity and adaptive capacity in Costal area of Bay of Bengal: District level summary
### 3.2 Neonatal and under-5 mortality

Figure 3 depicts the spatial distribution of neonatal and under-5 mortality rate (per 1000 live births) across 45 coastal districts of BoB. It is worth mentioning that a similar heterogeneity pattern remains in the case of both NMR and U5MR. The spatial pattern of NMR shows very high occurrence in most districts of Odisha, much higher than the national level, i.e. NMR and U5MR for India were 30 and 50 deaths per live births in India. On the contrary, a lower NMR was observed in Chennai and Kolkata, the megacities of the study area. However, in the
districts of Gajapati, Nayagarh, Prakasam, Kendujhar, Srikakulam, East Godavari, Puri, Jajapur and South 24 Parganas, NMR and U5MR surpassed India's average.

### 3.3 Association of NMR and U5MR with vulnerability

Figure 4 depicts the result of the scatter plot between the coastal vulnerability with neonatal and under-5 mortality rates. The radius of the circles represents the volume of total population of the district. Districts with higher levels of coastal vulnerability had higher rates of neonatal mortality and under-five mortality. The study found a positive association though the relationship was weaker in the NMR relative to U5MR.

OLS regression was applied to examine the effects of coastal vulnerability on child survival after adjusting other socio-economic components (Table 3). The coefficient of under-5 mortality was higher with coastal vulnerability index ($\beta = 67.58$, p value = 0.00) as compared to neonatal mortality ($\beta = 52.3$, p value = 0.00). Among the covariates, the prevalence of diarrhoea among children was significantly associated with neonatal and under-5 mortality across coastal districts of BoB. In addition, the proportion of using unimproved sanitation facility ($\beta = 0.26$, p value = 0.04) and unimproved sources of drinking water ($\beta = 0.36$, p value = 0.03) showed a significant positive association with district-level under-5 mortality rate.

**Table 3.** Estimated Effect of Coastal vulnerability and child mortality in BoB coastal districts, India: regression models
| Predictors                      | Neonatal mortality | Under-5 mortality |
|--------------------------------|--------------------|-------------------|
|                                | OLS                | SLM               | SEM               | OLS               | SLM               | SEM               |
| Coastal vulnerability         | 46.98** (17.52)    | 43.54*** (15.98)  | 44.86*** (17.33)  | 57.84** (22.52)   | 51.77** (20.77)   | 52.34** (22.03)   |
| Unimproved drinking water     | 0.15 (0.12)        | 0.14 (0.11)       | 0.09 (0.13)       | 0.30 (0.16)       | 0.28** (0.14)     | 0.31 (0.16)       |
| Prevalence of diarrhoea       | 0.52 (0.39)        | 0.61 (0.34)       | 1.05*** (0.30)    | 0.93 (0.50)       | 1.03** (0.44)     | 1.41*** (0.41)    |
| Unimproved sanitation         | 0.20* (0.10)       | 0.21** (0.09)     | 0.25*** (0.09)    | 0.22 (0.13)       | 0.24** (0.11)     | 0.30** (0.12)     |
| Proportion of Hindu           | -0.22 (0.16)       | -0.24 (0.14)      | -0.24 (0.13)      | -0.29 (0.21)      | -0.34 (0.19)      | -0.35 (0.17)      |
| Proportion of ST              | 0.06 (0.13)        | 0.03 (0.12)       | 0.02 (0.12)       | 0.32 (0.17)       | 0.27 (0.15)       | 0.26 (0.15)       |
| Proportion of full ANC        | -0.08 (0.14)       | -0.06 (0.12)      | 0.07 (0.11)       | -0.18 (0.18)      | -0.14 (0.16)      | -0.05 (0.15)      |
| Proportion of no vaccination  | -0.24 (0.13)       | -0.26** (0.12)    | -0.32*** (0.10)   | -0.31 (0.17)      | -0.32** (0.15)    | -0.32** (0.13)    |
| Constant                      | 16.28 (20.19)      | 13.63 (17.87)     | 2.84 (16.29)      | 33.72 (25.94)     | 30.67 (22.88)     | 24.25 (21.74)     |
| \(P\)                         | 0.15               | 0.15              | 0.15              | 0.15              | 0.15              | 0.37              |
| \(\Lambda\)                  | 0.48               |                   |                   | 0.48              |                   | 0.37              |
| \(\text{AIC}\)               | 331.53             | 332.81            | 327.22            | 354.11            | 355.15            | 351.07            |
| \(R^2\)                      | 0.47               | 0.47              | 0.56              | 0.60              | 0.61              | 0.64              |

