Restoration of Coastal Barriers and Descriptive Analysis of Cyclones: Tauktae and Yass

Bevelio Philip Goes*[1]

Abstract

The Indian Ocean is a region of high energy thus, fuelling the Geohazard; Cyclone. Cyclones that drift past the coastal regions or cross the coastline (landfall), cause major destruction and losses. During the bleak situation of the pandemic, the recent formation of two pre-monsoonal cyclones – Tauktae along the west coast and Yaas along the east coast within two weeks – inflicted further misery in India. Such abnormal frequency of pre-monsoon cyclones have raised many questions regarding the changes observed in climatological patterns. The Cyclone Tauktae is categorised as an 'Extremely Severe Cyclonic Storm' whereas the Cyclone Yaas is a lower intensity 'Very Severe Cyclonic Storm' making landfall at Saurashtra and Odisha respectively. Least flooding was experienced due to the higher water holding capacity of the ground before monsoons. The storm surges by both the cyclones were categorised as Very High-Risk Zones causing inundation and severely eroded seashores. Although cyclone Yaas had a lower intensity it was accompanied by greater surge heights, as it coincided with the occurrence of a supermoon. The development of a cyclone in proximity to the west coast has raised many eyebrows. An effort is made to understand the coastal dynamics and the future consequences of ignorance. The natural barriers have been destroyed in most regions for economic gain. The rising temperatures and sea level, deduce the increase in frequencies of intense weather patterns like cyclones.

Keywords: *Tropical Cyclone, Tauktae, Yaas, Intensity, Storm Surge, Inundation, Hazard, Mitigation, Restoration, Sandunes, Mangrove*

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1. Introduction

The Earth is a dynamic planet with various climatic phenomena occurring within the blanket of its atmosphere. The atmosphere is structured as layers of gaseous mixture with the lowest layer i.e., the Troposphere having the highest frequency of turbulences. These turbulences create various weather phenomena on the Earth's surface. The unequal heating of the atmosphere causes a difference in atmospheric pressure geographically, causing a large-scale flow of gases known as wind. Winds can be pervasive or local and occur with a temporal pattern.

The variable winds result in phenomena like cyclones and anticyclones. They are formed due to the combination of atmospheric pressure gradient, convection of air and moisture and the Coriolis effect causing the wind to spiral and ultimately form vortexes (intense circular storms) (Husain, 2011). The cyclones are low-pressure systems, with wind rotating in an anticlockwise and clockwise direction in the northern and southern hemisphere respectively with a minimum endured wind speed of 62 kmph (34 knots) spiralling upwards. Unlike anticyclones that diverge downwards with high-pressure centres, cyclones are a result of the convergence of winds into low-pressure areas. Cyclone; as it is known in India is derived from the Greek word 'CYCLOS' which means Coil of a Snake. It is also known as Typhoon in Western Pacific, Willy-Willies in Australia, Cordonazo in Mexico, Bagious in the Philippines and Hurricane in the United States of America (Devi, 2021). Cyclones can be classified into two types namely;

Temperate Cyclones: Also known as Extra-Tropical or Mid-Latitudinal cyclones; they occur in the mid latitudinal regions of both the hemispheres. The temperate cyclones extract their energy from horizontal gradients of temperature in the atmosphere and are a result of unstable conditions formed at polar regions due to clashing and convergence between the fronts (cold and warm air masses). The temperate cyclones have cold cores.

Tropical Cyclones: According to the World Meteorological Organization a tropical cyclone is a synoptic scale (3100 km), non-frontal disturbance, over tropical or subtropical waters, with organized convection and definite cyclonic surface wind circulation. As defined the Tropical cyclone occurs in low-pressure tropical regions i.e., between from equator and the Tropic of Cancer in the Northern hemisphere and Tropic of Capricorn in the Southern Hemisphere with temperatures between 25˚C to 27˚C. Approximately 80 tropical cyclones occur annually (Husain, 2011).

Tropical cyclones typically have an eye which is a central region of warm temperatures; shaped in a circular or elliptical eye. It is formed by the sinking of air from the upper levels to lower levels and thus characterized by calm winds, clear sky and lowest pressure with diameters ranging from 10 to 100 Km. Hence there is an abrupt hiatus in precipitation when the eye passes over an area. The region surrounding the eye have the maximum pressure and temperature gradient with the heaviest precipitation and strongest wind. This region is a ring of convective clouds spiralling inwards having a width of about 20-100 Km. Torrential rains, storms surges and wind gusts are the associated threats of cyclones. The strongest winds of cyclones occur near the surface. The Life cycle of a cyclone can be generalised into 4 stages namely;

1. Formative stage: This stage is the pre developmental stage of a cyclone that can last 3 to 10 days. Also known as Cyclogenesis it is believed to begin with the formation of depression.
2. Immature stage (1st day to 3rd day): The Immature stage is subsequent to the formation of depression and is the further progress of the low-pressure system. The central pressure falls gradually along with the increase in size and surface wind speed during the formative and immature stages.
3. Mature stage (2nd day to 3rd day): During the mature stage, intensity i.e., central pressure and wind, remains the same but the size of the system may increase.
4. Decaying stage (2-3 days): The last stage i.e., the Decaying stage occurs due to landfall, colder Sea or unfavourable atmospheric condition or the interaction with other Tropical Cyclones thus decreasing the wind intensity and increasing the central pressure.

The Indian ocean being located within the tropics; is a hotbed for cyclonic storms. The North Indian Ocean is inflicted by two tropical cyclone seasons; one being the pre-monsoon cyclone in May and the other being post monsoon during October-November. Interference from the monsoon circulation hinders the development of cyclones from June to September. From the 80 annual cyclones occurring over the globe, 5 cyclones originate in the North Indian Ocean. The ratio of tropical cyclones between the Bay of Bengal and the Arabian Sea is 4:1 (Mohapatra, 2015). These storms mostly persist within the oceans but some come in contact with the land. On approaching the land vast damages are caused by such a phenomenon. A total of 96 districts lying within 100

km from the coast and are directly prone to the effects of cyclones. In the Journal Article titled *Cyclone hazard proneness of districts of India* by M Mohapatra; 12 are classified as 'Very highly Prone', 41 districts are 'Highly Prone', 30 districts are 'Moderately Prone' and the remaining are 'Less Prone' districts based on the frequency of tropical cyclones. A cyclone over the north Indian Ocean typically has a life period of 5 days.

