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REVIEW ARTICLE

Review on evolving cyclone patterns in Bay of Bengal: Challenges for coastal agriculture

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Abstract

Tropical cyclones (TCs) are among the most destructive weather phenomena. This review examines the trends and drivers of TC activity, focusing on the Bay of Bengal (BoB) region. Rising global temperatures have led to warmer sea surface temperature, a key factor in TC formation and intensification. The BoB experiences an average of 5-6 cyclone annually, with peak activity in May, October and November. But pre-monsoon cyclonic storms are fewer, a higher proportion of them intensify into severe storms. Overall cyclone frequency has declined; however, their intensity and duration have increased, potentially due to climate change. Climate oscillations like the Indian Ocean Dipole (IOD) and El Nino Southern Oscillation (ENSO) significantly influence TC variability. La Nina, Negative IOD phase and the convective phase of the Madden–Julian Oscillation (MJO) enhance conditions favourable for cyclone development. These changing patterns have profound implications for agriculture in the BoB region. Cyclones often coincide with critical crop stages, causing severe yield losses. Understanding the influence of climate drivers such as ENSO and IOD on tropical cyclone activity in the Bay of Bengal is essential for developing region-specific adaptation strategies, including climate-resilient agriculture, early warning systems and sustainable land use. Future research should integrate long-term monitoring, high-resolution modelling and remote sensing to assess cyclone variability and impacts on coastal ecosystems. Emphasis on ecosystem resilience and nature-based solutions such as mangrove restoration will be critical to strengthen adaptive management, disaster preparedness and resilience under climate change-driven cyclone risks.

Keywords: Bay of Bengal; climate change; coastal agriculture; North Indian Ocean; tropical cyclones

Introduction

Tropical cyclones (TCs) are among the most catastrophic environmental disasters, particularly in coastal areas. Given their destructiveness and annual frequency, they are considered the second most devastating natural disasters after earthquakes (1). Henry Piddington is credited with coining the term cyclone, which derives from the Greek word cyclos, meaning "coiling of a snake". A tropical weather system with wind speed of at least 62 km/hr are referred to as cyclones. Globally, TCs in the Atlantic, Pacific and Australian oceans are known as hurricanes, typhoons and Willy Willy, respectively (2). A cyclonic storm is a massive vortex or whirl in the atmosphere surrounded by extremely strong winds that travel anticlockwise in the northern hemisphere and clockwise in the southern hemisphere. These are extremely low-pressure areas inside the Earth-atmosphere system (3). TCs have caused over 1945 disasters around the past 50 years, causing 779324 fatalities and US$ 1.4 trillion in monetary losses. This makes up 17 % of weather, climate and water-related disasters and they account for 38 % of both fatalities and economic losses during the same time period (4, 5).

The destructive nature of TCs has been exacerbated by ongoing the growing climate change. The Inter-Governmental Panel on Climate Change (6) assessment report detailed the continuous rise in atmospheric concentrations of greenhouse gases (GHG) such as carbon dioxide, nitrous oxide and methane. By the end of the twenty-first century, the atmospheric concentration of CO_2 is predicted to increase from 478 to 1100 ppm. Increase in global temperature is apparent with rise in greenhouse gases. In a very low greenhouse gas emission scenario (SSP1-1.9), it is expected to result in an average global surface temperature increase of 1.0 to 1.8 °C during 2081-2100. In the intermediate scenario (SSP2-4.5), it might increase by 2.1 to 3.5 °C, while in the high gas emissions scenario (SSP5-8.5), it could rise by 3.3 to 5.7 °C. Extreme daily precipitation occurrences are predicted to increase by approximately 7 % for every 1 °C increase in temperature (6). The deadly effects of global warming include heavy precipitation (7), an increased risk of drought, prolonged dry spells and total dry days (8).

Over the past 20 years, there has been a significant increase in scientific interest regarding the impact of climate change on tropical cyclone (TC) activity (9, 10). An increasing amount of research points to a complicated interaction between these two phenomena, wherein the strength and frequency of TC may be amplified by climate change (11). Research by Swain (12) suggests that a warmer climate may lead to a possible rise in the percentage of the TC intensity. Furthermore, TC paths may vary because of climate change-related modifications to atmospheric circulation patterns, there by subjecting previously untouched regions to their fury (13). Consequently, they have emerged as a central concern in the societal discourse surrounding climate change (14-16).

Coastal areas offer fertile soil and favourable climatic conditions, making them highly suitable for agriculture. They contribute significantly to the economy by supporting food production and supplying raw materials for various industries. However, due to their geographic exposure, these regions are particularly vulnerable to the impacts of tropical cyclones. Over time, frequent cyclonic events have posed severe challenges to agricultural sustainability, infrastructure and livelihoods in coastal zones. Considering these vulnerabilities, this review focuses on understanding the trends and patterns of tropical cyclones, particularly within the context of a changing climate as crucial in developing a region specific resilient practice.

Tropical cyclone genesis and development

Prior to analysing cyclone patterns in the context of climate change, it is essential to establish an understanding of the conditions that govern their formation and development. TCs are formed through interactions between the ocean and atmosphere. They are mainly propelled by high planetary winds, easterly trade winds, temperate westerlies and their own intense energy, which is combined with the heat from the sea. This indicates that it requires certain prerequisites to become a cyclone. In a region between 5 and 30°N and °S of the equator, tropical oceans with sea surface temperature of at least 27 °C is the primary requirement for the formation of TCs (17). TCs are fuelled by warm ocean waters, which supply the necessary latent heat for their creation and intensification. A positive association between SST and TC activity has been found in studies by (14, 18), indicating that warmer waters are favourable for higher TC formation and intensity development. Thus, the crucial threshold for TC formation is commonly regarded as being >26 ° C (79 °F) in most basins. Interestingly, two tropical ocean basins *viz*., the Benguela Current in the South Atlantic and the Peru Current in the eastern South Pacific do not support tropical cyclones due to a lack of adequate warm waters (19).

Other factors include vertical wind shear *i.e*., strong winds moving from different directions at different altitudes, can upset the vertical structure of a nascent storm and prevent it from further development. On the other hand, weak vertical wind shear facilitates the rise and efficient cooling of warm, moist air, which releases the latent heat that drives the storm and helps it to intensify (20). Sustaining the development of a TC requires a lot of moisture in the lower atmosphere. As warm, humid air rises within the storm, it cools and condenses, producing latent heat that promotes convection and storm expansion. The evaporative potential and high humidity regions over warm ocean surfaces supply the moisture content required for TC formation (21) (Fig. 1). In addition, enough Coriolis force must exist at least 500 km away from the equator for near gradient wind balance to ensue. Due to convection and subsequent condensation of rising air above the ocean's surface, atmospheric instability also promotes the production of huge vertical cumulus clouds (22). As tropical storms intensify, the rising air forms into severe thunderstorms and spreads out horizontally at the tropopause level (23, 24). These disruptions frequently have low pressure and weak circulation, which provide an ideal setting for the growth of structured convection and movement (25, 26).

