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Cyclogenesis and Odisha Coast, the Hotbed

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Abstract

Background: *Recurrent tropical cyclones of thermal origin in the Bay of Bengal have consistent impairment to the 480km Odishacoasts of the east coast of India. The ascribing causes are fierce wind, torrential rain, and storm surge inundations. The sea surface temperature (>270C), relative humidity, wind shear, Coriolis force, cyclonic disturbances, warm oceanic current, easterly trade wind, Indian Ocean Dipole, and upper air cyclonic circulation. Odisha receives a lion's share of the slams of cyclones of the Bay of Bengal which is shattering its coastal inhabitants and the ecosystem.*

Methodology and Results: *The cyclone data of the India Meteorological Department from 1891 to 2022are analyzed statistically. The categorization, naming, and cause of slam of cyclonic disturbances in the Bay of Bengal particularly along the Odisha coast are debated in the present study. The favorable geological stratification, meteorological players, and coastal features of the Odisha coast are discussed. The trends in landfall of various types of cyclones and the storms that shall brew and grow over BoB fabric from 1980 to 2020 have been using a machine-learning model.*

Conclusions: *There is a decrease in cyclogenesis frequency but an increase in amplitude, intensity, and severity is the present trend along with a southerly shift of landfall along the east coast. The changes in the coastal corridor, the discrete Eastern Ghats belt, and its seaward retro gradation are the reason that the southwest monsoon brings with it high wind shear, which has allowed the cyclones to slam the Odisha coast instead of the Gangetic coast and Godavari region.*

Keywords: *Anthropocene, Bay of Bengal, Cyclogenesis, ITCZ, Odisha coast, Soft Computing*

Introduction

The cyclonic disturbances over the Bay of Bengal(BoB) are formed either in situ or remnants of the cyclones receiver from the China Sea. The pre (Mar to May) and post-monsoon periods (Oct to Dec) of the year favor cyclonic disturbance (CD) formation over the Bay of Bengal (BoB). The north Indian Ocean (NIO) fabric is the breeding ground for cyclonic storms and favors the growth of migrant disturbances in the South China Sea. The two jinxes of cyclogenesis over BoB are less devastating, while a major fraction during the post-monsoon. The Inter-tropical Convergence Zone (ITCZ) which is the main player, is housed in the Southern Hemisphere during summer crosses the equator during the pre-monsoon period, and moves northerly in Northern Hemisphere. From April to December, cyclonic storms form in the close vicinity of the ITCZ or low-level conditional instability of the 2^{nd} kind (CISK) in the atmosphere where cyclonic vorticity pre-exists [1]; [2]

The Coriolis force and trade wind promote to augment the air circulation in the southern boundary from West to East in the BoB. Simultaneously the

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northern margin of the ITCZ helps the air rotation to move reversely from East to West. The cross travel of winds forms low-pressure areas (LPA) in peninsular India, helps to move along a trough line through the Indian landmass, and moves towards the disturbance in BOB.

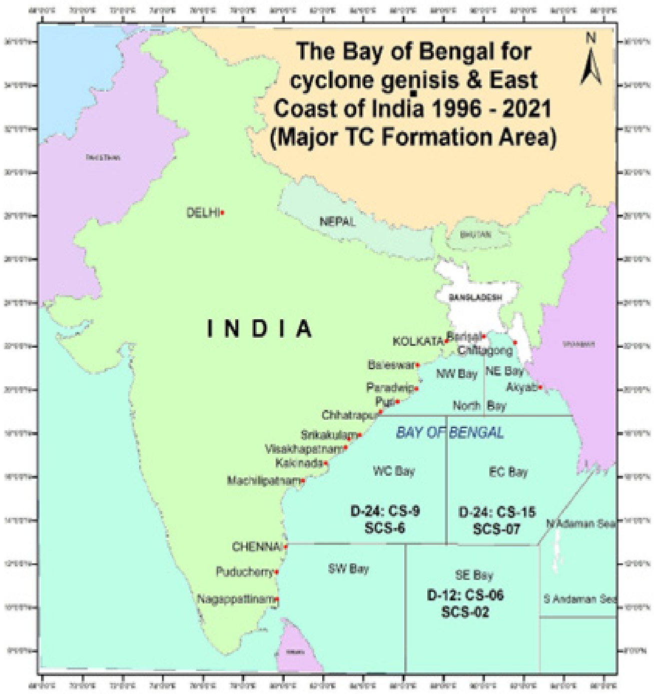


Fig 1: The incubation area of various disturbances of BoB in NIO (After 1996).

The 2.172 mn Km^2 area of BoB (0.6% of the total oceanic area)is tentatively divided meteorologically into 7 compartments without specific boundaries. During the monsoon season depressions and remnant storms of the South China Sea, the BoB disturbances were observed to be conceived in the southern part of BoB. The analysis of data from 1996 to 2020 reveals that a major share of the cyclogenesis starts either from the East Coast (EC)or from West Coast (WC) Bay (Fig-1) [3]; [4]

The Classification of BoB disturbances

The records of cyclones from IMD ledgers are available from 1891 whereas records are sporadic and unreliable as they are from history, Gazetteers, literature, and state sources. Systematicallytropical cyclones were classified into five categories during the 20th century ascat-1, cat-2…cat- 5 (wind speed of >252km/h or above) based on intensity and the wind force.

The super cyclone (SC) was added when the Cat-5 cyclone crossed Paradip Odisha on 31st Oct 1999. Later after the cyclone Phailin on 12th Oct 2013, a new category has been added as an extremely severe cyclonic storm (ESCS) [9]. The wind criterion was considered for the classification of ion bay disturbances in the Bay of Bengal (Table 1).

Review of Literature

Odisha'scoast receives the largest number of cyclones (holds 6th rank in the globe) with the utmost risk of encountering storm impacts, surges, winds, and inundation [7]; [8]. The anomalies in SST (sea surface temperature), PIOD or NOID (+ve and -ve Indian Ocean Dipole), ENSO (El Niño-Southern Oscillation), and Madden Julian Oscillations (MJO) play a pivotal role in shaping the tropical and subtropical climate [9]; [10]; [11]; [12]). Reliable track and time of propagation and slamming forecast are indispensable in predicting the cyclonic storms of higher-order to access surged devastation faced during landfall particularly (ESCS) since last 30 years 1990 to 2020 [13]; [11].