Based on intensity, the evolution of the tropical cyclone can be categorised as;

1. Low (L)/Well marked Low-pressure area: The initial and latter stages of the cyclone is formed as a low-pressure area with surface wind speeds below 31 kmph. This stage is categorised with the T number of; LLC/T 1.0
2. Depression (D): Categorised as T 1.5; the surface wind speeds range between 31 to 49 kmph.
3. Deep depression (DD): Following the depression is the Deep depression which is characterised by sustained surface wind speeds of 50 to 61 kmph. The T number is T 2.0.
4. Cyclonic storm (CS): This form of the low-pressure system is the initial storm and the T number range from T 2.5-3.0 with a surface wind speed of 62 to 88 kmph.
5. Severe cyclonic storm (SCS): Post the Cyclonic Storm is the Severe Cyclonic Storm as T 3.5 and the surface wind speed ranging between 89 to 117 kmph.
6. Very Severe cyclonic storm (VSCS): The Surface wind speed of the Very Severe Cyclonic Storm is between 118 to 166 kmph. The T number classification range from T 4.0-4.5.
7. Extremely Severe Cyclonic Storm (ESCS): The Extremely Severe Cyclonic Storm has a T number ranging from T 5.0-6.0 with surface wind Speed sustaining between 167 to 221 kmph.
8. Super Cyclonic Storm (SuCS): The Super Cyclonic Storm is the ultimate evolutionary form of the cyclone with the surface wind speeds being above 222 kmph and the T number ranging between T 6.5 to 8.0. (Mohapatra & Sharma, 2019).

All cyclones do not achieve the complete evolutionary forms. They can attain maximum intensities of any form within the 8 stages.

In May 2021, a unique and event struck the coastal belts of India. Still reeling under the influence of the 2nd wave of the COVID-19 pandemic, two mighty cyclones

namely Tauktae and Yaas attained landfall within two weeks creating further setbacks in India. The pre-monsoon tropical cyclones Tauktae and Yaas formed on either flank of the Indian peninsula. This unique phenomenon resulted in vast devastation and also provided an insight into the understanding of climatology and its future impacts. Therefore, the cyclogenesis, its physical characteristics, associated damages and the climatic impact of the two cyclones is analysed through this article.

1.1. Etymology and Description of Tauktae and Yaas

A panel comprising of thirteen countries, that include India, Pakistan, Bangladesh, the Maldives, Myanmar, Oman, Thailand, Sri Lanka, Iran, Saudi Arabia, Qatar, Yemen and the United Arab Emirates is led by the UN Economic and Social Commission for Asia and Pacific (UN ESCAP) and the World Meteorological Organisation for naming the cyclones within the tropical region. A new list comprising of 169 names of cyclones was released in 2020, with each country suggesting 13 names each. Such a panel is created for easy identification of the storms thus enabling easy warning notifications globally. The names are kept simple to avoid technical names thus facilitating effortless spreading of awareness and remembering to the common people. The Indian Meteorological Department (IMD) is among the six Regional Specialised Meteorological Centres (RSMC) authorised to issue advisories and propose names for the tropical cyclones in the region of the north Indian Ocean (Yeung & Mitra, 2021).

The word 'Tauktae' (pronounced Tau'Te) is derived from the Burmese dialect which means 'gecko'; a lizard. The Cyclone Tauktae is categorised as T 5.5 Category 3 storm with 125 mph wind speed according to the Joint Typhoon Warning Center (JTWC). This is equivalent to Extremely Severe Cyclonic Storm; the categorisation by Indian Meteorological Department (IMD). According to IMD, the central pressure (eye) of Tauktae is 950 mb. In the 2021 North Indian Ocean cyclone season; Tauktae is the second depression, first cyclonic storm, first severe cyclonic storm, first very severe cyclonic storm, and first extremely severe cyclonic storm (Korosec, 2021).

'Yaas' literally means 'a tree that has a good fragrance' and is derived from the English word Jasmine. This cyclone is the second cyclone of the 2021 North Indian Ocean cyclone season categorised as T 4.0 i.e., a Very Severe Cyclonic Storm with the broken low to medium cloud mass arranged as a shear pattern. The minimum cloud top temperature was -93°C. The system of Yaas is embedded with intense to very intense convection layers.

The next Cyclone to occur will be named 'Gulab', recommended by Pakistan which basically means a rose.

2. Data

For mapping, the inundation area caused by storm surges from both the cyclones, the pre-cyclone and post-landfall SAR data of Sentinel 1 from the Sentinel Hub were acquired. The advantage of SAR remote sensing is its capability to penetrate cloud cover, thus producing rasters devoid of cloud hindrance. Data to represent the development of the cyclone and the parameters (intensity and surge height) of Tauktae and Yass were obtained from the Meteorological and Oceanographic Satellite Data Archival Centre (MOSDAC) portal which is a repository for the INSAT-3D satellite archives from Regional Specialized Meteorological Centre (RSMC), New Delhi and the periodic surge height guidance from Indian National Centre for Ocean Services (INCOIS). Remotely sensed rainfall data was acquired from the PERSIANN imagery through the Centre for Hydrometeorology and Remote Sensing (CHRS) data portal. The ALOS PALSAR DEM raster of Goa was acquired from the ASF Vertex portal to create a topographical profile of the Coastal region. Apart from the geospatial data; bulletins from IMD, editorials from news resources, research articles on cyclones and a webinar – 'Cyclones & Storm Surges', by NIDM-IMD were referred for the study.