In the Indian Ocean, formation of tropical cyclone is categorised when the highest sustained wind speed hits 62 km/ hr and the pressure level around the centre drops by 5 to 6 hPa from the surrounding atmosphere. A mature tropical cyclone is characterized primarily by a concentric pattern of extremely turbulent cumulus thundercloud bands with a warm eye of

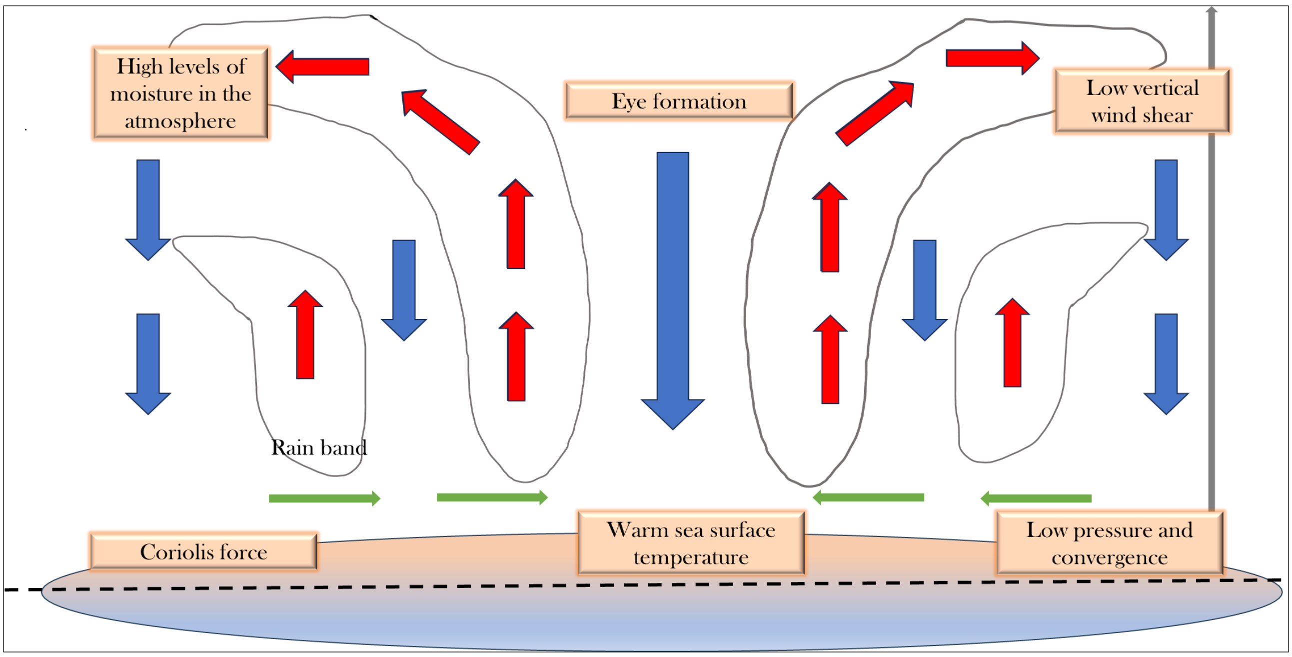

Fig. 1. Favourable conditions for genesis and development of tropical cyclones.

roughly 200 to 500 km in diameter (27, 28). As soon as a tropical cyclone's supply of warm and moist air starts to diminish or suddenly cut off, it loses strength in terms of its low pressure at centre, internal warmth and extremely fast speeds. This occurs when it crosses across frigid waters or after it touches down on land (2). Finally, a tropical cyclone can bring with it strong winds, copious amounts of rain, large waves and in certain situations, extremely severe storm surges and coastal flooding (29, 30).

Global scenario in tropical cyclones

The oceans are classified into several basins for cyclone-related studies. Western North Pacific (WNP), Eastern North Pacific (ENP), South Pacific Ocean (SPO), North Atlantic Ocean (NAO), North Indian Ocean (NIO), South Indian Ocean (SIO) and South Atlantic Ocean (SAO) are the seven basins. Agencies such as the World Meteorological Organisation (WMO) coordinating naming across basins, the India Meteorological Department for North Indian Ocean, the Japan Meteorological Agency (JMA) for Northwest Pacific and the National Hurricane Centre (NHC) for North Atlantic and Eastern North Pacific are the nodal agencies for naming cyclones depending on these basins.

Extreme tropical cyclone episodes have increased in frequency over the last few decades across all basins. It is widely recognised that TC intensity rises with global warming. From previous studies (31), there has been a consistent and significant rise in violent tropical storms (TCs) worldwide since 1970. This increase has been observed primarily in the North Pacific, Indian and Southwest Pacific oceans and may be associated with global warming. Every year, two to three storms make landfall in the North Atlantic (NA), with the highest sea surface temperature recorded during the period of August to October (32). An average of three to four storms is also recorded in the Northeastern Pacific (NEP). According to several research works (10, 33), there may be a rise in storm intensity in this changing change scenarios. With an average of 10 to 11 typhoons per year, the Northwest Pacific (NWP) is the most active basin among the other basins (34). Peak activity runs from May to November, with July and August month records the most activity in this region. On an average, eight cyclones occur in the North Indian Ocean (NIO) per year, of which three to four intensify into severe cyclonic storms (35). The peak cyclonic activity occurs during the period of April to May and October to November. Some studies suggest a potential increase in the severity of TCs in this region, despite trends being inconclusive. Among the basins, South Indian Ocean (SIO) is the least active region, which experiences only one or two strong cyclonic storms annually. Usually, the season lasts from November to April. There are hints of potential increases in TC activity despite the paucity of available data in this basin (36).

Scenario in the Bay of Bengal

Cyclonic activity in the North Indian Ocean (NIO) has drawn attention over the last five decades, because it is the site of nearly 60 % of global casualties due to intense rainfall, high storm surge and terrestrial flooding (37, 38). NIO encompasses both Arabian Sea and Bay of Bengal. India has a coastline of approximately 7516 km, of which about 5400 km is along the mainland. TCs affect the entire coast with variable frequencies and intensities. The disaster potential is very high upon landfall in both Bay of Bengal and Arabian Sea causing torrential rainfall, devastating wind and storm surges (39, 40). TCs affect 13 coastal states and Union Territories (UTs) across the country. Four east coast states *viz*., Tamil Nadu Andhra Pradesh, Odisha and West Bengal, as well as one union territory (Puducherry) and one west coast state (Gujarat), are especially vulnerable to tropical cyclone (41).