The wind-oceanic coupling during the cyclogenesis period is reducing the TCs number, and increasing the intensity in NIOas the effect of surged SST (threshold) and TC-induced cooling has gone down [14]; [15]. The warm pool at an altitude of 200 millibar (mb) is ascribed as one of the causes for the development of cyclonic disturbances before their formation over BoB and generally before 3-4 days earlier, [16][17]. Depending upon the positioning of the cyclones names differ in different countries such as Typhoons (China Sea), Tropical Cyclones(Indian Ocean), Hurricanes (Caribbean Sea), Tornadoes (USA), Wily Willies(Northern Australia), Baguio (Philippines), and Taifu (Japan), [18], [19]. Intensified post-monsoon super cyclones were reported during 1831, and 1885, and a similar type on 31st Oct 1999 land slamming at Paradip with unique fast intensification, reasonably small eye radius, wind speed > 270 kmph, huge surge > 6m, and consistent long life after slamming, [20].

The deadliest cyclone that shattered the Andhra coast was in the years 1946, 1977, and 2014, in Tamil Nadu in the year1979, in West Bengal in 1993 and 2018, in Odisha in 1971, 1989, 1999, 2013, and 2019 (Foni), [10]; [21]. The Odisha coast comprises deltas, sandy (central), stony (south), and muddy (North) beaches, spits, barrier islands, tidal flats, dunes, beach ridges, lagoons, swamps with mangroves (North), and

Table 1: The classification of tropical cyclones in the Indian Ocean based on wind velocity, a pressure difference of the eye, and the physical damages (IMD)

Category	Life	(Change pressure)	Wind speed	Beafaurt's scale	Offshore (allowed)	Wave height	Sea status
Disturbanc-es	days	ΔhPa (mb)	kmph	Number	Activities	in m.	
Low-pres-sure /Well marked (LP/ WLP)	--	<4.0	<31	1-6	all	0-3	calm-rough
Depression (D)	02	4-6	31-49	5-6	all	2.5-4.0	Mod-Rough
Deep depression (DD)	03	7-10	50-61	07	alerted	4-6	Very Rough
Cyclonic Storm (CS)	3.5	11-15	62- 88	08	No fishing	6 - 9	High
Severe Cy-clonic Storm (SCS)	4	16-20	89-118	09-12	Suspension of fish-ing, and all coastal activities	>14m	Very High
Very Severe CS (VSCS)	5	21-66	119-167	10		>14m	Phenomenal
Extreme Severe CS (ESCS)	5	67-79	168 - 221	12-14		>14m	
Super Cy-clone (SuC)	5.75	>80	>222	>14		>14	

Note: Mean wind speed over 3 minutes, speed in kmph (sustained), ΔhPa =change of atmospheric pressure in S.I. unit as Hecta-Pascal (hPa),(Source: IMD report [5].

mangrove associates (South) are responsible for hit by cyclones approaching from SSW/SE direction, [22]; [8]; [23].

Different researchers forecast the frequency and intensity and track cyclones' exercise applications of different soft computing models. They are of opinion that the ANN (artificial neural network) is better than conventional linear or multiple regression methods [24]; [25]; [26]; [27]; [28]; [29]; [30]. Research on cyclogenesis by utilizing computational models has been tried for predicting CDs and CSs over the Indian Ocean [31]; [32]; [33]; [34]; [35]. The highest number of CS that slams Indian coasts are Odisha (ranked 1st), West Bengal, Andhra Pradesh, and Gujarat as temperature range between $26.5^{o}C$ to $29.3^{0}C$, [36], [27].SST cooling is reported and relatively at a higher rate during pre-monsoon cyclogenesis in the North Indian Ocean and the fall is 4 to 6^{0} C whereas post-monsoon cyclogenesis is at a higher rate of landfall intensity (LI) than those of 1980, [38], [39], [40].

Objective

The trend in cyclogenesis in the Bay of Bengal during the post-Holocene (1891-1949), pre-Anthropocene (1950 – 1980), and the present period of Anthropocene (1980 –May 2021) is demarcated by the geological factors, human-induced carbon footprint, and climate-induced players who changed the SST, carbon sequestration and cyclogenesis in NIO. A prediction was mentioned for the period 2021-2030 using suitable machine learning models.
The frequency and place of landfall along the north of east coast in India of BoB storms are ever-changing. The risk and the vulnerability of the coastal state out of five along the east coast of India need identification so that adequate storm disaster ameliorative measures are less visible in past literature. To bridge the gap, the concurrent study is to point out the causes of slamming a major share of the BoB storms along the 480km long Odisha coast.

Methodology

The present scope of the study is to collect the cyclonic disturbances in the Bay of Bengal basin which is one of the vibrant gulfs of the North Indian Ocean (NIO). Its present geographical poisoning, vibrant physiography, and stratigraphy are engulfing a lion's share of the cyclonic disturbances formed in the NIO. The classification, naming, and players in the process have been reported. The cyclogenesis in the Bay of Bengal, its formation processes, intensification, movement, land slamming, and concurrent management policies are the focal point of the research.

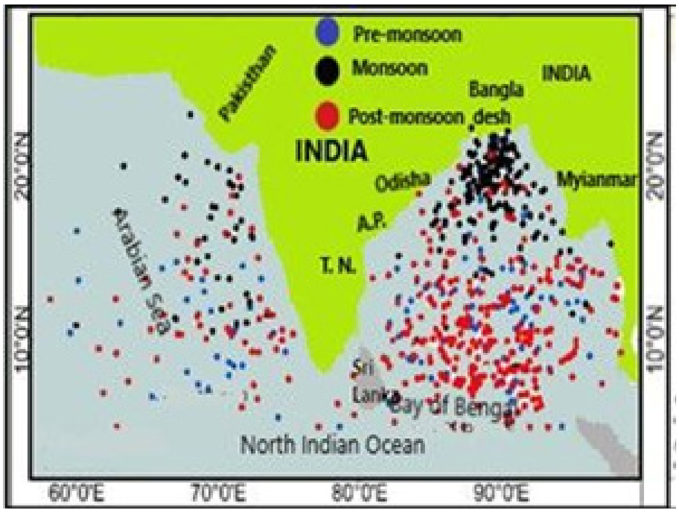
The soft computing study uses cyclogenesis data for 40 years starting from 1981 to 2020 based on Indian Meteorological Department publications and Wiki data. Three time-dependent observations such as CD, CS, and SCS are considered for prediction. The machine learning approach that is widely used for classification and prediction is preferred over traditional ARIMA (Auto-Regressive Integrated Moving Average). The present study makes use of WEKA, a popular software tool for the application of machine learning algorithms. The tool enables the creation of lag variables and converts the time series forecasting problem into a supervised machine learning problem. It also provides configuration options for the number of time units to forecast.