3. Methodology

3.1. Analysis

Time-series comparison of the data is tabulated for understanding the pattern of the cyclone intensity, squalls and surge heights. The cyclone intensity recorded from the data sources were at regular intervals of 6 hours during the six days and five days of cyclones Tauktae and Yaas respectively. The per-day maximum rainfall level as well as the surge height- above the astronomical tide – were considered for each coastal state during the period of the cyclonic development. The inundated area along the coast at the location of landfalls is mapped by calculating the difference between both the pre-cyclone and post-landfall SAR images using the raster calculator. The pixels with the maximum index (difference) signify the flooded region. The DEM raster of Goa is taken as an example to display the coastal profile.

3.2. Data Illustration

The Cyclone intensities, storm surges and rainfall data are represented as bar, area and line graphs respectively. The INSAT-3D raster represents the cloud cover and its temperature at the landfalls of the respective cyclones. The tracks of both the cyclone along with periodic date and intensities are depicted in a layout (Fig. 1.). The topographical profile of the coast is represented using the elevation from the DEM. The inundated area of both the landfall locations is mapped as a layout.

4. Tracking the Development of the Cyclones

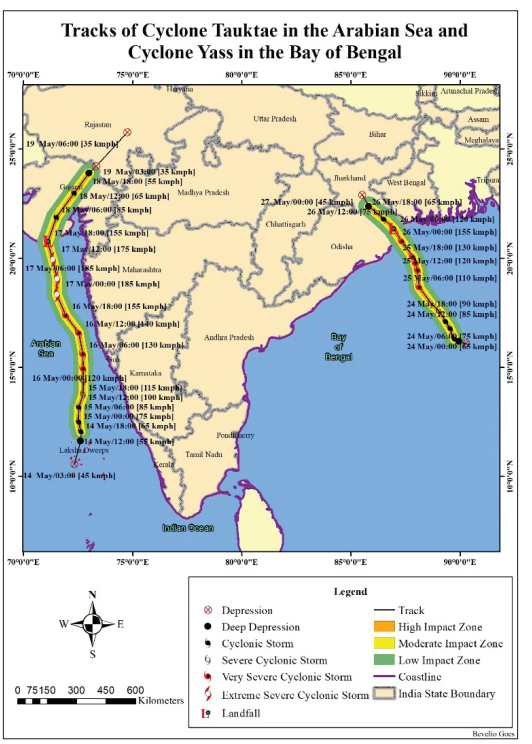
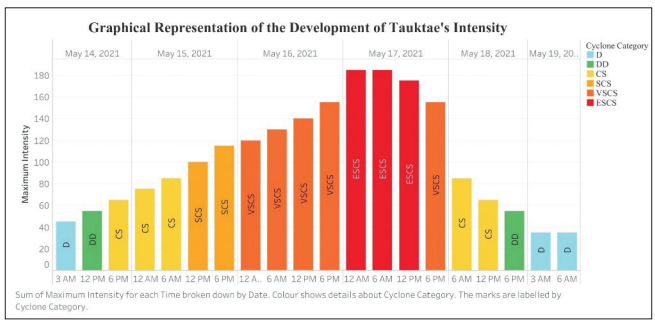


Figure 1: Tracks of Cyclone Yaas and Tauktae with the respective category evolution, intensities and classified impact zones. Each impact zone is a buffer of 10, 15 and 25 kms for the High, Moderate and Low Impact Zones respectively; as classified by ISRO in the BHUVAN portal.

4.1 Cyclogenesis and Subsequent Development

4.1.1 Track of Cyclone Tauktae (13th May 2021 - 19th May 2021)

Tauktae originated from a tropical disturbance, which was first monitored by the Indian Meteorological Department on May 13, 2021.



Graph 1: Intensity Bar Graph of Cyclone Tauktae. As observed is the steady increase in intensity of Tauktae and the rapid decrease after landfall.

i) A Well-Marked Low Pressure (WML) Area originated over the southeast Arabian Sea and the adjacent Lakshadweep area on 13th May 2021 at 08:30 am IST.

ii) The Probability of cyclogenesis i.e., the formation of depression (D) was observed at the east-central region of the Arabian Sea. This depression moved with a speed of 19 kmph in the North-Northeast wards' direction.

iii) This depression then intensified into a Deep depression (DD) at 08:30 am IST on 14th May 2021. The convection of clouds led to the formation of a curved band pattern with a cloud top temperature of -93˚C. The surface wind speed of this system ranged from 50-75 kmph.

iv) Later the system enhanced into a Cyclonic storm (CS) at 06:00 am IST on 15th May 2021 over the east-central region of the Arabian Sea moving northwards with a speed of 12 kmph. The magnitude of the surface wind speed ranged from 80 to 90 kmph. Through the INSAT imagery in Fig. 2., Tauktae is described with a ragged eye pattern.

v) At 05:30 pm IST on 15th May 2021, the storm intensified to Severe Cyclonic Storm (SCS) with a surface wind speed ranging from 95-115 kmph over east-central Arabian Sea.

vi) A Very Severe Cyclonic Storm (VSCS) over the east-central Arabian Sea with a speed of 19 kmph was formed at 08:30 pm on 16th May 2021 moving North-Northwest wards. The wind speed magnitude was from 115-185 kmph.