OLS-Ordinary Least Square Model, SLM-Spatial Lag Model, SEM-Spatial Error Model; Standard errors in parentheses, *** p < 0.01, ** p < 0.05

The result of SEM showed a spatial association between coastal vulnerability and NMR - U5MR. Of the two spatially estimated models, the study found a lower AIC value for the SEM model. With respect to neonatal mortality, the coefficient was largest for coastal vulnerability \((\beta = 44.86, p \text{ value} = 0.00)\). Further, the coastal vulnerability was significantly associated with under-5 mortality \((\beta = 52.34, p \text{ value} = 0.01)\). In the spatial lag model, a 10-point increase in unimproved sources of drinking water across the districts was associated with a 3-point increase in U5MR. In addition, diarrhoea among children was significantly associated with NMR \((\beta = 1.05, p \text{ value} = 0.03)\) and U5MR \((\beta = 1.41, p \text{ value} = 0.00)\). Also, unimproved sanitation facilities \((\beta = 0.28, p \text{ value} = 0.04)\) was a strong predictor of NMR \((\beta = 0.25, p \text{ value} = 0.00)\) and U5MR \((\beta = 0.35, p \text{ value} = 0.00)\) in these spatial models. Similarly, a 10-point increase in coverage of child vaccination was associated with a 3-point decrease in
NMR and U5MR. We observed that the U5MR model showed a greater AIC value with a pseudo R square value of 0.64 than the NMR model across 45 coastal districts of BoB.

4. Discussions And Conclusion

IPCC has declared that climate change has a very high confidence in disease's global burden [58]. Further climate change, sea level rise to one meter in the present century has intensified cyclone affecting the socio-economic and culture cohesion through displacement of coastal communities [59]. A large proportion of rural population in India lives near the coastline, depends on agriculture, fishery and forestry. Almost every year, moderate to severe cyclone hits the coastal districts of BoB, leading to significant cause of economic and human loss. In this context, our estimates highlight several important issues related to coastal vulnerability and its linkages with neonatal-child mortality in BoB coast of India.

The paper analyses the vulnerability level of the east coastal districts or BoB coast of India stretching for 1400 km and supporting large number of rural populations as well as some important cities and state capitals. Findings reveal that northern districts located close to the apex of BoB are more prone to exposure of vulnerability of coastal cyclones as compared to the southern part. The reasons are varying; first, the topography of the northern part of BoB bordering West Bengal and Odisha are flatter than the southern part where eastern hills stand along the coastline; second, the funnel shape apex of the BoB exactly collides with the northern coast (along with Bangladesh), that helps intensification of wind speed [9]; third, the urban proportion of southern districts are more and thus it has better adaptive capacity, as revealed in the estimate. Poor adaptive capacity attributed to the high degree of vulnerability in selected districts is mostly rural, agrarian, and generally located in West Bengal, Odisha, and parts of Andhra Pradesh.

The study establishes that the districts with a higher degree of coastal vulnerability experience a higher neonatal and under-5 mortality rate. Further, under-5 mortality is more strongly associated with the coastal vulnerability index in the districts of BoB as compared to neonatal mortality rate. Exposure to climate shocks like cyclones is harmful to young children as the shocks lead to reduced food intake and increased infectious diseases. In addition to economic hardship, medical access and utilization are also compromised during such catastrophize affecting the children disproportionately [60–63]. Therefore, it is essential to understand whether climate change poses a threat to children's health, and if so, where support is most needed. In the coastal districts, water and waste disposal quality in terms of drinking water and sanitation facility are the major determinants of child's survival. The drinking water and sanitation help to improve people's overall health and quality of life [64–66]. The risk of communicable diseases among vulnerable communities is due to the water and unimproved sanitation facilities [67]. The evidence from Amphan, 2020 affected areas of Bangladesh has reported an increase in the number of diarrhoea and skin disorders due to the usage of polluted pond water as their primary source of water for varying use. In addition, people also suffered from dysentery, jaundice, and eye irritation after the said cyclone [68]. Few studies undertaken in India reveals that excessive precipitation is associated with an increased risk of contracting water borne diseases such as diarrhoea among children under five [69]. Furthermore, Bhattacharjee et al. 2010 has reported an increase of Vibrio fluvialis (diarrhoea) along the cyclone affected areas after Aila, 2009 cyclone [70]. Indeed, the present study substantiates the findings of Dimitrova and Bora (2020) by revealing that in these coastal districts of India, the quality of water and waste disposal in terms of drinking water and sanitation facility are the major determinants of child's survival [69]. So, it is evident that due to coastal cyclones, the water-sanitation facilities are not up to the mark that leads to higher mortality.
WHO and UNICEF recommends measles vaccination and Vitamin-A supplements for children during an emergency [71]. In India, after any major disasters, the government organized mass vaccination campaigns to limit the spread of infection and fatality [72]. However, Mallik et al (2011) identified major geographical, infrastructural constraints for mass measles vaccination campaigns in the Aila cyclone-affected areas [73]. In general, India's healthcare infrastructure, manpower and accessibility are inadequate, especially in remote areas [74] and this could promote child mortality in vulnerable districts.