Data consideration

The data reporting and hazard risk recording of cyclonic storms were started in 1891 through India Meteorological Department (IMD). The subcontinent has experienced 1597 cyclonic disturbances (CDs), out of which 670 and 321 numbers of CDs have developed and slammed the EC and WC of India. The lion's shares of 100 CSs (19.12%) out of a total of 523 cyclonic storms have intensified from CDs and have made their landfall along the Odisha coast till May 2021 inclusive of the VSCS "YAAS" [10].

Past History

As per the record, the devastating intensified storm that slammed the Odisha coast was in 1737 (Oct), 1831 (Oct), 1864 (Oct), 1885 (22nd Sept), 1942, 1967, 1971, 1977, 1999 (Super Cyclone), 2013 (Phailin), 2014 (Hudhud), 2018 (Titli), Fani (3rd May 2019), and YAAS (26th May 2021) [41]. At times the remnants of typhoons of the South China Sea intrude into BoB south or North Andaman Sea, intensify, and move towards the East coast of India. Many cyclones formed in May and take a curvature heading towards the Myanmar coast. Pre-monsoon CSs cause severe devastation and give less rainfall. Only meager CS formed in BoB from June-Sept in NE/NW Bay. From Oct. to Dec, storms are devastating and slam all along the east coast of India, and rarely move towards Bangladesh and Myanmar coast, Fig 2 (a) and Fig 2(b).



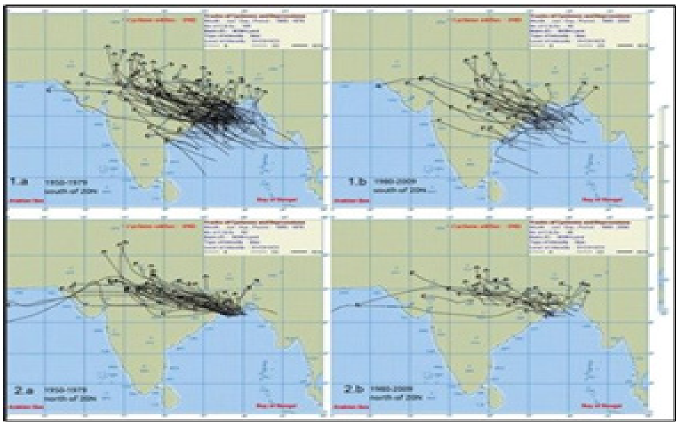


Fig 2(a): Thecyclogenesis place during pre, active, and post-monsoon in NIO (Source: Pal et al 2020) **Fig 2(b):** the frequency of track of CSsin Northwest bay on monsoon days (E-Atlas, IMD)

Past statistics

The cyclones (BoB+ AS + in-land) have been considered for the periods 1891 -1949 (post-Industrial revolution and post-Holocene epoch), 1950 -1979 (global atomic activities, i.e., pre-Anthropocene period),and 1980-2022, (Golden spike period of Anthropocene when the rate of demographic growth exceeded the rate of food production in India). The anthropogenic activities with high greenhouse gas accumulation have surged global warming, Regional

Table 2: The number of CDs, CSs, and SCSs that landfall the different coasts of India

Year	Cyclonic disturbances (CDs)				Cyclonic storms				Severe Cyclonic storms			
	BoB	AS	In-land	Total	BoB	AS	In-land	Total	BoB	AS	In-land	To-tal
1891-1949 (NO)	630	74	67	771	285	53	9	347	94	29	3	126
1891-1949 (%)	81.7	9.60	8.7	100.0	82.1	15.3	2.6	100	74.6	23.0	2 4	100
1950-1979 (No)	329	72	37	438	126	34	4	164	75	21	1	97
1950-1979(%)	75.1	16.4	8.5	100	76.8	20.7	2.5	100	77.3	21.7	1.0	100
1980-2020 (No)	261	89	38	388	111	47	1	159	67	31	0	98
1980-2020(%)	67. 3	22.9	9.8	100	69.8	29.6	0.6	100	68.4	31.6	0.0	100
Acronyms: No: Number; BoB: Bay of Bengal; AS: Arabian Sea												

The % of CDs (D + DD's) formed for the three consecutive periods were 81.7%, 75.1%, and 67.3% during the period 1891-1949, 1950-1979, and 1980 - 2020 respectively (Fig 4 (a), (b) and (c)).

sea level rise has increased the sea surface area to receive more insolation to have a significant impact on the meteorology and climate.

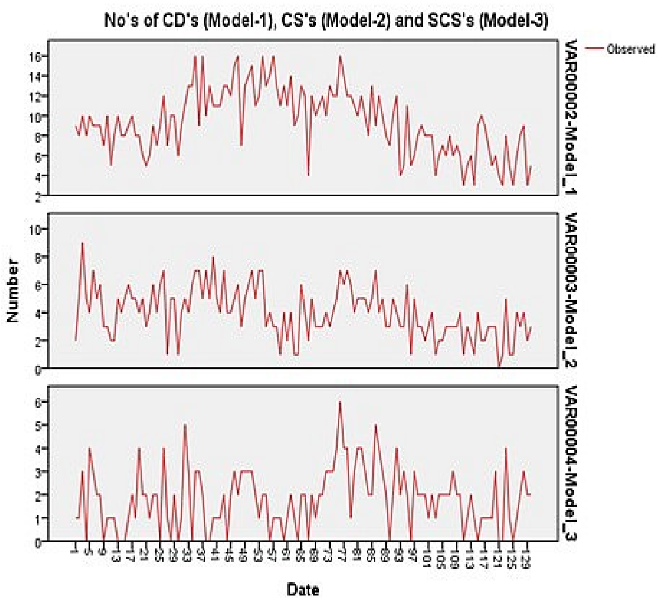
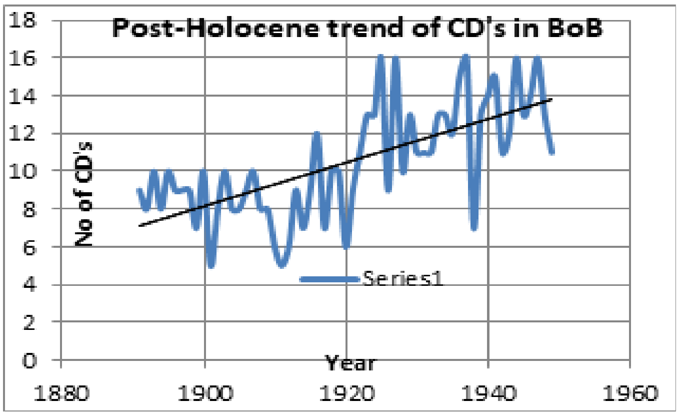


Fig 3: The No's of formation of CD, CSs, and SCS in BoB (Source IMD)

The analysis of data reveals that the number of CDs and TCs formed during the post-Holocene, Pre Anthropocene, and golden spike period of Anthropocene shows changes (Fig 3, Table 2).