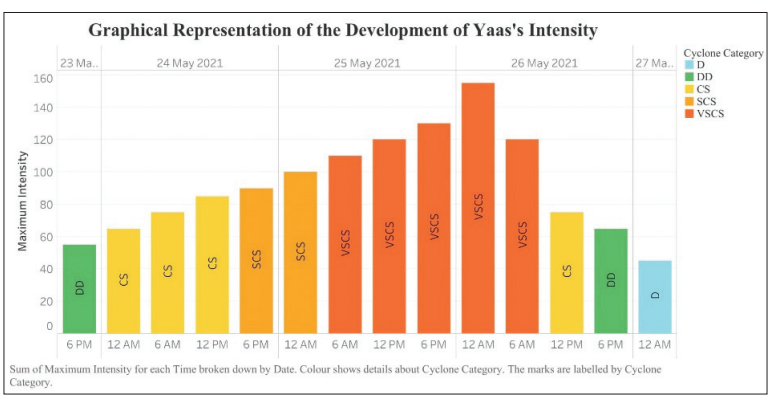
vii) At its peak the cyclonic system of Tauktae formed as an Extremely Severe Cyclonic Storm (ESCS) over east-central region of the Arabian Sea at 05:30 am IST on 17th May 2021 moving North-Northwest wards with a speed of 20kmph and surface wind speed reaching a magnitude of 210 kmph.

viii) On 17th May 2021, upon landfall at Saurashtra, the intensity of the system decreased from ESCS to VSCS with surface wind speed decreasing to 150-175 kmph.

ix) On 18th May 2021 the system further weakened to a CS and then to a depression over south Rajasthan and adjacent Gujarat.

x) The remnant of the Tauktae system moved north-eastward from Rajasthan to Uttar Pradesh as a low-pressure area with scattered low to medium cloud cover.

4.1.2 Track of Cyclone Yaas (23rd May 2021 – 27th May 2021)



Graph 2: Intensity Bar Graph of Cyclone Yaas. As observed is the steady increase in intensity of Yaas and the rapid decrease after landfall.

i) A Low-Pressure Area over the North Andaman Sea and the adjoining east-central Bay of Bengal originated on 22nd May 2021.

ii) Later a Depression was formed moving with a speed of 4 kmph towards West-Northwest direction.

iii) This system intensified into a deep depression located 600 km North-Northwest wards of Port Blair on 23th May 2021 at 11:30 am IST. The magnitude of the wind speed lied between 50-70 kmph.

iv) 24th May 2021 at 05:30 am IST the deep depression converted to a Cyclonic Storm moving in the direction of North-Northwest. The surface wind speed magnitude ranged from 50 to 70 kmph.

v) Later at 11:30 pm the cyclone Yass intensified into a Severe cyclonic storm over north-western region of the Bay of Bengal with surface wind speed from 100 to 120 kmph.

vi) The next day i.e., the 25th at 05:30 am IST the storm enhanced into a very severe cyclonic storm moving with a speed of 15 kmph north-westwards. The surface wind speed of the system ranged from 115 to 185 kmph. On 26th May 2021 the system made landfall over Odisha.

vii) This system then weakened to a Cyclonic storm on 26th May 2021 at 05:30 pm IST with surface wind speed from 75-95 kmph, leading into a depression on 27th May 2021 at 11:30 am IST and ultimately led into a well-marked low pressure over Bihar and east Uttar Pradesh.

viii) Similar to cyclone Tauktae the remnant of Yaas broke into low to medium clouds in central and North-eastern states of India and the Bay of Bengal.

4.2 Landfall

The phenomenon of the cyclone moving over the land after intensifying in the ocean is known as landfall. In a landfall, the eye of the cyclone moves across the coast towards the land thus intersecting the coastline. The peculiarity of the cyclone is that the fiercest winds do not occur within the eye but in the immediate surroundings of the eye. This explains the higher intensity of the cyclone effects before the landfall. The landfall generally is accompanied by strong wind gusts, severe storm surge and torrential downpour thus causing massive damage to the region. As observed in the tracks of Cyclones Tauktae and Yaas, after the landfall the storm generally weakens rapidly. This is due to the interaction with the rugged terrain and the absence of the required source i.e.; ocean heat and moisture are not available on land.

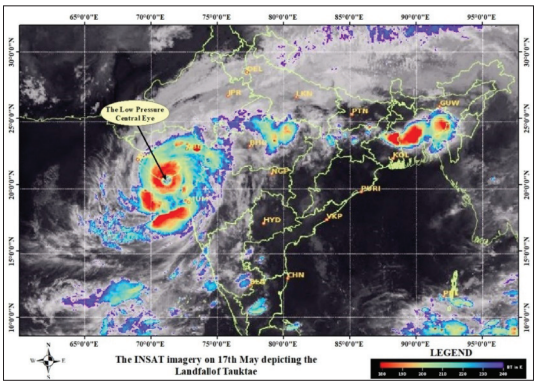


Figure 2: Layout of INSAT-3D image depicting the landfall for cyclone Tauktae along with the Cloud top temperatures. Minimum Cloud top temperature is -93°C and presence of a warmer ragged eye is observed. (Image Courtesy: MOSDAC)

The eye of the storm will cross the Gujarat coast between Una and Diu in the Saurashtra region with a slightly lower wind speed (155-165 kmph) than the attained peak speed of 210 km (TWC India Edit Team, 2021). According to PK Jena; Odisha's Special Relief Commissioner (SRC) the cyclone Yaas landfall occurred near Dhamra port in Odisha at 9.15 am IST on 26th May 2021. The landfall process took 3-4 hours to complete.

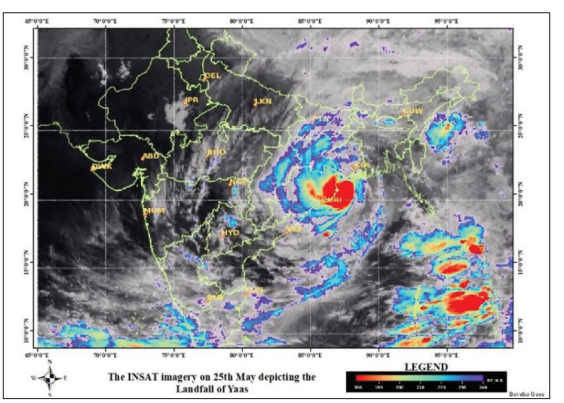
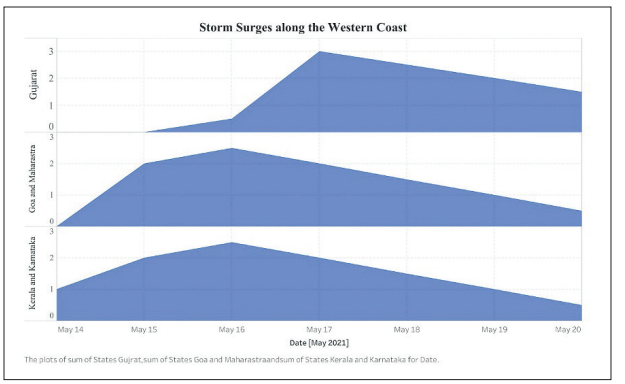