The present study has adopted an innovative approach to estimate vulnerability index. The most common weakness of the pre-existing studies of vulnerabilities in India is the use of satellite data. Here, we used existing credible secondary data from well established sources to compute the index. Through this measure, considering sensitivity, exposure and adaptive capacity, we identified the problem, quantified it, and assessed the index value in formulating development strategies to reduce the risk and vulnerabilities. In the context of increasing frequency and severity of coastal cyclone, the need of the hour to have better planning and protection strategies for Indian coast to safeguard coastal environment, human health, and livelihoods.

The policies related to climate change and coastal vulnerability in India are lacking in implementation. A recent research on climate change strategies, covering 136 coastal cities in 68 countries, observed the lack of effective climate change adaptation policies with no signs of implementation in nearly half the cases. Six major Indian coastal cities were included in the analysis of which three are from the BoB coast, i.e. Chennai, Visakhapatnam and Kolkata. For six Indian cities, only eight policies were identified by the team, which explicit inclusion of plans to prepare for the impacts of climate change; a plan at the national level, six at state and only one at local level (for Gujarat in the West Coast of India). This exhibits the lack of concrete measures at the city government stage [75].

Overall, current policies in India are not adequate to deal with the challenges of coastal vulnerabilities. The issue of displacement is addressed mostly as a post-disaster response, while there is a serious need for more comprehensive national and state polices on forestall managed adaptation for at-risk coastal populations. Early response mechanism and safeguarding households especially those with small children in terms of water sanitation, immunization, safety during such climate catastrophe are essential in areas where cyclone vulnerability is high in India.

**Declarations**

**Acknowledgement**

We are thankful to the Editor and reviewers for their encouraging comments that helped us to revise the manuscript. The authors would like to thank International Institute for Population Sciences (IIPS), Office of the Registrar General & Census Commissioner and India Meteorological Department (IMD) for providing publicly accessible data.

**Contribution statement**

Arup Jana: conceptualization, mapmaking, analysis, writing.

Subhojit Shaw: writing and analysis
Aparajita Chattopadhyay: conceptualization, writing, editing.

**Ethical approval and Consent to participate**

The analysis is based on secondary data available in the public domain for research; thus, no approval was required from any institutional review board (IRB).

**Competing of interests**

The authors declare that they have no conflict of interests.

**Funding**

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

**Availability of data and materials**

The datasets used in the study are available at the following links:

NFHS: [http://rchiips.org/nfhs/factsheet_nfhs-4.shtml](http://rchiips.org/nfhs/factsheet_nfhs-4.shtml), Census data: [https://censusindia.gov.in/](https://censusindia.gov.in/)

IMD data: [https://mausam.imd.gov.in/imd_latest/contents/cyclone.php](https://mausam.imd.gov.in/imd_latest/contents/cyclone.php) and MSME report: [https://msme.gov.in/](https://msme.gov.in/).

**References**

1. Deo AA, Ganer DW. Tropical cyclone activity over the Indian Ocean in the warmer climate. InMonitoring and prediction of tropical cyclones in the Indian Ocean and climate change. 2014 (pp. 72-80). Springer, Dordrecht.

2. United Nations Environment Programme (UNEP) With a Foreword by Kofi Annan, UN Secretary-General. Global Environment Outlook 3: past, present and future perspectives. Environmental Management and Health. 2002 Dec 1;13(5):560-1.