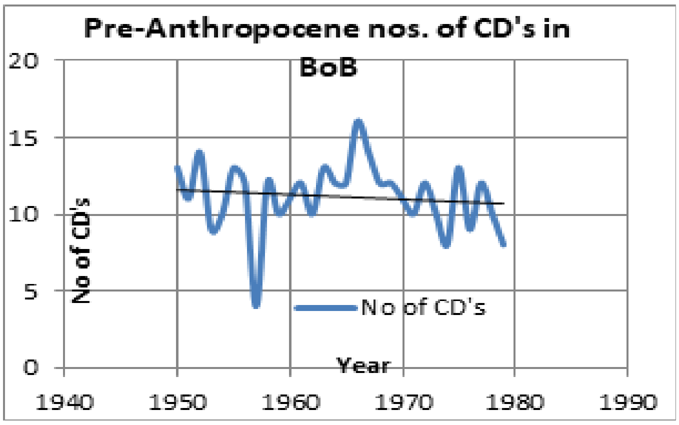


Fig4(a) and (b): Number of CDs in BoB during post-Holocene and Pre-AnthropoceneCDsin BoB

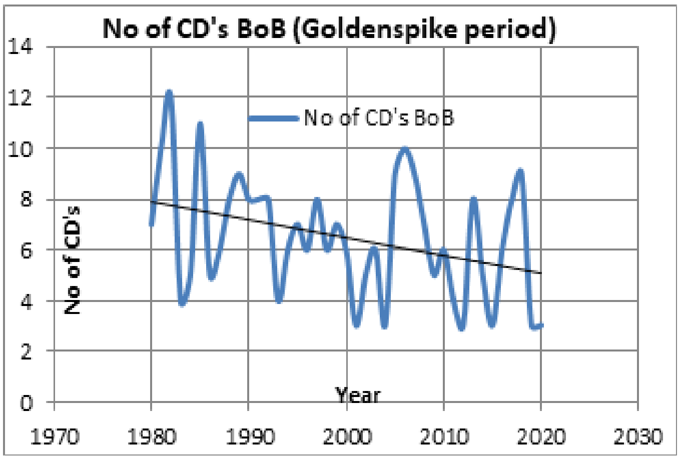


Fig4 (C): The annual trend of CDs in BoB (Golden spike period of Anthropocene Epoch

Those CDs that were intensified to CSs and above during the same periods were also increasing gradually to 82.1%, 76.8%, and 69.8% **(Fig 4 (d), (e), and (f)).**

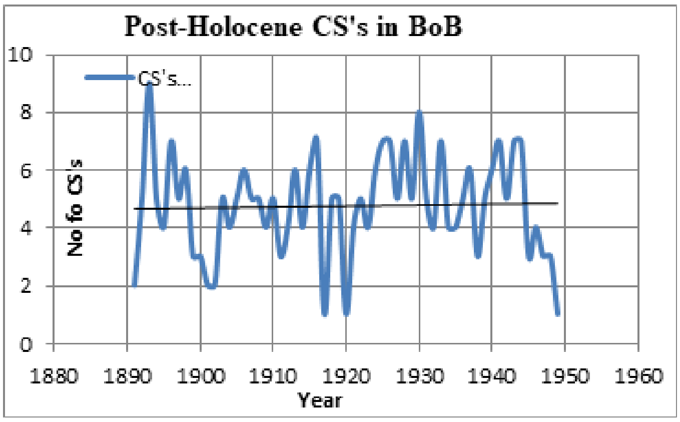


Fig 4(d): Trend of post-Holocene CSs in the Bay of Bengal

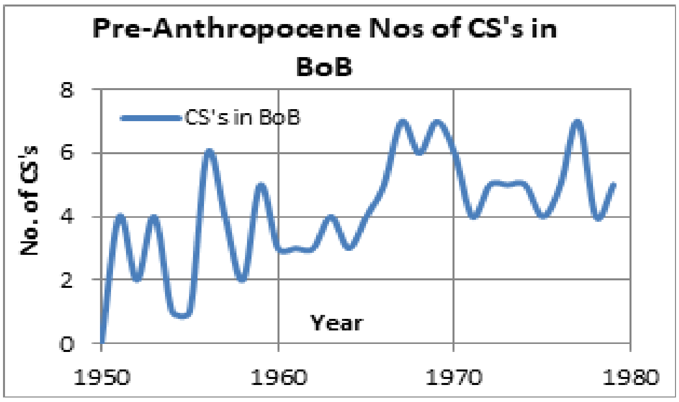


Fig 4(e): Pre-Anthropocene Epoch

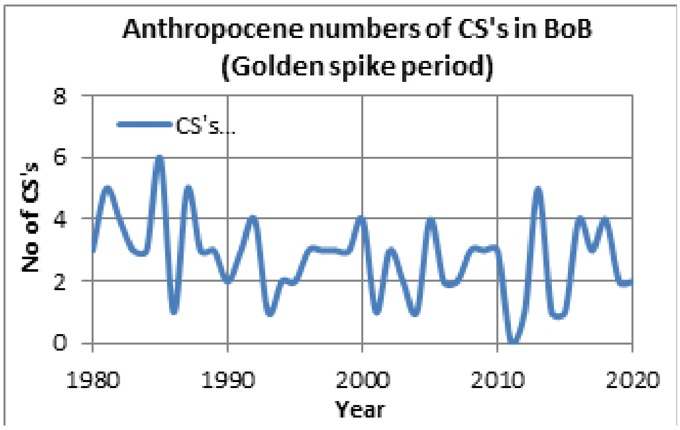


Fig 4 (f) Golden spike period trend of CS in BoB.

However, observations during Post Holocene, pre-Anthropocene, and golden spike periods except that the growth from numbers of CS, SCS, VSCS, ESCS, and SuChas showed a decreasing trend of 74.6%, 77.3%, and 68.4% respectively, but with higher intensified CS's during the same periods. Among all the cyclonic formulations, 29% of the total disturbances have affected the Odisha coast. The vulnerability of the Odisha Coast Zone is relatively high in comparison to other adjacent states like West Bengal (14%), Andhra Pradesh (13%), and Tamil Nadu (7%) (IMD Report).