Figure 3: Layout of INSAT-3D image depicting the landfall for cyclone Yaas along with the Cloud top temperatures. As observed, the minimum Cloud top temperature is -93°C and there is absence of an eye pattern. (Image Courtesy: MOSDAC)

5. Impact of the Tauktae and Yaas

5.1 Impact of Cyclone Tauktae along the West Coast

Cyclone Tauktae is one of the strongest cyclones along the west coast. The depression over the Lakshadweep resulted in inundation of the low-lying areas by tidal waves about 1 meter above the astronomical tide.

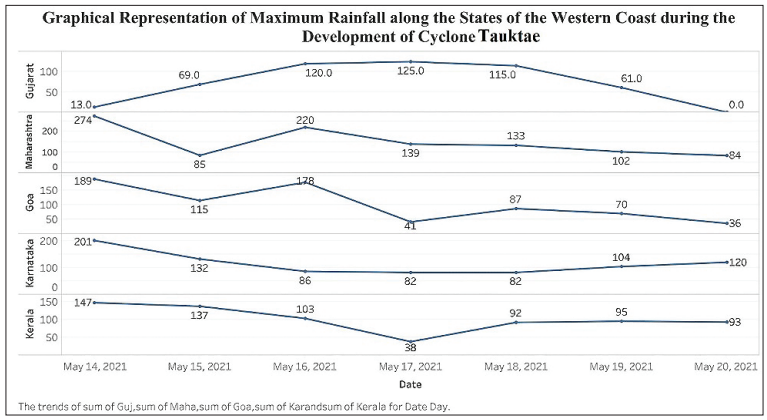


Graph 3: Daily Storm Surge heights above the astronomical tide for each coastal region during Tauktae's development. The landfall state; Gujarat experienced a later commencement of the surged but had the highest average surge of 3 meters.

The states of Kerala, Karnataka, Goa, Maharashtra experienced massive squalls which led to the destruction of thatched houses as well as 'pucca' houses, threat to flying objects, destruction of power and communication poles, metalled and unmetalled roads, railways, uprooting of trees and decrease in visibility. Being in the range of 100 to 200 km from the western coasts of Kerala, Karnataka, Goa and Maharashtra, the states endured wind gusts of more than 100 kmph. The city of Mumbai suffered wind speed up to 114 kmph as recorded by the weather station at Afghan Church in Colaba, which is the highest recorded wind gust in Mumbai in the past 70 years. Due to the landfall and the cyclone reaching its peak near the coast of Saurashtra, the State of Gujarat experienced the highest squalls with magnitudes of 170-185 kmph.

Apart from gusts, torrential precipitation is also one of the accompanied calamities. On 17th May parts of Mumbai like the Juhu Airport experienced rainfall of more than 300 mm within 24 hrs. This is the highest recorded rainfall amount in the month of May.

The coastal state of Goa and Kerala experienced rainfall of 145 mm from 14th to 16th May. The Saurashtra and Kutch were impacted with rainfall in excess of 200 mm. Apart from the coast, the inland states like Rajasthan, Haryana, Uttar Pradesh, Delhi and the Northeastern states experienced low intensity but heavy rainfalls from the remnant of the cyclone. Delhi received 60 mm of rainfall which is the highest in May in 35 years. The capital state also experienced the lowest temperature during this month at 23°C since 1951.



Graph 4: Daily maximum rainfall for each western state.

The entire western coast experienced large tidal waves leading to flooding of the low-lying areas. With wave heights between 4-5 meters, the coasts experienced massive erosions. The coastal region of Kerala and Karnataka experienced storm surges of 1 meter whereas the coasts of Goa and Maharashtra experienced tidal surges reaching 2.5 - 3 metres. The Kutch and Saurashtra region was most affected by the storm surges as the intensity of the Tauktae was highest before the landfall. The Gulf of Khambhat being a funnel-shaped bay concentrated the surges thus facilitating the tidal waves to be reaching 5 meters.

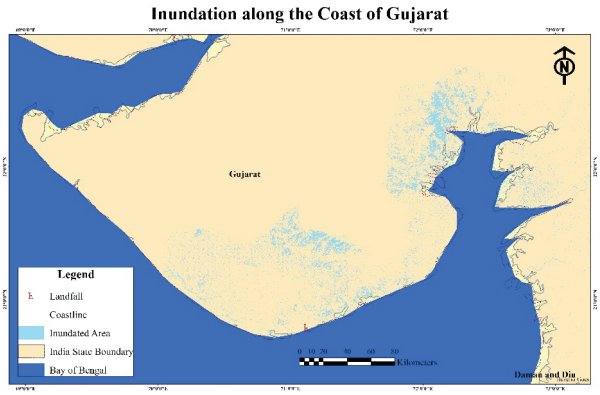


Figure 4: Map depicting the inundation caused by storm surge along the coast of Gujarat with a total inundation area of approximately 3482.6 km². As observed high inundation occurred near the Gulf of Khambhat due to the funnel shaped coastal configuration.

All these combined forces led to huge destruction. Strong wind gusts destroyed houses, huts, and state infrastructures. It also led to the uprooting of trees, communication and electricity poles creating blackouts, blockage of transport routes and also afflicting mobile connectivity. 70% of the state of Goa was in darkness for more than 48 hrs with more than 500 trees being uprooted. The intense rainfall-induced flooding and landslides in high terrain areas of Gujarat. The cyclone occurring during the pre-monsoon period ensured high seepage of rainwater into the ground thus reducing the risk of higher flooding in the affected areas. Indian Meteorological Department (IMD) stated that the low-pressure area in the North Indian region attracted high moisture content from the Arabian Sea thus ensuring rainfall for two more days till May 20th after the diminishing of the cyclone.