3. UCS. Impacts of global warming: people, health. Climate Hot Map: Global warming effects around the world. Union of Concerned Scientists, United States of America. 2011

4. Wiek A, Ries R, Thabrew L, Brundiers K, Wickramasinghe A. Challenges of sustainable recovery processes in tsunami affected communities. Disaster Prevention and Management: An International Journal. 2010 Aug 31.

5. Khadria B. Migration in South and South-West Asia. :23.

6. Sahoo B, Bhaskaran PK. Assessment on historical cyclone tracks in the Bay of Bengal, east coast of India. International Journal of Climatology. 2016 Jan;36(1):95-109.

7. Rani M, Rehman S, Sajjad H, Chaudhary BS, Sharma J, Bhardwaj S, Kumar P. Assessing coastal landscape vulnerability using geospatial techniques along Vizianagaram–Srikakulam coast of Andhra Pradesh, India. Natural Hazards. 2018 Nov;94(2):711-25.

8. Harley CD, Randall Hughes A, Hultgren KM, Miner BG, Sorte CJ, Thomber CS, Rodriguez LF, Tomanek L, Williams SL. The impacts of climate change in coastal marine systems. Ecology letters. 2006 Feb;9(2):228-
9. Nicholls RJ, Wong PP, Burkett V, Codignotto J, Hay J, McLean R, Ragoonaden S, Woodroffe CD, Abuodha PA, Arblaster J, Brown B. Coastal systems and low-lying areas. 2007.

10. Dasgupta S, Huq M, Wheeler D. Drinking water salinity and infant mortality in coastal Bangladesh. Water Economics and Policy. 2016 Mar 11;2(01):1650003.

11. Ramasamy R, Surendran SN. Possible impact of rising sea levels on vector-borne infectious diseases. BMC infectious diseases. 2011 Dec;11(1):1-6.

12. Registrar General, I. Census of India 2011: provisional population totals-India data sheet. Office of the Registrar General Commissioner. 2011 https://censusindia.gov.in/2011census/population enumeration.html. Accessed 6 Jul 2021.

13. Rangachari, R., Kanija, V.K., Gupta, AC. And Baweja. Water resources development scenario in India. CWC, MoWR, GoI. 2011.http://cwc.gov.in/water-info. Accesssed 6 Jul 2021.

14. Ahammed KB, Pandey AC. Characterization and impact assessment of super cyclonic storm AMPHAN in the Indian subcontinent through space borne observations. Ocean & Coastal Management. 2021 May 1;205:105532.

15. Baidya DK, Maitra S, Bhattacharjee S. Facing post-cyclone disaster in times of COVID-19 Pandemic in India: possible testing strategy to reduce further spread of disease. Asia Pacific Journal of Public Health. 2020 Sep;32(6-7):376.

16. Giribabu D, Muvva VR, Joshi NK, Rao SS. Assessment of epidemiological implications due to serial tropical cyclones in India: introspecting the recent sanitation interventions. Disaster medicine and public health preparedness. 2021 Apr;15(2):181-90.

17. Kantamaneni K, Sudha Rani NN, Rice L, Sur K, Thayaparan M, Kulatunga U, Rege R, Yenneti K, Campos LC. A systematic review of coastal vulnerability assessment studies along Andhra Pradesh, India: A critical evaluation of data gathering, risk levels and mitigation strategies. Water. 2019 Feb;11(2):393.

18. Kumaran M, Ghoshal TK, De D, Biswas G, Raja RA, Anand PS, Panigrahi A, Vijayan KK. Aquaculture-based production systems for the livelihood security of coastal farm families in the risk-prone agro-ecosystem of India: an appraisal. Aquaculture International. 2020 Apr;28(2):805-14.

19. Nowak-Szczepanska N, Gomula A, Chakraborty R, Koziel S. Nutritional and weight status of Indian mother-child dyads experienced by a natural disaster. Maternal & Child Nutrition. 2021 Jul;17(3):e13164.

20. Shaw J, Taylor RB, Forbes DL, Ruz MH, Solomon S. Sensitivity of the coasts of Canada to sea-level rise. Ottawa: Geological Survey of Canada; 1998 Dec 31.

21. Klein RJ, Nicholls RJ. Assessment of coastal vulnerability to climate change. Ambio. 1999 Mar 1:182-7.

22. Hennecke WG, Greve CA, Cowell PJ, Thom BG. GIS-based coastal behavior modeling and simulation of potential land and property loss: implications of sea-level rise at Collaroy/Narrabeen Beach, Sydney (Australia). Coastal Management. 2004 Oct 1;32(4):449-70.