Formation of cyclones in BoB

The TCs in BoB form when sea surface temperature is high (>26.5^{0}C), the warm water column of 50m depth (the energy source), and highly moist air rise above the ocean surface are common during the months(April to Dec). Release and transfer of latent heat to penetrate the surrounding warm moist airs create more wind and the system grows. The system moves NW-ly in BoB (at time curves) and intensifies further with favorable climatic conditions of the Bay. The continuous supply of moisture from the surroundings makes the system dynamic and makes it capable of transgression. On landfall, the moisture supply is hindered and the cyclones divulge and dissipate. The eye of an intensified storm has a diameter ranging from 30 -60 km with almost calm wind, visible blue sky, least precipitation, and fair weather with 0-2^0 C warmer than the surficial temperature. [42]; [43]; [20]; [18]; [44]). A well-developed cyclonic storm should have noticeable structural elements like a boundary layer, central eye and its wall, cirrus cloud shield (CDO: Cloud-dense overcast), rain bands, and upper tropospheric outflow. Failure to penetrate the cloud column with sufficient wind and moisture, the cyclone shall not grow and tend to decay and die. [45]. However, other propelling factors are IOD,

Table3: The trend in the formation of CSs in BoB during monsoon seasons during the post-Holocene, Pre Anthropocene, and present golden spike period

Year	JUNE		July		August		September	
	No	% of total CS	No	% of total CS	No	% of total CS	No	% of total CS
1891 - 1949	30	27.03%	36	32.43%	22	19.82%	23	20.72%
1950 - 1979	6	20.69%	5	17.24%	5	17.24%	13	44.83%
1980-2020	2	20%	2	20%	1	10%	5	50%

ENSO, ITCZ positioning, and upper-tropospheric westerly trough, which are important as they could force huge volumes of wind shear (vertical) over CDs, which may inhibit strengthening.

Propelling of circulations in BoB

After the formation, of the cyclone, the track may be conventional or nonconventional and at times also undergo dissipation and decay. Conventionally, the concurrent wind force propels the system to travel with sufficient vorticity forced by the Coriolis force (anti-clockwise in BoB), the centripetal force action of the earth's rotation, and the gravitational forces, [43]. The conjoint factors are low altitude positive vorticity, low shear force in layers of vertical wind shell, SST (> 26.5° Celsius), surged convective uncertainty, and high RH in the low and mid-troposphere [46]. The genesis moves forward continuously in W to NW quadrant and never takes a reverse course toward the equator. Occasionally systems remain geostatic and accumulate more energy for changing direction or recurving the system collapse or recurvate of disturbances during pre-monsoon occur in the BoB, with general propagation track is NW-ly in BoB (NIO [47]; [48].

Fewer cyclones during SW monsoon

During SW-monsoon days, a monsoon trough is developed from NW India to the zone of cyclonic disturbances in the bay till intensification maximum up to the deep depression stage only. Such Oceanic disturbances have a short stay within the Bay. They dissipate without further intensification and cross the Odisha or WB coast and decay with spells of heavy rain, Table3.

The trend information CS's of frequencies observed higher during the post-Holocene period, July has the highest number which has drastically reduced during the pre-Anthropocene period. Monsoondata reveals September month has become conducive for monsoon cyclones in the BoB.

Prediction using Machine Learning Models

A large series of data from 1891 to date is available. But data from the golden spike period (1980- 2020) has preferred to be used as there is an abrupt change in cyclogenesis after the golden spike period of the Anthropocene epoch. The conducive parameters for cyclogenesis that have changed thermal status over the Bay of Bengal by the active Barren Island volcanic activity, Sunda Island geographical turmoil, global warming, and carbon sequestration after 1980 onwards. Three time-dependent observations such as CD, CS, and SCS are considered for prediction. The study makes use of WEKA, a popular software tool for the application of machine learning (ML) algorithms. The tool enables the creation of lag variables and converts the time series forecasting problem into a supervised ML problem. It also provides configuration options for the number of time units to forecast.

Two popular machine-learning algorithms, Linear Regression (LR) and Sequential Minimal Optimization Regression (SMOreg) selected as candidates for the problem at hand. Linear regression is used to predict the value of a dependent variable *y*based on the value of an independent variable and can be expressed using $y = f(x) + e$, where*f* is the mapping function and *e* is the prediction error.SMOreg works on a support vector machine (SVM) and supports both linear and nonlinear regression models. The sequential minimal optimization (SMO) algorithm has been a very effective method for training SVM on classification tasks. The SMOreg is a generalization of SMO to handle regression problems [50].

Both the regression algorithms are set to their default configurations in the tool environment. Linear

Regression uses Ridge regression to avoid over-fitting and SMOreg uses Normalized Poly Kernel as a nonlinear kernel function. The performances of both algorithms are evaluated using the holdout method taking 70% as the training data and 30% as the test data. The RMSE (Root Mean Squared Error) is taken as an evaluation parameter to assess the accuracy of prediction. The RMSE values of both algorithms for 10 steps ahead (2021-2030) are observed on training and test data. On average, SMOreg generates slightly less error than that Linear Regression (Tab-4). Hence, SMOreg is selected for forecasting cyclogenesis in the present study (Siddique et al, 2021).

Table4: RMSE of Algorithms

Algorithm	Train	Test
LR	1.88048	2.74179
SMOreg	1.78064	2.56852

Results

The machine learning method,SMOreg has been used for forecasting TC such as the number of CDs, number of CSs, and number of SCSs and above that shall occur in the coming decade 2021 to 2030 over BoB fabric. The forecast results are shown in Tab-5 and Fig. 5 at a 95% confidence level.

Table5: Forecast using SMOreg

Year	CD	CS	SCS	Actual	%excess/ less
2021	5	1	1	VSCS (YAAS); CS (Gula-b);SCS(Sa-hen); CS(-Jawad), DD (BoB-03)	Less by 10%; growth would have favored
2022	4	2	1	Ongo-ing; DD (01 &02); SCS(Asani); DD(BoB-7); CS (Sitrang)	Less by 20%;Three DDS
2023	5	2	2		
2024	7	1	1		
2025	6	2	1		
2026	6	2	1		
2027	6	1	0		
2028	5	2	1		
2029	4	1	0		
2030	5	1	1		

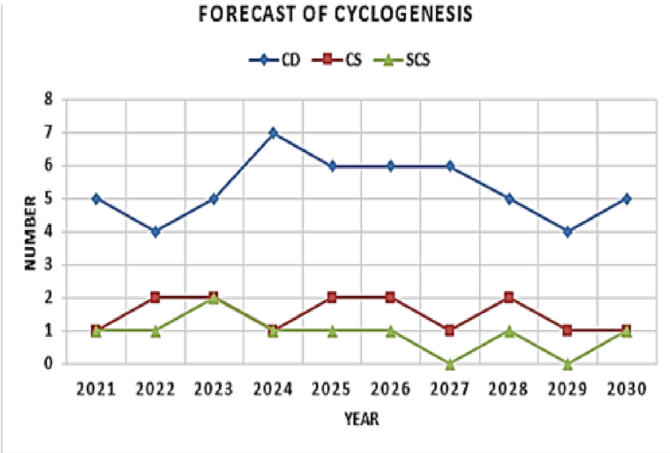


Fig 5. Cyclogenesis Forecast using SMOregfor the period 2022 to 2030

Odisha coast; the cyclone hotbed:

Odisha is highly prone to landfall tropical cyclones, and about 100 out of a total of 523 numbers formed in the BoBfrom 1891 to May 2021. The number of pre and post-monsoon cyclones and above that formed in BoB and slammed the Odisha coast from 1970 until May 2021 were21 and 28 numbers respectively which is the highest among all adjoining states along the east coast of India (Sahoo et al, 2018). The Coastal districts like Balasore, Bhadrak, Kendrapara, and Jagatsinghpur, are categorized as P-1 vulnerability, and the districts Ganjam, Khordha, and Puri are highly prone (P-2) categories as per IMD. Depressions and DDs formed during the monsoon period are more between WB, and the Odisha coast. The IMD recorded district-wise probable maximum storm surge (PMSS), and probable maximum precipitation (PMP) averaged cyclones and severe cyclones that have slammed the Odisha coast till 2020are in Table 6.

The north Odisha coast is vulnerable to CS, and SCS. These districts have high PMSS (Storm surge), and PMP (Rainfall) Values. It is due to the coastline irregularities. It is also observed that the number of cyclones slamming the northern coasts of Odisha during the late 20^{th} century has decreased but that of the south Odisha coast has increased in the 21^{st} century.

Table6: The statistics of the cyclonic storms and severe cyclonic storms with surge and rainfall averaged those landfalls in different districts of Odisha (Source IMD data 1891 to 2021))

District	CS by May 2021	SCSby May 2021	Average wind speed	Storm surge (PMSS)	Average r/f (PMP)	Physiographic coastal stratigraphy
Unit	Number	Number	Kmph	meter	cm	Characteristics
Ganjam	11	5	100	4	48	Straight
Puri	6	1	140	4	60	Convex coast
Khordha	4	0	100	4	52	West coast Chilika
Jagatsinghpur	17	4	140	6.5	60	Bulged coast
Kendrapara	17	6	65	8.5	60	Concave, plunged
Bhadrak	17	4	140	9.5	60	Concave, plunged
Balasore	28	5	75	11	60	Bulged coast

Why Odisha Coast hotbed for Cyclones of BoB

Stratigraphy: The positioning of the Bay of Bengal and the nonappearance of any oceanic fabric of the vast tectonic region over southeast Asia except Andaman and Nicobar Islands, India within Myanmar, East Malaysia, Brunei, Indonesia, Philippines, Singapore) and the East coast of India. The only barriers are fully submerged 85^0 and partly submerged 90^0C ridge. The northern coast of Odisha has a curved shallow bottom and meso-tidal areas are adding to coastal floods.

Coastal Geography, and Landscape: The cyclonic circulation instigated by the aeolian and Coriolis forces, and El-Niño Southerly Oscillation being little protested by coastal land mass moves in an NW-ly direction and move towards geographically favored landscape i.e. the sinusoidal curved Odisha coast mostly between Chilika and Dhamara Offshore lineaments (COL & DOL).

Shape Factor: Triangular funnel shape of the BoB accelerates storm surges especially during full or no-moon days (added with daily diurnal tides) during the pre-monsoon period when the estuaries are depleted. The high population density residing in low contour areas, flat slopped about 100km stripped delta, river systems, and 2^{nd}largest lagoon Chilika and anastomosed drainages (Bhitarkanika) add to the vulnerability of cyclones. The retrograded coastal canopy from mid of Chilika Barrier spit to the Subarnarekha estuary,(Sarkhel et al., 2019)

Meteorological factors: The emergent cyclones formed and intensified from low-pressure areas to the specified tropical storm. They move towards the coast propelled by the adjacent pressure, sea surface temperature (SST), Tropospheric relative vorticity, inverse tropospheric vertical wind shear, monsoon trough, and Coriolis force. The disturbances over BoB oceanic fabric form grow and propagate under favorable conditions, to the ultimate destination of slamming landmass which is either the Odisha or the AP coast (Akter et al., 2017).

Temperature anomaly: The most crucial factor is sea surface water temperature (SST) which has a positive relationship with TC formation in BoB. A tropical cyclone requires a warm temperature of around 27°C to form in BoB and such a suitable temperature is common. The Arabian Sea has a lower temperature due to the vast expanse, due to incursion of dry air of the Arabian Peninsula (desert), and critical wind shear during monsoon. Positive Indian Ocean dipole (PIOD) frequently prevails, high RH and conducive for the brewing of CDs over BoB, and trade winds provide the propagation direction.

Salinity strength: BoB is less saline than the Arabian Sea as a huge flow from inland rivers debouches the bay. The rate of evaporation is high in fresh water in contrast to saline water. Atmospheric (UACYCIR) instability (divergence), mid-tropospheric high RH (Relative humidity), preexisting oceanic disturbances, and warm moist air become promising for cyclone genesis (Gray, 1975[36]).

Retreating ITCZ: the geographical setting of Odisha favors a suitable path for the retreating SW monsoon and on-setting NE monsoon during October. The returning path covers eastern Bihar, South of West Bengal, total coastal Odisha, and the northern coasts of AP. At the time when the SST is warm (>26.5^{0}C), BoB experiences the formation of most of the CDs and above in BoBfavoured by the W-wind from the pre- to post-monsoon period. But during Jan and Feb. the ITCZ shifts near the equator of the Southern Hemisphere (Fig 6(a) & 6(b).