Despite being one of the most severely affected regions globally, most cyclones originate in the Bay of Bengal before striking India's east coast than in the Arabian Sea, with a ratio of 4:1 (42-44). BoB basin produced nearly 75 % of the tropical cyclone genesis in North Indian Ocean (45). Their impact is disproportionately severe and catastrophic, particularly when it affects the coasts bordering the north Bay of Bengal. According to National Cyclone Risk Mitigation Project (NCRMP) data, 58 % of cyclones created in the Bay of Bengal make landfall on the eastern coast (46). Several super cyclones with storm surges have occurred in the Bay of Bengal basin over the last two decades, causing more damage (Aila in 2009, Sidr in 2007 and Michaung in 2023), affecting coastal areas (Orissa Super Cyclone in 1999, Hudhud in 2014 and Bulbul in 2019), economic losses (Giri in 2010, Phailin in 2014 and Amphan in 2020).

Variability and trends in the BoB

Long-term trends in tropical cyclones

Tropical cyclones are classified based on their maximum sustained surface wind speed (MSW). This classification may differ from that of other global basins, such as the commonly used Saffir-Simpson hurricane wind scales in the Atlantic and Pacific basins. Table 1 shows the Indian classification of these low-pressure systems. Analysing the path of cyclones over BOB using the e-atlas accessible at India Meteorological Department (IMD), New Delhi (https://rsmcnewdelhi.imd.gov.in/), it is indicated that there are 254 cyclonic disturbances (wind speed exceeding 32 km/hr) and 96 severe cyclonic storms (wind speed exceeding 89 km/hr) generated across BoB between 1971 and 2020 (42). In recent decades, the number of SCS has declined significantly during 2001-2010 compared to 1971-1980 (Fig. 2). However, previous researchers (43) found that SCS increased by around 65 % during the warming period of 1951-2007 by investigating the genesis and severity of TCs over the NIO basin on a yearly basis. This may be related to the findings of former researchers (31), who discovered that the number and proportion of cyclones reaching SCS are increasing in almost all basins throughout the world, illustrating the impact of climate change. These analyses indicate that the trend in the frequency of severe cyclonic storms over BoB does not follow a similar

Table 1. Classification of cyclonic disturbances in the North Indian Ocean

Category	Wind speed (knot)	Wind speed (kmph)	Pressure deficit (hPa)
Depression (D)	17–27	31–49	1.0-3.0
Deep depression (DD)	28–33	50–61	3.0-4.5
Cyclonic storm (CS)	34–47	62–88	4.5-8.5
Severe cyclonic storm (SCS)	48–63	89–118	8.5-15.5
Very severe cyclonic storm (VSCS)	64–119	119–221	15.5-65.6
Super cyclonic storm (SuCS)	120 or more	222 or more	>65.6

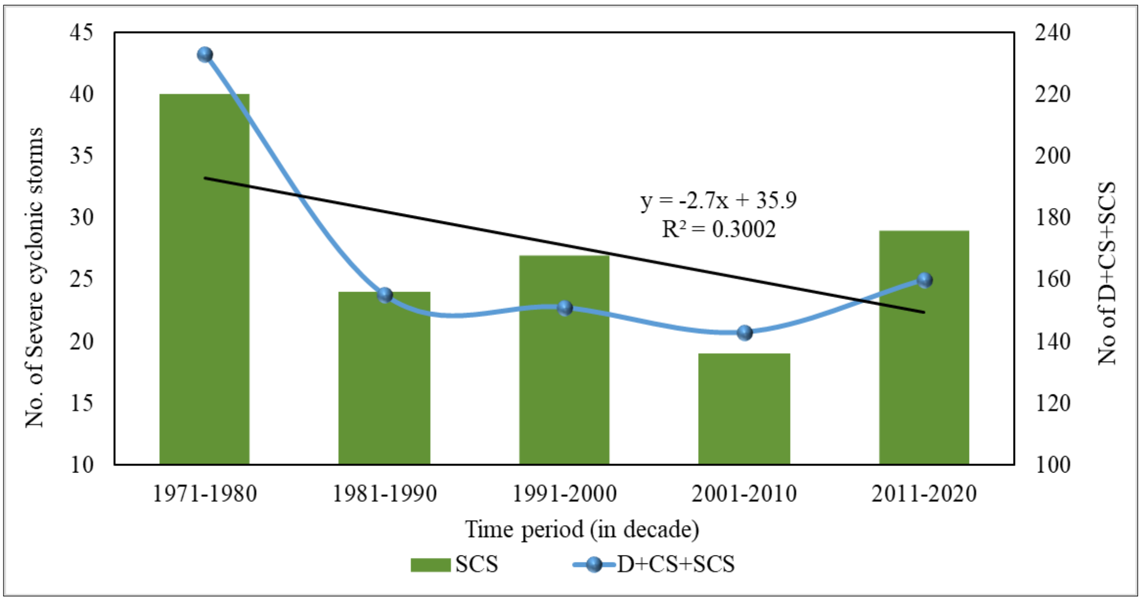

Fig. 2. Variation in decadal frequency of cyclonic disturbances or depressions (D), cyclonic storms (CS) and severe cyclonic storms (SCS) in the BoB region (smooth curved line). The bar diagrams depict SCS.

pattern over the decades.

Seasonal distribution and intensification of cyclones

The cyclonic systems may not form in every month of the year. Analysing the monthly distribution of these 3 different types of cyclonic systems for the period 1971-2020 reveals that months between May and December have the highest number of cyclones, with November being the most conducive month for the formation of SCS (Fig. 3). Approximately 80 % of cyclonic disturbances in April turn into extremely severe cyclonic storms, even though there are comparatively fewer cyclonic systems formed in this period. However, this transition is found to be 71 % in May and November. Each year, there is a 44.3 % and 61.0 % chance of depression intensifying into CS and CS intensifying into SCS (Fig. 4). However, the analysis of recent decades between 2001-2010 and 2011-2020 suggested that the percent chance of depression intensifying into CS (38.1 to 49.1 %) and CS intensifying into SCS (45.8 to 61.5 %) has been increased. This decadal rise in storm severity results in frequent strong storms disrupting wetland ecosystem, estuarine habitats and lead to prolonged saltwater intrusion, particularly along low-lying coastal zones such as Odisha and West Bengal.