Figure 5: Waves hitting the Gateway of India in Mumbai on May 17, 2021 (AFP/Sujit Jaiswal).

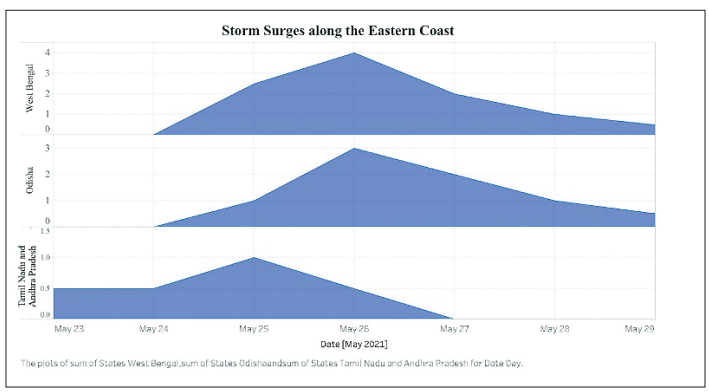
The greatest threat from cyclone Tauktae is the storm surge, especially near the region of landfall. The entire western coastline faced erosion thus destroying beaches, embankments and shacks. Apart from erosion, surges also inundated low lying areas and caused saltwater destruction in Lakshadweep, Kerala, Goa, Maharashtra and Gujarat. Such huge storm surges hindered and fishing activity which is a major occupation of the coastal regions. Many houses, structures and boats along the coast were destroyed. In Trivandrum, the roads along the coast were damaged by storm surges. As the highest storm surges were along the coast of Gujarat, vast areas of Saurashtra were inundated.

Figure 6: File photo on 19th May 2021 in Utorda, Goa. It depicts the seawater intrusion to the right of the picture due to the diminished sandune. (Regan Fernandes)

Not only do these disasters cause economic losses but also result in a high number of casualties. 16 fishermen were missing off the Kanyakumari coast. The sinking of barge P305 belonging to the Oil and Natural Gas Company (ONGC) resulted in 66 deaths off the Mumbai coast. The reported deaths due to the cyclone in Kerala were 10, 3 in Goa, 8 deaths in Karnataka, Maharashtra accounted for 18 deaths and Gujarat being the most affected accounted for 64 deaths. This total amounts to 169 deaths due to cyclone Tauktae. Around 80 people were injured as a result of the cyclone. The deaths reported were due to house collapses, drowning at sea, lightning strikes and other accidents linked to the cyclone. This cyclone also affected parts of Pakistan.

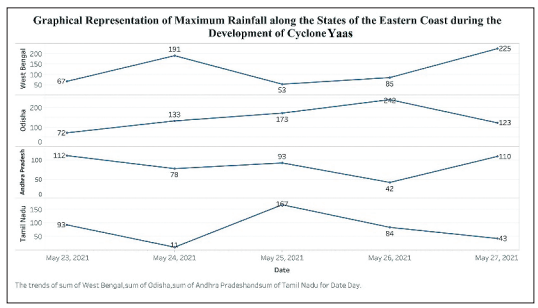
5.2 Impact of Cyclone Yaas along the East Coast

Unlike Tauktae, the cyclone Yaas is a VSCS thus being of lesser intensity. The worst affected states were West Bengal and Odisha with gale winds reaching 85 kmph. Sightings of tornados were also reported in Hooghly and North 24 Parganas districts on 25th May. Approximately 80 houses were destroyed in West Bengal. Torrential rainfall in West Bengal and Odisha were approximately at 90 mm on 24th May. This rainfall was not only restricted within the Coastal states of West Bengal and Odisha but also in the adjacent inland states of Bihar, Jharkhand and North-East India.



Graph 5: Daily Storm Surge heights above the astronomical tide for each coastal region during Yaas' development. Although not being a landfall state, West Bengal experienced the highest average surge at 4 meters.

Though the intensity of Yaas was lower, the storm surged during the cyclonic system of Yaas was greater than that caused by Tauktae. This greater storm surge was due to the lunar position during the cyclonic period. The full moon was closely aligned with the perigee thus being a supermoon and resulting in huge spring tides. The surges reported in Odisha ranged between 5 to 6 meters. In West Bengal, the reported wave heights in East Midnapore ranged between 3-5 meters.



Graph 6: Daily maximum rainfall for each eastern state.

Similar to Tauktae the gusts caused by this cyclone also destroyed houses, uprooted trees and communication and electricity poles leading to power outages near the coastal areas. Storm surges affected the coastal regions of West Bengal and Odisha ahead of the landfall leading to massive inundation, as most of the region is a low-lying plain. Compared to Tauktae the number of deaths due to Cyclone Yaas in India is lower-resulting in 6 deaths.

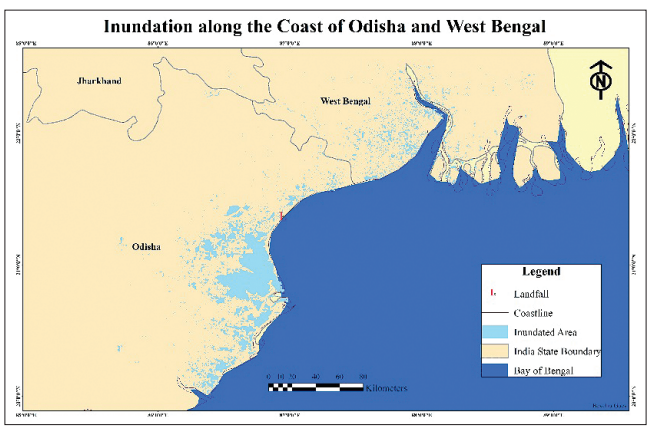


Figure 7: Map depicting the inundation caused by storm surges along the coasts of Odisha and West Bengal with a total inundation area of approximately 4275.82 km^2.