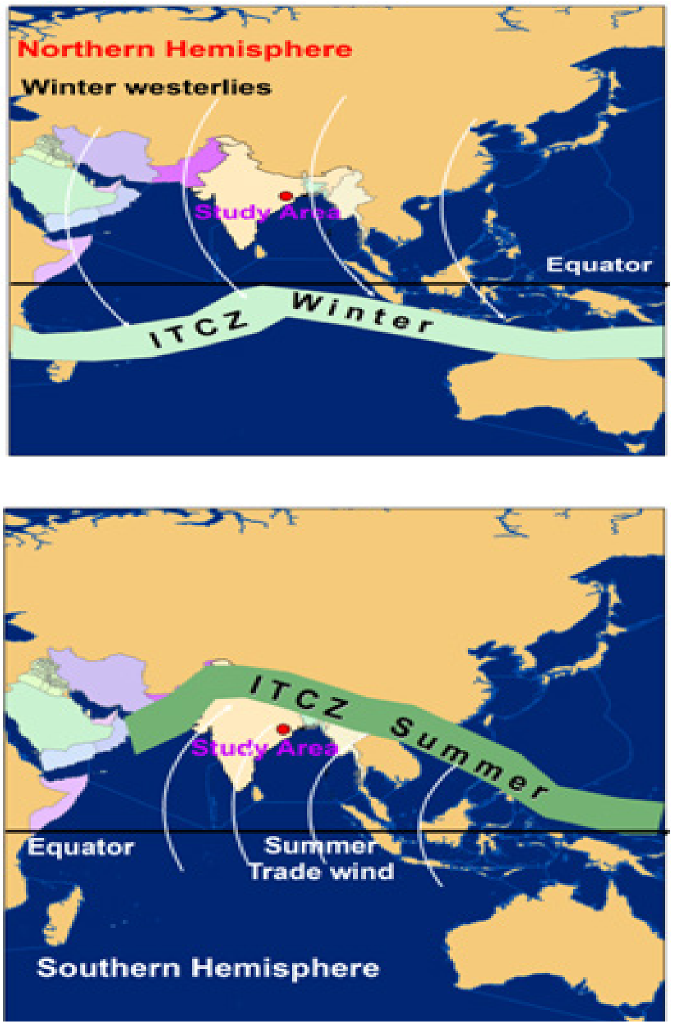


Fig 6(a): Shift of ITCZ during winter and (b) summer seasons that brews cyclones in the NIO

Source: modified: https://scied.ucar.edu/docs/why-monsoons-happen

Flat terrain: The 10-100km deltaic coastal strip on Odisha coast though in Eastern Ghats belt hills (EGB) have hillocks that could not be high enough to be an obstacle to resist propagation of cyclonic storms of BoB. The land slamming of cyclones is opposed by high altitude mountains of EGB and WGB hills range on the Southern coasts (east and west) of India. The high mountains do not allow storms to landfall along the coastlines of TN, Kerala, and Karnataka. The Mahanadi and the Godavari delta are wide, and flat, with flat deltaic terrain and welcome the BoB cyclonic storms for unobstructed landfall.

Oceanic Chemistry: Warmer and sweeter (as more freshwater flows to the BoB) contributing to a higher amount of vapor formation which is conducive to cyclone formation. Global warming and tectonic and volcanic activities have made BoB a warm pool, low depth has increased carbon sequestration of the Bay.

Remnant cyclones: During NE monsoon days (Nov, and Dec) the CS are frequently the remnants of the typhoons received from the China Sea or the Malay Peninsula. They enter the BoB from the back of the Andaman and Nicobar Islands of India, and further intensify in strength due to favorable warm temperatures of sea and travel towards a landmass. Those cyclones rarely landfall the Odisha coast.

Irregularities along the coast: The 480.4km long Odisha coast reported by [52] has been updated by Kankara2018as 549.5km. Continuous erosion and deposition have created more irregularities along the coastline, continuous loss of mangroves, and mangrove associates and an increase in the numbers of ports harbors/Jetties are also inviting more numbers of BoB storms to slam the Odisha coast.

Discussion

Conducive physical-environmental factors for cyclogenesis may be troposphere and stratosphere dynamics or terrestrial/oceanic thermodynamics. The pre-monsoon days' high insolation over BoB adds energies to the upper sea surface and makes it conducive for cyclogenesis and movement of ITCZ from the southern to the northern hemisphere. During the post-monsoon period (Oct to Dec), the BoB is very much energized and active. The retreating of the Southwest monsoon and the onset of the Northeast monsoon is due to the shifting of ITCZ from North to south. The easterlies pick up moisture from BoB and strengthen to form most of the TCs over BoB, and the east coast from Tamil Nadu becomes prone to cyclones during Nov and Dec.
The passive period for cyclones formation activities along the Odisha coast is delimited during the winter months (DJFM) and the active SW monsoon days (JAS). Major cyclonic disturbances that occur in the Bay of Bengal during active SW monsoon days intensify up to deep depression. During the 20th century, the ITCZ, the trajectory of SW monsoon movement was west to easterly starting from the desertification of Harappa civilization, Cherrapunjihasthe highest rainfall in Meghalaya. The anomalies' highest rainfall (wettest day) has shifted westward to Mawsynram, indicating the westerly shift of the SW monsoon from the east with ITCZ

positioning fluctuation. The shift indicates Odisha coast is gradually becoming a hotbed for the slam of BoB CSs (Mishra et al, 2021).

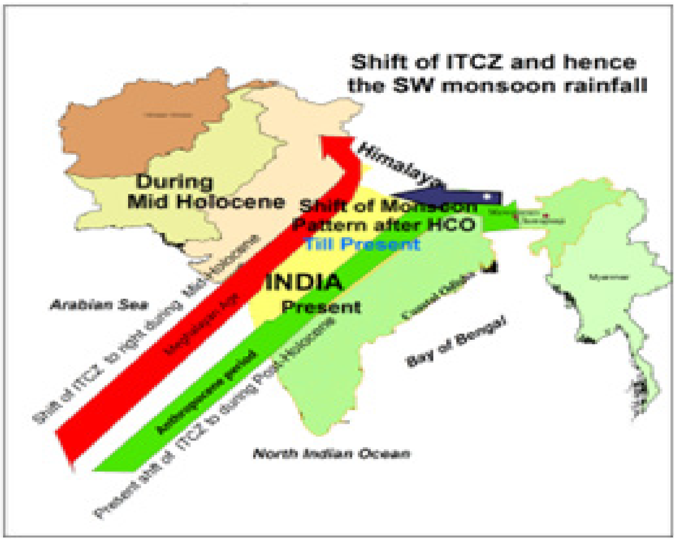


Fig 7: The shift of track of SW monsoon over India4200YBP to date [53]

The geographical positioning and480.4km long coastal Odisha (Ramesh et al., 2012) (≈20% of total EC) with alternate concavity are prone to landfall ofBoB disturbances and receive ≈40% of cyclonic storms that hit the east coast of India. The Coastal landmass from the Puri coast to Bramhani estuary has been plunged into the Bay of Bengal welcomes a major part of landfall. Two large wetland masses start at the southern and the northern fringe, the Bhitarkanika and southern fringe of the Chilika lagoon where the land bulging starts.