Landfall and lifecycle patterns of tropical cyclones

In around half a century, 84 cyclones had made landfall (Fig. 5). Previous studies (47) showed that about 60 % of TCs produced over Bay of Bengal landfall in various locations along India's east coast, 30 % impact the coasts of Myanmar and Bangladesh and over 10 % dissipate over the ocean. This also shows that there is no conclusive trend in the number of landfalling cyclones in the Bay of Bengal over the decades. According to all this research, there was no apparent trend in the frequency of cyclones. Previous research (48) suggests that variations in the occurrence of extremely powerful tropical cyclones are not consistent across the world. Conversely, the decadal examination of RSMC data across the various cyclonic disturbance categories shows that the proportion of severe cyclonic storms has increased in the last ten years. The lifetime (lifecycle) of each cyclone occurred over BoB was studied using best track data available at RSMC for different decades (1991-2020). This data, recorded with the help of satellites, revealed that the lifecycle of cyclonic, severe cyclonic and very severe cyclonic storms has increased in recent decades (Fig. 6). This indicates their longer presence in the BoB basin which could affect coastal areas and other inland regions with torrential rainfall and storm surges (49). This result suggests that the BoB basin is being impacted by global warming (38, 50).

Globally, the strength of tropical cyclones will continue to increase with increases in intensity of 2 to 11 % by 2100 due to global warming, based on high-resolution dynamical models' future forecasts (10). However, most modelling studies forecast a drop in the overall frequency of global tropical cyclones coupled with a rise in the average number of severe category tropical cyclone in response to anthropogenic global warming (51, 52). According to the recent findings of previous studies (53), tropical cyclones are gaining momentum swiftly, getting more powerful and holding onto their strength for extended periods of time. In coastal and near-shore locations, slower tropical storms with longer durations were formed, resulting in more damage and impact over the coastal regions. Slow moving cyclones have the potential to do greater damage than those that move more quickly (54). According to recent studies, these cyclones have shown a tendency to stall near coastlines, increasing the duration of flooding and sediment erosion. Such trends not only degrade geomorphology but also affect coastal vegetation.

Factors influencing their variability

Indian Ocean Dipole (IOD)

Cyclonic storm formation and development can also be affected by various land and atmospheric oscillations *viz.*, IOD, ENSO, MJO and others *etc.*, The IOD, also known as the Indian Ocean Zonal Mode (IOZM), represents an important mode of climate variability in the Indian Ocean on inter-annual timescales (36). An IOD event typically begins in May/June, peaks in October-November and ends in the early months of the winter (December). The eastern tropical Indian Ocean and the western tropical Indian Ocean have water that is warmer rather than usual create a positive (+ve) and negative (-ve) IOD period. The modulation of oceanic and atmospheric conditions in the Indian Ocean region and around the world is significantly impacted by

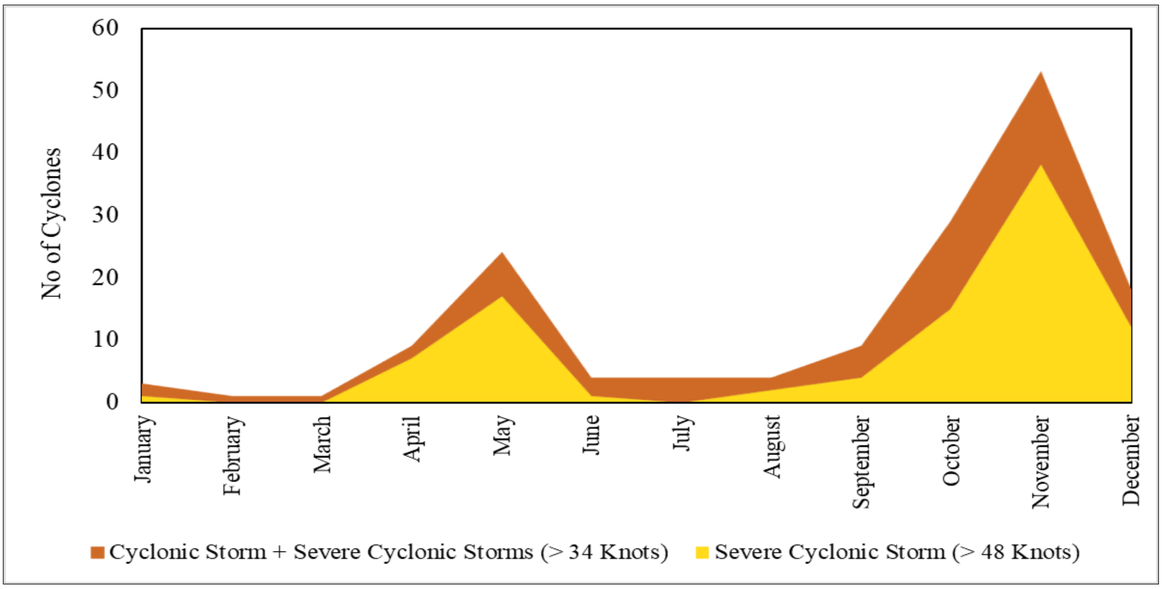

Fig. 3. Monthly frequency of cyclonic storms over the Bay of Bengal during 1971-2020.

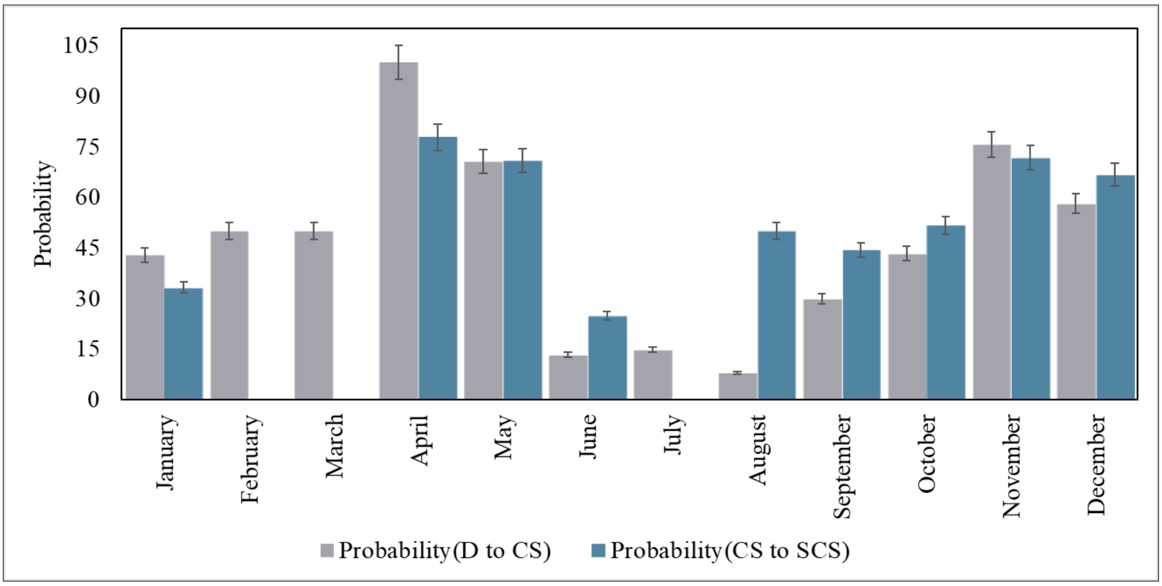

Fig. 4. Monthly probability of Intensification of D to CS and CS to SCS over the Bay of Bengal (*D-Depression, CS-Cyclonic Storm and SCS-Severe Cyclonic Storm*).