6. Mitigation Measures Engaged during the Cyclones

The disaster impact caused by cyclones can be reduced by; hazard and vulnerability analysis, preparedness and planning and most importantly the early warning

and mitigation. The Early warning system (forecasting) involves the prediction of interrelated cyclonic attributes like track, areas threatened by winds, rainfall and storm surge. The Indian Meteorological Department (IMD) which also acts as the RMSC, is the warning and forecast centre for cyclones occurring in the North Indian Ocean. With the forecast of cyclone Tauktae on 13th May and of cyclone Yaas on 19th May, the national forecaster issued warnings, possible damages and advisories to people living within the red alert zones under the threat of the two cyclones. The national warnings by IMD are conducted in five stages i.e.;

1. *Pre-cyclone Watch:* Such a warning is issued when a formation of a cyclonic disturbance that has the potential to intensify into a Tropical Cyclone is identified. The color code for this warning is Yellow.
2. *Cyclone Alert:* This bulletin is issued at least 48 hrs prior to the expected cyclone. The color code is Orange.
3. *Cyclone Warning:* This warning indicates the latest position of the Tropical Cyclone along with its characteristics like intensity, landfall time and position, the height of storm surge, damages expected and the actions suggested and is issued at 24 hrs before the cyclone. The color code is Red.
4. *Post-Landfall Outlook:* During the cyclonic system a warning at about 12 hrs before landfall and till the end of the cyclone is issued.
5. *De-Warning:* Post the cyclonic effects, when the tropical cyclone weakens into depression a De-Warning is issued.

Many techniques that are used to forecast the location and intensity of cyclones include; Radar, Statistical and Synoptic analysis, NMP models and most importantly through Satellite imagery. The INSAT-3D is one of the major satellite sensors for tracking cyclones. The rainfall is monitored by rain gauges and by the advanced use of remotely sensed images of PERSIANN, STAR, IMERG and other such sensors. One of the major approaches for storm surge guidance is by tide gauges and by surveying high watermarks. Such techniques are limited in number, perishable and lack accuracy. To compensate for this deficit, analytical nomograms and dynamic models are created for storm guidance using characteristics like intensity, pressure drop, landfall and storm motion.

IMD had urged the concerned authorities to take action by keeping the 5 districts of Kerala on red alert for 15th May, Gujarat under a red alert for 17th and 18th May and

warning about damages over Porbandar, Gir Somnath Botad and Bhavnagar, Amreli Junagarh and the Coast of Ahmedabad. The fishermen were advised not to conduct fishing along and off the Karnataka coast till May 17 and along and off Maharashtra, Goa and Gujarat coast till May 18. More than 2 lakh people along the coast of Gujarat were evacuated. Camps were set up for 87 people in Kerala. Apart from warnings and evacuations, many response teams were arranged during the cyclonic system to restore the trail of destruction rescue people. Initially, the National Disaster Response Force (NDRF) Director General SN Pradhan had assigned 53 NDRF teams; each having a strength of 47 personnel to tackle the after-effects of Tauktae for the western coast. Of these, 24 teams were pre-deployed to maintain the well-being during the cyclone whereas the rest were kept as backup. Due to the high impact and intensification of cyclone Tauktae the NDRF had increased the number of teams to 100. Apart from NDRF in Goa and Kerala the Indian Navy and Army helped in clearing debris and assist in the restoration of connectivity. The Indian Air Force arranged 16 transport aircraft and 18 helicopters on operational readiness in peninsular India necessitated due to Cyclone Tauktae.

The IMD marked the coastal region of Odisha and Bengal as a red alert. Around 15 to 20 lakh people were evacuated from the zones marked as a red alert. To restore the damages and rescue people about 106 teams of NDRF were deployed. West Bengal and Odisha each were provided with 46 teams. More than 2500 trees and poles that obstructed properties and roads were removed and more than 1000 persons were rescued by the Indian Defence Forces along with the coast guards. According to the Press Trust of India (PTI) a total of 404 rescue teams that include the NDRF, 205 Fire service teams, 60 from the Odisha Disaster Rapid Action Force (ODRAF) and 86 groups of tree-cutters were deployed in Odisha. In West Bengal and Andhra Pradesh huge number of fire brigades, police and disaster relief personnel were deployed for rescue operations. The Eastern Command of the Indian Army deployed 17 cyclone relief columns, comprising of specialised army personnel with their associated equipment and inflatable boats in West Bengal. Also, 22 teams of NDRF and State Disaster Response Force (SDRF) were deployed in Bihar. The landfall also resulted in massive damages in Bangladesh.

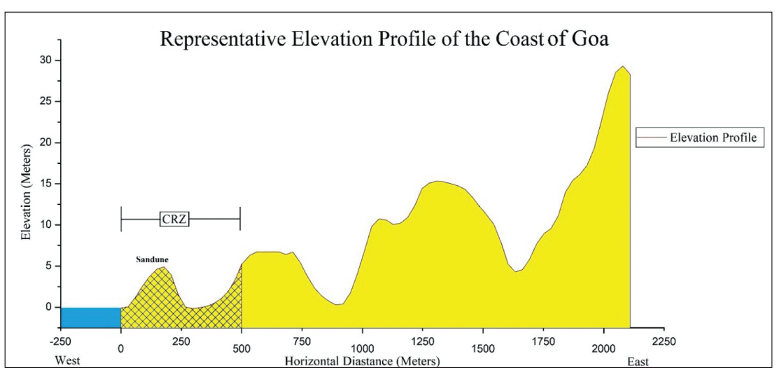
7. Conclusion

Occurrence of cyclones in the Indian ocean is common during May on the eastern coast of India over the Bay of Bengal. The occurrence of two pre-monsoonal cyclones – one on the western coast and the other on the eastern coast of India is an uncharacteristic phenomenon to transpire.