23. Abuodha PA, Woodroffe CD. Assessing vulnerability to sea-level rise using a coastal sensitivity index: a case study from southeast Australia. Journal of coastal conservation. 2010 Sep;14(3):189-205.

24. Marghany M, editor. Applied Studies of Coastal and Marine Environments. BoD–Books on Demand; 2016 Sep 14.
25. Cazenave A, Llovel W. Contemporary sea level rise. Annual review of marine science. 2010 Jan 15;2:145-73.
26. Jiang L, Huang X, Wang F, Liu Y, An P. Method for evaluating ecological vulnerability under climate change based on remote sensing: A case study. Ecological Indicators. 2018 Feb 1;85:479-86.
27. Rani M, Rehman S, Sajjad H, Chaudhary BS, Sharma J, Bhardwaj S, Kumar P. Assessing coastal landscape vulnerability using geospatial techniques along Vizianagaram–Srikakulam coast of Andhra Pradesh, India. Natural Hazards. 2018 Nov;94(2):711-25.
28. Brown JM, Morrissey K, Knight P, Prime TD, Almeida LP, Masselink G, Bird CO, Dodds D, Plater AJ. A coastal vulnerability assessment for planning climate resilient infrastructure. Ocean & Coastal Management. 2018 Sep 1;163:101-12.
29. Ružić I, Dugonjić Jovančević S, Benac Č, Krvavica N. Assessment of the Coastal Vulnerability Index in an area of complex geological conditions on the Krk Island, Northeast Adriatic Sea. Geosciences. 2019 May;9(5):219.
30. Cutter SL, Boruff BJ, Shirley WL. Social vulnerability to environmental hazards. Social science quarterly. 2003 Jun;84(2):242-61.
31. Kim J, Gim TH. Assessment of social vulnerability to floods on Java, Indonesia. Natural Hazards. 2020 May;102(1):101-14.
32. Mazumdar J, Paul SK. Socioeconomic and infrastructural vulnerability indices for cyclones in the eastern coastal states of India. Natural Hazards. 2016 Jul;82(3):1621-43.
33. Sharma U, Patwardhan A. Methodology for identifying vulnerability hotspots to tropical cyclone hazard in India. Mitigation and adaptation strategies for global change. 2008 Aug;13(7):703-17.
34. Grace K, Davenport F, Hanson H, Funk C, Shukla S. Linking climate change and health outcomes: Examining the relationship between temperature, precipitation and birth weight in Africa. Global Environmental Change. 2015 Nov 1;35:125-37.
35. De Waal A, Taffesse A, Carruth L. Child survival during the 2002–2003 drought in Ethiopia. Global public health. 2006 Jun 1;1(2):125-32.
36. Xiong XU, Harville EW, Buekens P, Mattison DR, Elkind-Hirsch K, Pridjian G. Exposure to Hurricane Katrina, post-traumatic stress disorder and birth outcomes. The American journal of the medical sciences. 2008 Aug 1;336(2):111-5.
37. Sun S, Weinberger KR, Yan M, Anderson GB, Wellenius GA. Tropical cyclones and risk of preterm birth: a retrospective analysis of 20 million births across 378 US counties. Environment International. 2020 Jul 1;140:105825.
38. Grabich SC, Robinson WR, Engel SM, Konrad CE, Richardson DB, Horney JA. Hurricane Charley exposure and hazard of preterm delivery, Florida 2004. Maternal and child health journal. 2016 Dec;20(12):2474-82.
39. Simmons LE, Rubens CE, Darmstadt GL, Gravett MG. Preventing preterm birth and neonatal mortality: exploring the epidemiology, causes, and interventions. InSeminars in perinatology 2010 Dec 1 (Vol. 34, No. 6, pp. 408-415). WB Saunders.
40. Baqui AH, Rosen HE, Lee AC, Applegate JA, El Arifeen S, Rahman SM, Begum N, Shah R, Darmstadt GL, Black RE. Preterm birth and neonatal mortality in a rural Bangladeshi cohort: implications for health programs. Journal of Perinatology. 2013 Dec;33(12):977-81.
41. Waring S, Zakos-Feliberti A, Wood R, Stone M, Padgett P, Arafat R. The utility of geographic information systems (GIS) in rapid epidemiological assessments following weather-related disasters: Methodological issues based on the Tropical Storm Allison experience. International Journal of Hygiene and Environmental Health. 2005;208:109–16.