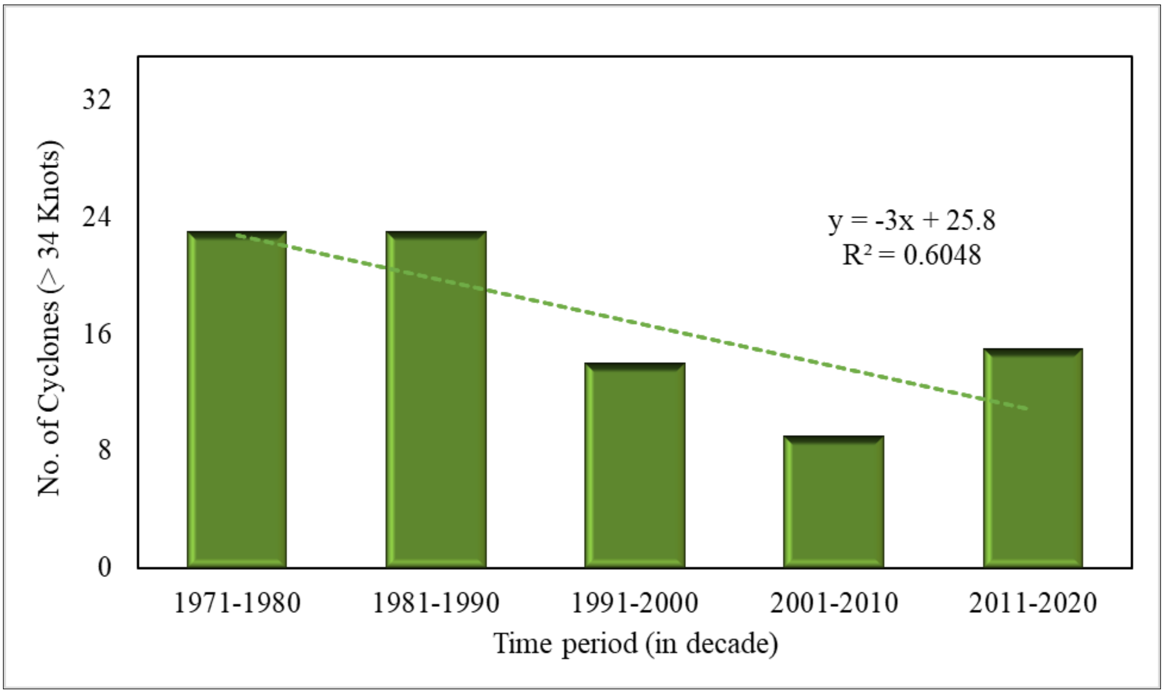

Fig. 5. Decadal variation in the number of landfalling cyclones (>62 km/h) over the Bay of Bengal.

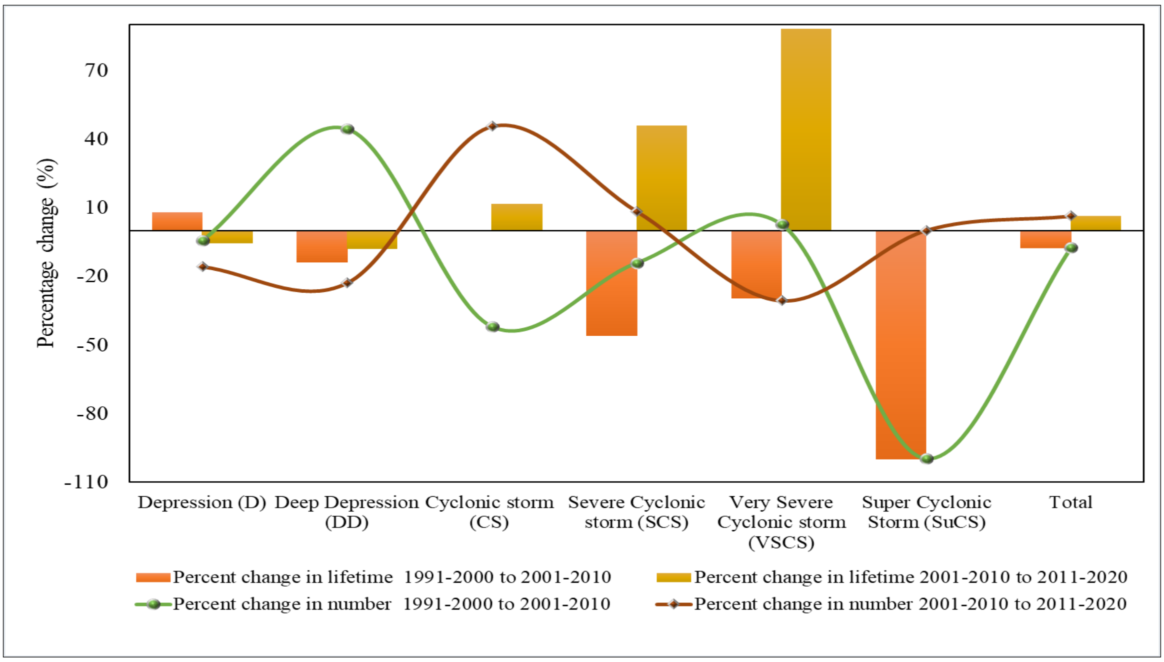

Fig. 6. Decadal changes in the number and lifetime of different tropical cyclone category over the Bay of Bengal.