Being one of the fiercest cyclones to hit the west coast in decades, Tauktae was categorised as an Extremely Severe Cyclonic Storm on 16th May at night. According to JTCW the tropical cyclone Tauktae is the fifth-strongest cyclone on record in the Arabian Sea. Previously, most cyclones in the Arabian Sea tracked either directly towards Gujarat or migrated west of the Arabian Peninsula. But on 17th May, the centre of Tauktae tracked only 140 km west-southwest of Mumbai, India. During both the cyclone seasons, storm strikes around Mumbai seldom occur due to the prevailing meteorological conditions. According to National Oceanic and Atmospheric Administration (NOAA), since 1903 only five cyclones have been tracked within 100 km of Mumbai. With the recent Tauktae hitting the entire west coast – Kerala, Karnataka, Goa, Maharashtra, Gujarat – forecasters believe climate patterns are changing. The cyclone Yaas is among the many preceding cyclones to hit the eastern coast of India with Odisha and West Bengal being landfall prone zones during a cyclonic system. The presence of 1250 early warning systems in coastal villages and 450 cyclone shelters in Odisha, has drastically reduced the casualty rate since 2000 (Mahapatra, 2021).

The impact of both the pre-monsoon cyclones was more confined than regional. Due to the high seepage capacity of the ground, the flooding by precipitation was minimal. Apart from gales the storm surges caused seawater ingression in both the western as well as the eastern coast. The impact of a storm surge is associated with cyclone intensity, bathymetry of the coastline, angle at which the cyclone strikes the coast, coastal configuration and also the time of landfall (Mohapatra, 2015). The funnel shape coastal configuration of the gulf of Khambhat concentrated the storm surges thus causing the extreme inundation. The occurrence of the supermoon during the landfall of Yaas further intensified the storm surges. Perpendicular motion of the cyclone towards the coastline lead to surges of higher intensity as compared to parallel motion. Hence the coastal areas that did not experience the landfall, had significantly lower surge heights. The saltwater inundation caused by the surges damage vegetation and reducing soil fertility in the long run. The flooding caused by storm surges also

pollutes freshwater water sources like rivers, lakes and groundwater thus reducing the availability of potable water. The storm surges during the landfall of both the cyclones were categorised as Very High-Risk Zone. The coast is a geomorphologically dynamic region. Due to sand mining, unscientifically built seawalls, breakwater and infrastructure across certain coastal regions, the scenario of coastal erosion has worsened thus destroying the protective coastal relief features. Natural barriers such as sandunes (Figure 6.) and coastal vegetation protect the inland from such surges and thus minimizing the inundation. The coastal vegetation not only acts as a barrier but also hold the soil beneath thus reducing the erosive effects of surges and winds. Water is a hazard when it is excessive, deficient or contaminated. Comparing the sandune height in Graph 7 and the surge heights in Graph 3 and 5, one can conclude that such natural reliefs can be 'lifesavers against the wrath of the sea', during storms. A Cyclone, result in excessive water content, and its contamination thus damaging the surrounding as well as creating a shortage of potable water.



Graph 7: Topographical profile of the coast in Sernabatim, Goa. The sandune height observed is approximately at 5 meters.

The Arabian Sea and the North Indian Ocean were observed with warmer sea waters with temperatures ranging from 30°C to 32°C. These temperatures are above the average climatological temperatures from 1981 to 2010. The source of cyclones to fuel its deep convective storms is partly due to the result of increased temperatures. Until 2010 there were no observations of category 4 or stronger cyclones since 1998 over the Indian

Ocean. Since then, six category 4 or stronger cyclones (including Tauktae) have formed. According to (Dam, 2021) 'India's monsoon rainfalls will likely increase by 5% for every degree Celsius of global warming. This suggests that with increasing temperatures in the Arabian Sea and the North Indian Ocean more energy will be available to develop cyclones of higher intensities and the rainfall pattern will be more chaotic with shorter timespans and increased intensities. A Red alert was issued by IMD on July 19 in the coastal region of Goa and Maharashtra. Intense spells were experienced on the west coast in July. Wind gusts of 65km/hr during this period caused extreme damages in various parts of the coast. In Goa due to heavy rainfall, the northern villages were flooded, damages were caused to the archaeological site; Safa Masjid, caving of roads due to heavy flow of water, the collapse of Pailul-Sattari bridge, houses, landslides at the Ghats disrupted rail and interstate bus traffic, destruction of mobile connectivity are some of the damages caused. IMD stated that the rainfall during August and September is likely to be on the higher side of normal in Madhya Pradesh, West Bengal, Odisha, Jharkhand, Bihar and the North Eastern States. Such devastation is an uncommon spectacle in Goa and is the worst monsoon flood since 1982, providing an insight into the changing climatic pattern. Though the intensity was lower than the cyclone, the lack of seepage capacity of the ground was the major reason for the flooding.

The trend in the rising temperature of the Arabian Sea in the past 3-4 years has increased the probability of powerful tropical cyclones over the Arabian Sea (Murakami, et. al, 2017). Although some experts believe that rising temperature is not the only reason for the increased cyclonic events. As tropical cyclones become frequent on the western as well as the eastern coast of India, emphasis should be laid on restoring and protecting the natural barriers. Therefore, with this predicted future of a combination of factors like rising sea levels, warming oceans, climate change, rapid intensification, shorter timespans and changing meteorological conditions; there will be an increase in quantitative as well as the qualitative risk of cyclones. A disaster of such monstrous level cannot be prevented but its impact can be reduced by preservation and restoration of natural shields like coastal vegetation and sandunes, improved preparedness, immediate relief, providing accurate early warning, building resilient structures and using the ingenuity of science to create technological solutions.

8. Acknowledgment

The Author is thankful to National Institute of Disaster Management (NIDM) and the Indian Meteorological Department (IMD) for providing with valuable webinars that contributed in this study

The Author is also grateful to RSMC New Delhi (IMD), INCOIS, CHRS, BHUVAN (ISRO), for provision of valuable geospatial data through respective portals.

The Author expresses his gratitude to the professors of Central University of Karnataka and Parvatibai Chowgule College for providing an understanding of the Geoinformatics and Climatology and also to his parents and family for providing the support and motivation in accomplishing this study.

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