42. Bhunia R, Ghosh S. Waterborne cholera outbreak following Cyclone Aila in Sundarban area of West Bengal, India, 2009. Transactions of The Royal Society of Tropical Medicine and Hygiene. 2011;105:214–9.

43. Panda S, Pati KK, Bhattacharya MK, Koley H, Pahari S, Nair GB. Rapid situation & response assessment of diarrhoea outbreak in a coastal district following tropical cyclone AILA in India. The Indian journal of medical research. 2011 Apr;133(4):395.

44. Sehgal SC, Sugunan AP, Vijayachari P. Outbreak of leptospirosis after the cyclone in Orissa. National Medical Journal of India. 2002 Feb;15(1):22-3.

45. Loftus C, Afsharinejad Z, Sampson P, Vedal S, Torres E, Arias G, Tchong-French M, Karr C. Estimated time-varying exposures to air emissions from animal feeding operations and childhood asthma. International journal of hygiene and environmental health. 2020 Jan 1;223(1):187-98.

46. Evans RW, Hu Y, Zhao Z. The fertility effect of catastrophe: US hurricane births. Journal of Population Economics. 2010 Jan;23(1):1-36.

47. Anttila-Hughes J, Hsiang S. Destruction, disinvestment, and death: Economic and human losses following environmental disaster. Available at SSRN 2220501. 2013 Feb 18.

48. Miranda I. The Long-run Effects of Tropical Cyclones on Infant Mortality.2019. Master's Theses. 1187.

49. Finlay J. Fertility response to natural disasters: the case of three high mortality earthquakes. World Bank Policy Research Working Paper. 2009 Mar 1(4883).

50. Nobles J, Frankenbarg E, Thomas D. The effects of mortality on fertility: population dynamics after a natural disaster. Demography. 2015 Feb 1;52(1):15-38.

51. India Meteorological Department. Electronic Atlas of Tracks of Cyclones and Depressions in the Bay of Bengal and the Arabian Sea, Version 1.0/2008” CD Rom, India Meteorological Department, Chennai. 2008.

52. Brooks N. Vulnerability, risk and adaptation: A conceptual framework. Tyndall Centre for climate change research working paper. 2003 Sep;38(38):1-6.

53. Abdullah AN, Zander KK, Myers B, Stacey N, Garnett ST. A short-term decrease in household income inequality in the Sundarbans, Bangladesh, following Cyclone Aila. Natural Hazards. 2016 Sep;83(2):1103-23.

54. Burslem DF, Whitmore TC, Brown GC. Short-term effects of cyclone impact and long-term recovery of tropical rain forest on Kolombangara, Solomon Islands. Journal of Ecology. 2000 Dec;88(6):1063-78.

55. Soares MB, Gagnon AS, Doherty RM. Conceptual elements of climate change vulnerability assessments: a review. International Journal of Climate Change Strategies and Management. 2012 Feb 24.

56. IIPS and ICF. National Family Health Survey (NFHS-4), 2015-16. International Institute for Population Sciences (IIPS), Mumbai, India. 2017.

57. Woodward A, Smith KR, Campbell-Lendrum D, Chadee DD, Honda Y, Liu Q, et al. Climate change and health: on the latest IPCC report. The Lancet. 2014;383:1185–9.

58. IDMC, 2020. Global Report on Internal Displacement 2019. www.internal displacement.org/global-report/grid2019/
59. Oliver-Smith A. Sea level rise and the vulnerability of coastal peoples: responding to the local challenges of global climate change in the 21st century. UNU-EHS; 2009.

60. Adair LS, Fall CH, Osmond C, Stein AD, Martorell R, Ramirez-Zea M, Sachdev HS, Dahly DL, Bas I, Norris SA, Micklesfield L. Associations of linear growth and relative weight gain during early life with adult health and human capital in countries of low and middle income: findings from five birth cohort studies. The Lancet. 2013 Aug 10;382(9891):525-34.

61. Alderman H, Hoddinott J, Kinsey B. Long term consequences of early childhood malnutrition. Oxford economic papers. 2006 Jul 1;58(3):450-74.

62. Black RE, Allen LH, Bhatta ZA, Caulfield LE, De Onis M, Ezzati M, Mathers C, Rivera J, Maternal and Child Undernutrition Study Group. Maternal and child undernutrition: global and regional exposures and health consequences. The lancet. 2008 Jan 19;371(9608):243-60.