this pattern of SST variability (55). Due to their differing sea surface temperature (SST) anomalies, tropical cyclones (TCs) in the BoB and the Indian Ocean Dipole (IOD) have a complex and varied interaction. The SST anomalies in the Indian Ocean follow an east-west dipole pattern, with the western and eastern tropical Indian Oceans exhibiting opposite anomalies. Studies confirmed that North Indian Ocean SST anomalies are cold in the west and warm in the east when the Indian Ocean is in the negative phase of the IOD. This can strengthen convection over the BoB and result in anomalous cyclonic atmospheric circulations at low levels. This increases the frequency of TC occurrences in the BoB and is favourable for TC generation. The Dipole Mode Index (DMI), which measures the SST gradient between the western and southeastern equatorial Indian Ocean, is used to represent these phases. When it is positive, it is referred to as positive IOD and vice versa. Correlation results between the number of cyclonic storms and DMI values indicate a negative relationship between them. It confirms the above statement of negative phase (negative values of DMI) of IOD being the favourable condition for the formation of frequent cyclonic activities in the BoB basin (Fig. 7). The findings from previous studies (55), also support that SST heating or cooling with a typical IOD pattern might alter air circulations, which in turn affect North Indian Ocean TC activity. For instance, Cyclone Amphan (2020) reached super cyclonic strength within 24 hrs, largely due to elevated SSTs and a concurrent marine heatwave in the BoB. Such rapid intensification allows minimal time for preparation and leads to widespread destruction of mangroves, as witnessed in the Indian Sundarbans, where canopy density dropped by over 40 % after repeated storms. IOD events impact basins TC activity by altering the conditions of TC genesis and by modifying the steering flow, which in turn impacts the trajectories of TCs. Positive or negative IOD occurrences can either strengthen or weaken the westerly steering flow over the BoB, resulting in fewer or larger westward migrating tropical cyclones west of 90°E (36, 56). In previous studies (31), IOD

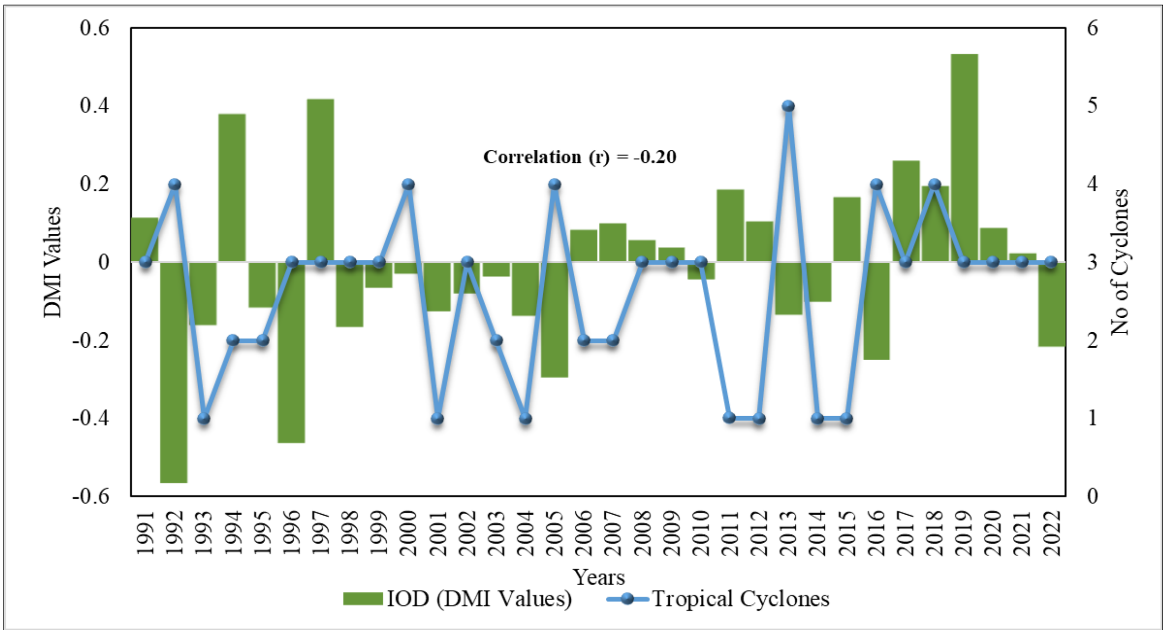

Fig. 7. Comparison of DMI values with number of cyclones (>62 km/h) over the Bay of Bengal (Dipole Mode Index (DMI) values obtained from https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI).

episodes play a significant role in regional climatic changes in the Indian-Pacific area and are linked to tightly coupled ocean-atmosphere-land interactions (57). Even though, the relationship is not always simple and it is difficult to directly link TC occurrences to the IOD because of the intricate interactions between the IOD and other climate phenomena such as El Nino-Southern Oscillation (ENSO) and regional air circulation patterns. Moreover, the IOD may have an impact on the spatial distribution of TC development inside the BoB. Accordingly, positive IOD events may cause TC activity to shift southward, while negative IOD events often favour TC formation in the northern Bay of Bengal (55).

El Nino-Southern Oscillation (ENSO)

ENSO is the primary dominant interannual pattern in the tropics which links ocean and atmospheric system (58). Phases of ENSO *viz*., El Nino and La Nina, affect climate patterns worldwide. El Nino causes distinct warming in the eastern and central tropical Pacific and La Nina causes anomalous cooling in the same regions. Walker Circulation is an east-west circulation pattern induced by the zonal distribution of tropical surface heating (59). During ENSO events, the atmospheric response to sea surface temperature anomalies in the equatorial Pacific disturbs the Walker circulation, affecting global oceanic and atmospheric conditions significantly (60). Like the DMI, SOI (Southern Oscillation Index) is a standardized metric based on observed changes in sea level pressure (SLP) between Tahiti and Darwin, Australia. Negative values of SOI indicate El Nino across the eastern tropical Pacific and vice versa. Correlation studies between number of cyclonic storms and SOI values recorded over the period, 1991-2020 indicates a positive relationship between these two parameters (Fig. 8). Many previous studies have looked at the association between ENSO and seasonal TC activity in various tropical basins (61). El Nino occurrences cause warmer sea surface temperature and weaken the Walker Circulation, increasing the vertical wind shear over the Bay of Bengal, thereby suppressing tropical cyclone activity (62). This can make circumstances more favourable for TC development, especially during the pre-monsoon season (May-June) (62). However, former researchers (62) found that tropical cyclone activity over the BoB decreased during warm ENSO phases in the severe cyclone months of May and November. Meanwhile, TC activity increases and the genesis location shifts to the east of BoB during La Nina regimes. During the cold regime, the number of extreme TC cases, those classified as above VSCS, increased dramatically in the BoB (63). This describes the complex relationship between ENSO and TC over Bay of Bengal.

The lifespan of TCs can cause significant impact on the intensity of cyclones and the harm caused by it. Studies indicate that the El Nino years have a shorter lifetime for TCs than La Nina and neutral ENSO years (55). Combination of ENSO and IOD can have a considerable impact on TC activity. Yuan and Li (64) determined that most El Nino events coincide with IOD events and practically every positive IOD occurs during an El Nino year since 1970. A study covering the period between 1993 and 2010 found that all positive (negative) IOD years coincided with El Niño (La Niña) years, with the exception of 1993 and 1996 (63). Vardah, Titli, Gaja *etc*. were significant impact caused cyclones formed during El Nino years. According to studies, more severe cyclones emerge during La Nina years under ENSO type and during positive IOD under IOD type (Nilam in 2012, Thane in 2011). Furthermore, attribution of specific TC occurrences purely to ENSO remains difficult due to natural climate variability and the complex interplay of many components.