During monsoon season, the CDs of BoB form as depressions and lie over a monsoon trough line along ITCZ, which extends from NW India to the northern fringe of the BoB. There is a shift in the positioning of the TEJ (Tropical Easterly Jet) (TEJ) along with the shift in the location of the ITCZ. Till September, the trough line and the TEJ firmly establish their positioning along an east-to-west direction except for a break in monsoon.

ML summery on CDs over BoB

Machine learning techniques and various soft computing models are applied for short-term and long-term forecasts of TCs and predict intensity and change in intensity, wind field, path, track, storm surge, SST, air moisture, air pressure rainfall, and impact of the cyclonic storms [54]; [55].

Results

Analysis of 130years tropical storm data generated by IMD to date reveals that:

Major cyclones formed during May take a curvature ENE and slam the Myanmar coast, whereas during June-Sept they landfall along the northeast coast between Kolkata and Ongle (AP). The storms of post-monsoon hit anywhere along the west coast of India and were devastating.

Active monsoon cyclones have drastically decreased representing the impact of climate change and anthropogenic stresses.

Three distinct partitions due to climate changes synchronous with Anthropocene, plate tectonics, geological, and global warming impact cyclogenesis in BoB. The three periods under analysis are

(a) **Period I**: Post Holocene 1891-1949 (Industrial revolution period);

(b) **Period II:** Pre-Anthropocene Period 1950-1979 (after atomic testing or explosion and pre-independent India) and

(c) **Period III:** Golden spike period (1980- May 2021).

The trend of formation of % of BoB **CDs** was75.1-81.7% before 1979 But has decreased to 67.3% during Period III whereas CSshave reduced from 76.8-82.1% to 69.8% and several higher-order storms (SCS, VSCS, ESCS, and SuC) 74.6%,77.3% to 68.4% respectively in the three periods.

The prediction of CDs, CSs, and higher-order storms show that their number shall reduce with time from 2021to 2030.

The 480km of Odisha coast has become a hot spot for the slam of BoB storms in the last decade and also the place of landfall shifted from north to south gradually.

Cyclone prevention and Mitigation:

[58] reported that about 80% of cyclone disaster deaths are caused by CS formed in BoB. The steps adopted to prevent the bio-system incongruities are to ameliorate deaths; trauma and damage to the

Table 7: The cyclogenesis prediction using soft computing methods by various workers

Method used	Area of Study	Prediction for	Result	Reference
Multiple linear regression (ANN, MLR)	Western North Pacific Ocean. 1997-2004	cyclone intensity prediction scheme (SCIPS)	Intensity rise, increase in a lead hour (12to 120h)	Sharma et al., 2013[56]
Neural network (NN model, MLR)	NIO (Post-mon- soon months)	Number of Seasonal TCs	Sept. favors the TC activity over AS	Nath et al., 2015[33]
K-Nearest Neighbor Tech (ML Tech.)	Thunderstorms	In storms and no storms	>82% compatible;	Chakrabarty et al., 2015[26]
SVM and neural network	BoB, AS	classification and prediction	Accuracy is better	Benifa et al., 2021[30]
Hybrid genetic algorithmXP boost	Bay of Bengal	Tropical cyclone categories	A better model to apply than others	Karthik et al., 2020[34]
Adaptive Neuro-Fuzzy Inference System (ANFIS)	Caspian Sea (Anzali)	Atoms. pressure and Wave Height	Fails during long lead time	Akbarinasab et al., 2019[28]
Generative adversarial- social network (GAN)	Typhoons Korea Peninsula	Typhoon track prediction	Averaged error of 95.6 km	Rüttgers et al., 2019[29]
neural net architect ture 1 (NNA 1, and 3()	BoB, and AS of the NIO	Track and Intensity prediction (TCs)	Least prediction error by NNA-1	Choudhury et al 2015[27]
Soft Comp. (ANFIS /SVM) technique, LSTM/CNN models	North Pacific Ocean	SST prediction	An increasing trend in SST.LSTM/CNN models better	Haghbin et al. 2021[57]
Regression (LR) and Sequential Minimal Optimization Regression (SMOreg),	Arabian Sea of NIO	Frequency of TCs	An increasing trend in TCs	Mishra and Ojha 2020[35]
LR or SMOreg	**Bay of Bengal**	TC's Frequency	**decreasing trend**	Present study

ecosystem. The hazard, needs vulnerability analysis, awareness creation, early prediction, widespread warning, and prompt preparedness to meet exigencies like food, health, bovines, ecosystem, bio-system, and finally post-cyclone long-term mitigation measures. The activities can be served by early warning through prediction, and monitoring. There is a need for setting institutes to educate the affected mass by generation, presentation, and dissemination of warning, pre cyclone preparedness. The state and central government through their line departments interact by coordinating state/central disaster management organizations, and post-cyclone disaster management the risk and vulnerability of the cyclones are minimized.

The CDs formed over the north coastal area of BoB cross Orissa or West Bengal coast within a day or two. These short-lived systems have landfall very quickly, which is one of the reasons for their non-growth as CS. The increase in the intensity and frequency of cyclonic storms along the Odisha coast has forced the local government to improve its short-term and long-term preparedness and response capacity by providing more action plans through the Odisha Authority. Odisha State Disaster Management (OSDMA), and Odisha disaster rapid action force (ODRAF) is constituted to combat storm devastations. Disaster management is enforced through the responsibility of prevention, alleviation, readiness, response, relief, and restoration in connection with natural disasters.

Conclusion

The reason is that the southwest monsoon brings with it high wind shear, which hinders cyclone development, and variation in wind layer shear. After trying with LR and SMOrgmodels, the prediction by the latter model seems to be better considering the strengths and limitations of both models. The features, like track, intensity, velocity, storm surge, life span, and rainfall, along the coastal areas are the forecasting factors that make the job of the meteorologist challenging. The predictions under anthropogenic climate change and global warming need more expertise and scientific methods like averaging, statistical, numerical, hybrid modeling, and simulations correlating with past storms to forecast the upcoming features. Thus, it suggests further research studies.

Declaration

Ethics approval and consent to participate: The results/data/figures in this manuscript have not been published elsewhere, nor are they under consideration by another publisher. All authors of the manuscript have read and agreed to its content and are accountable for all aspects of the accuracy and integrity of the manuscript.

Consent for publication: Informed consent was obtained from all individual participants included in the study.

Availability of data and materials: Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

Competing interests: Authors have declared that no competing interests exist. The products used for this research are commonly and predominantly used products in our area of research and country. There is no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. No, I declare that the authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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Article Highlights: The predictions under anthropogenic climate change and global warming need more expertise and scientific methods like averaging, statistical, numerical, hybrid modeling, and simulations correlating with past storms to forecast the upcoming features. Thus, it suggests further research studies.

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