63. Hoddinott J. Shocks and their consequences across and within households in rural Zimbabwe. The Journal of Development Studies. 2006 Feb 1;42(2):301-21.

64. Dey NC, Parvez M, Islam MR, Mistry SK, Levine DI. Effectiveness of a community-based water, sanitation, and hygiene (WASH) intervention in reduction of diarrhoea among under-five children: Evidence from a repeated cross-sectional study (2007–2015) in rural Bangladesh. International journal of hygiene and environmental health. 2019 Sep 1;222(8):1098-108.

65. Prüss-Ustün A, Wolf J, Bartram J, Clasen T, Cumming O, Freeman MC, Gordon B, Hunter PR, Medlicott K, Johnston R. Burden of disease from inadequate water, sanitation and hygiene for selected adverse health outcomes: an updated analysis with a focus on low-and-middle-income countries. International journal of hygiene and environmental health. 2019 Jun 1;222(5):765-77.

66. Semba RD, de Pee S, Kraemer K, Sun K, Thorne-Lyman A, Moench-Pfanner R, et al. Purchase of drinking water is associated with increased child morbidity and mortality among urban slum-dwelling families in Indonesia. International Journal of Hygiene and Environmental Health. 2009;212:387–97. doi:10.1016/j.ijheh.2008.09.001.

67. Watson JT, Gayer M, Connolly MA. Epidemics after natural disasters. Emerging infectious diseases. 2007 Jan;13(1):1.

68. Rafa N, Jubayer A, Uddin SM. Impact of cyclone Amphan on the water, sanitation, hygiene, and health (WASH2) facilities of coastal Bangladesh. Journal of Water, Sanitation and Hygiene for Development. 2021 Mar;11(2):304-13.

69. Dimitrova A, Bora JK. Monsoon weather and early childhood health in India. PloS one. 2020 Apr 10;15(4):e0231479.

70. Bhattacharjee S, Bhattacharjee S, Bal B, Pal R, Niyogi SK, Sarkar K. Is Vibrio fluvialis emerging as a pathogen with epidemic potential in coastal region of eastern India following cyclone Aila?. Journal of health, population, and nutrition. 2010 Aug;28(4):311.

71. World Health Organization. WHO-UNICEF joint statement: reducing measles mortality in emergencies. World Health Organization; 2004.

72. Mohan A, Murhekar MV, Wairgkar NS, Hutin YJ, Gupte MD. Measles transmission following the tsunami in a population with a high one-dose vaccination coverage, Tamil Nadu, India 2004–2005. BMC Infectious Diseases. 2006 Dec;6(1):1-6.
73. Mallik S, Mandal PK, Ghosh P, Manna N, Chatterjee C, Chakrabarty D, Bagchi SN, Dasgupta S. Mass measles vaccination campaign in Aila cyclone-affected areas of West Bengal, India: an in-depth analysis and experiences. Iranian journal of medical sciences. 2011 Dec;36(4):300.

74. Shaw S, Sahoo H. Accessibility to Primary Health Centre in a Tribal District of Gujarat, India: application of two step floating catchment area model. GeoJournal. 2020 Apr;85(2):505-14.

75. Olazabal M, de Gopegui MR, Tompkins EL, Venner K, Smith R. A cross-scale worldwide analysis of coastal adaptation planning. Environmental Research Letters. 2019 Dec 11;14(12):124056.

**Figures**

Figure 1

BoB coastal districts of India affected by cyclones (100 km inland buffer). Source: Indian meteorological department, Government of India (IMD)
Figure 2

(a) Number of new displacements due to natural disaster in India; (b) Frequency of cyclones over BoB. Source: based on https://www.internal-displacement.org/countries/india; http://www.imdchennai.gov.in/cyclone_eatlas.htm

Figure 3
Spatial distribution of (a) neonatal mortality rate; (b) Under-5 mortality rate in coastal districts of BoB, 2015-16. Note: Number of districts follows as the base map (Fig.1) of the study. Source: NFHS4, prepared by authors.

**Figure 4**

Graphs visualizing the scatter plots between vulnerability and Neonatal mortality (a) and Under-5 mortality (b) across the BoB coastal districts of India. Note: Size of circle proportional to total population of the district, 2011. Number of districts follows as the base map (Fig.1) of the study. Source: prepared by Authors.