Madden-Julian Oscillation (MJO)

MJO is an ocean-atmosphere interaction phenomenon characterised by changes in winds, clouds, pressure and rainfall that shift eastward along the equator. Tropical convective anomalies and related circulation anomalies migrate eastward over a 30 to 60 day period (65). It is an eastward-moving wave of wind and convection in the tropics that has a substantial impact on tropical cyclone (TC) activity in the Bay of Bengal. Conditions for TC formation in the BoB improve during the convective phase of the MJO, which is characterised by increased rainfall and low-level convergence across the Subcontinent and the Indian Ocean (66). Changes in TC genesis and tracks are more pronounced and they are primarily due to MJO-driven modulations in large-scale

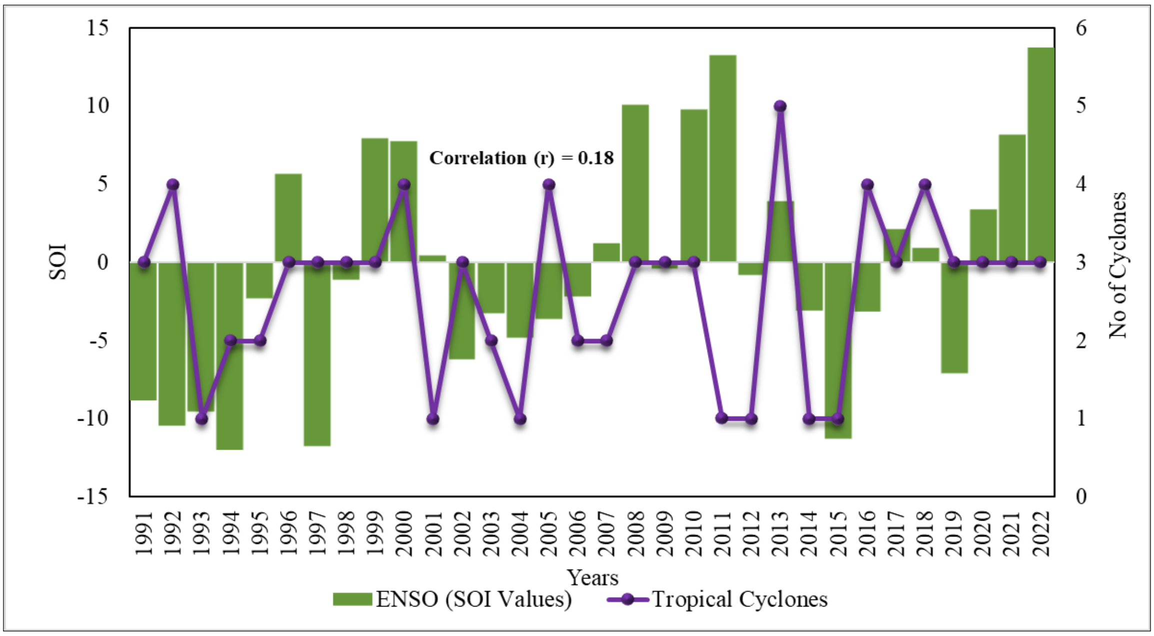

Fig. 8. Comparison of SOI values with number of cyclones (>62 km/h) over the Bay of Bengal (Southern Oscillation Index (SOI) values obtained from http://www.bom.gov.au/climate/enso/soi/).

environmental conditions *viz.*, sea surface temperature, sea level pressure, deep convection, lower and upper-level winds, mid-tropospheric relative humidity and vertical wind shear (67, 68). The interaction between ENSO and MJO in modulating TC activity has also been documented (69). In La Nina conditions, when the MJO is active over the BoB, environmental conditions are more conducive for intensive TC activity compared to the similar MJO phase under El Nino conditions. In previous studies (69), the primary and secondary factors that contribute to the strengthening of TCs in the BoB during the La Nina regime are increased mid-tropospheric humidity and reduced vertical wind shear. In addition to change in cyclone formation zones and landfall locations, the combined effects of these oscillations impact previously less-exposed regions, thereby stressing unprepared coastal habitats.

Impact in the coastal ecosystem

As observed, these changing patterns in TC have profound impact over coastal agriculture and allied sector in the BoB region. It can pose a serious threat to coastal ecosystem, predominantly in low-lying delta regions like the Sundarbans. One of the most affected environments in coastal region is the mangrove forest, which acts as a buffer against cyclonic winds and storm surge. For example, Cyclone Amphan in 2020 caused a massive destruction in the Sundarbans, damaging the forest area and leading to large scale destruction (70). Remote sensing analysis also indicates that the super cyclones formed once 7 to 12 year per period affected 20 % or more of the mangrove area (71). In addition, these ecosystems are already stressed by sea-level rise and human encroachment and losing their ability to protect inland areas, endangering both biodiversity and the livelihoods of dependent communities (72). Estuarine and intertidal ecosystems also experience changes after cyclonic storms. After Amphan, studies in the Ganges estuary indicated a decline in species richness, a key component of the estuarine food chain and web (73). These changes in species composition can alter trophic dynamics and affect fishing yields, which were critical for local economies. Additionally, cyclones increase turbidity and nutrient fluxes, disrupting primary productivity and leading to hypoxic conditions in shallow estuarine waters (74).

Wetlands and freshwater ecosystems are also vulnerable to saltwater intrusion during cyclonic storm surges. Cyclones can cause widespread salinization of freshwater ponds, affecting aquatic fauna such as freshwater turtles, amphibians and estuarine crocodiles (75). In many areas, embankment breaches allowed the seawater to remain trapped for weeks, disrupting agricultural fields and posing long-term risks to food security (76). These impacts are not limited to ecological systems but directly influence drinking water availability and public health. The geomorphology of coastal landscapes also changes significantly after cyclones. Post-Amphan satellite imagery showed that the coastal regions in the Sundarbans underwent erosion (77). Newly formed creeks and sandbars redefined tidal channels and shifted estuarine dynamics, raising concerns about future flood vulnerability and saline ingress into inland regions. These physical changes often make previously habitable zones unliveable, forcing climate-induced migration from low-lying coastal villages (78).

Tropical cyclones have wide-ranging and increasingly compounding effects on India's coastal ecosystems (Fig. 9). The destruction of mangrove belts, wetland salinization, disruptions in aquatic food chains and long-term coastal transformation affects ecosystem. Although some systems can recover over time, the rising frequency and severity of tropical cyclones due to climate change highlight the need for integrated adaptation strategies. These include strengthening mangrove restoration efforts, developing early-warning systems rooted in local ecological knowledge and reinforcing nature-based embankments. Continuous ecological monitoring and community participation are vital to enhance coastal resilience in the face of these escalating disturbances (79).

Future directions

Future research on tropical cyclones (TCs) over the Bay of Bengal (BoB) should prioritize an integrated approach to understand the combined effects of long-term climate change and short-term climate oscillations such as the IOD, ENSO and MJO. While historical records highlight variability in frequency, intensity and landfall patterns, further works should be focused on relative contributions of tropical cyclone rainfall to the regional

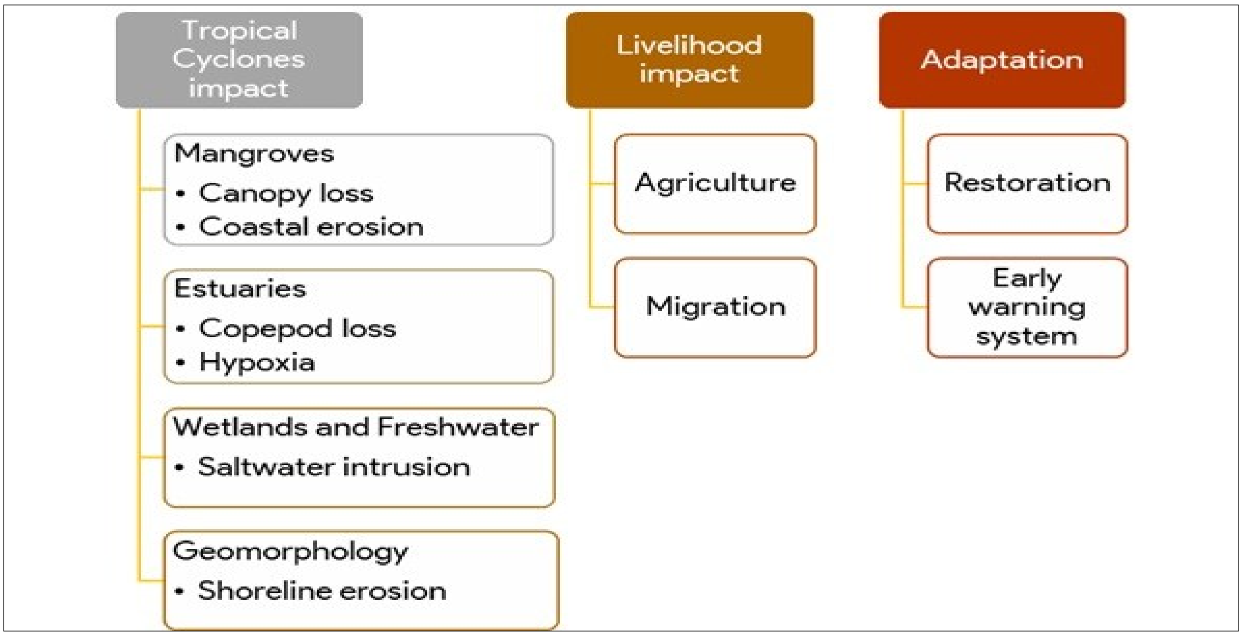

Fig. 9. Impact of tropical cyclones on the coastal ecosystem.

precipitation. High-resolution coupled ocean atmosphere models, along with satellite observations and reanalysis datasets, can improve projections of cyclone genesis, intensification and changes in lifecycle under future warming conditions. Additional importance should be given on slow-moving and long-lived cyclones, which pose escalating risks of flooding, erosion and saltwater intrusion in low-lying coastal zones. Improved downscaling techniques can also help assess local impacts on ecosystems such as mangroves, estuaries and wetlands. Furthermore, linking cyclone dynamics to ecosystem resilience and socio-economic vulnerability will be critical for developing effective early warning systems, climate-resilient infrastructure and adaptive land-use planning. An inter disciplinary framework that integrates atmospheric science, coastal ecology and community-level adaptation strategies will be essential to enhance preparedness and resilience against intensifying cyclones over BoB in a changing climate.

Additionally, research works should also focus on strengthening nature-based solutions such as large-scale mangrove and dune restoration, while integrating ecosystem-based disaster risk reduction into climate adaptation strategies. A key direction is the development of comprehensive, multidisciplinary impact assessments that combine ecological, biological and physical indicators to capture the full scope of cyclone disturbances. Advancements in remote sensing and field monitoring will be essential to improve cyclone impact prediction and ecosystem recovery over time. Long-term studies on resilience and thresholds of ecosystems like mangroves and coral reefs are needed to understand recovery dynamics and potential tipping points. Future studies should address current knowledge gaps in linking vegetation indices, biodiversity and geomorphological changes in cyclone-prone regions. Finally, translating scientific findings into conservation planning, sustainable coastal management and adaptive community-based strategies will be critical for enhancing resilience to future climate-driven cyclones.

Conclusion

Tropical cyclones are the most devastating extreme event, resulting in severe loss of life and property destruction, particularly along coastal regions. Analysis has shown that the post-monsoon season sees the highest number of cyclonic disturbances over the Bay of Bengal basin. Despite the minimal number of pre-monsoon cyclonic systems, a high proportion of cyclonic disturbances develop into severe cyclonic storms. The number of cyclonic disturbances classified as severe cyclonic storms is expected to grow with climate change. The frequency and intensity of TCs in the BoB have increased over time, posing a significant threat to vulnerable coastal areas. This trend indicates that tropical cyclones have become a persistent threat to the ecological and socio-economic stability of coastal regions. The Bay of Bengal has experienced a growing frequency of intense cyclonic storms during the pre-monsoon and post-monsoon periods, coinciding with critical stages of agricultural activity. The impact on coastal agriculture is further exacerbated by secondary effects such as flooding, soil degradation, saline water intrusion and damage to infrastructure and irrigation systems. In this context, it is essential to integrate cyclone trends and climate projections into agricultural planning and management. While early warning systems and improved disaster preparedness are crucial, they must be complemented by targeted adaptation strategies to enhance the resilience of farming communities. Developing climate-resilient crop calendars, promoting salt-tolerant varieties and strengthening local capacities will be key to sustaining agricultural productivity and livelihoods in cyclone-prone coastal regions.

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Authors' contributions

SM and GV conceptualized the study. SM, BK, PK performed the methodology and did formal analysis and investigated the study. SM wrote the original draft. GV, DGa and SV reviewed and edited the article. PS and SK supervised the study. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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