CHANGES IN THE FREQUENCY OF TROPICAL CYLONES OVER NORTH INDIAN OCEAN IN RESPONSE TO TROPICAL INDIAN OCEAN WARMING

by

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(2015 -20-026)

THESIS
Submitted in partial fulfilment of the
requirements for the degree of

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COLLEGE OF CLIMATE CHANGE AND ENVIRONMENTAL SCIENCE
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2021

DECLARATION

I, hereby declare that this thesis entitled "**CHANGES IN THE FREQUENCY OF TROPICAL CYCLONES OVER NORTH INDIAN OCEAN IN RESPONSE TO TROPICAL INDIAN OCEAN WARMING**" is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associate ship, fellowship or other similar title, of any other university or society.

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Certified that this thesis entitled "**CHANGES IN THE FREQUENCY OF TROPICAL CYCLONES OVER NORTH INDIAN OCEAN IN RESPONSE TO TROPICAL INDIAN OCEAN WARMING**" is record of research work done independently by Ms. SHEREENA JOSHI (2015-20-026) under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship, or associate ship to her.

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Shereena Joshi

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SYMBOLS AND ABBREVIATION

%	Percentage
M	Meter
Cm	Centimeter
m/s or ms^{-1}	Meter per second
Km	Kilometer
Sq.km	Square Kilometer
Mb	Millibar
hPa	Hecta Pascal
Kt	Knot
m/s	Meter per second
^{0} C	Degree Celsius
i.e.,	That is
Etc	Et cetera
/	or
~	Approximately
+	Positive
-	Negative
ξ_{850}	Low Level Relative Vorticity
M	Mid Tropospheric Relative Humidity
RH	Relative Humidity
I	Tropospheric Instability

Lat.	Latitude
Long.	Longitude
M	Mean
σ / SD	Standard Deviation
N	North
S	South
E	East
NW	Northwest
NE	Northeast
SW	Southwest
GHG	Greenhouse Gas
NIO	Northern Indian Ocean
NOAA	National Oceanic and Atmospheric Administration
IMD	Indian Meteorological Department
IPCC	Intergovernmental Panel for Climate Change
SST	Sea Surface Temperature
SWM	Southwest Monsoon
ITCZ	Inter Tropical Convergence Zone
IO	Indian Ocean
BOB	Bay of Bengal
ARB	Arabian Sea
TC	Tropical cyclone

D	Depression
CS	Cyclonic storm
SCS	Severe cyclonic storm
VSCS	Very severe cyclonic storm
ESCS	Extremely severe cyclonic storm
SST	Sea Surface Temperature
SLP	Sea Level Pressure
JJAS	June, July, August, and September
OND	October, November, and December
ERSST	Extended Reconstructed Sea Surface Temperature
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
Q	Specific Humidity
SPSS	Statistical Package for the Social Service
KGPI	Kotal Genesis Potential Index
NGPP	New Genesis Potential Parameters
JTWC	Joint Typhoon Warning Centre
NCEP	National Centre for Environmental Prediction
NCAR	National Centre for Atmospheric Research
NDMA	National Disaster Management Authority
SQRT	Square Root

INTRODUCTION

CHAPTER 1

INTRODUCTION

Disaster is an unexpected incidence occurring from forces that are mainly outside human control, strikes quickly with little or no warning, which causes or threatens serious disruption of life and resources, including loss of life and harm to many people, and requires thus, mobilization of efforts over that which are usually provided by statutory. India, the land of diversity, is being haunted by different types of natural disasters. Natural catastrophes in India, many of them are associated with the climate of India, cause widespread death and loss of property. India ranks among the most disaster-prone countries globally, producing many environmental hazards that make India's challenges unique and complicated. These challenges are all the more significant considering the impact of climate change on India's weather pattern and possible land use in India. Some of the natural disasters that India experiences include earthquakes, cyclones, floods, tsunami, landslides, volcanic eruptions, and avalanches. Among them, cyclones become the most alarming threat. ‘Cyclone’ comes from the Greek word cyclos, which means “coils of a snake”. Henry Piddington first used it, an officer in the Kolkata Port, for the tropical storms in the North Indian Ocean appear like coiled serpents of the sea. Tropical cyclones are rotating weather disturbances that originate in the tropics. They are intense circular storms in warm tropical oceans characterized by low atmospheric pressure, high winds, and heavy rainfall. TCs extends over hundreds of miles. Tropical cyclones generate winds exceeding 119 kilometers (74 miles) per hour, absorbing energy from the ocean surface and retaining its strength if it prevailed in warm water. In severe cases, winds can exceed 240 kilometers (150 miles) per hour, and gusts may surpass 320 km (200 miles) per hour. With this powerful wind, a catastrophic phenomenon called a storm surge can reach up to 6 meters (20 feet) above sea level. Such a mixture of powerful winds and water causes cyclones a severe threat to seaside regions in the tropics and subtropical regions of the world. However, if they get far enough north, they usually move eastward due to the impact of the mid-latitude westerly jet stream.

Whirling motion is more powerful, while the doldrums in ITCZ are far from the equator over oceans. It occurs as an autumnal equinox (August-September). At this time, there are some benefits, the air is overheated, and the sun is over the equator. However, because of the high specific heat, water, and mixing, ocean waters in the northern hemisphere receive the highest temperatures in August. In contrast, June and July are the hottest months on the continent. India has a challenging and disastrous history of tropical storms.

Globally, the India is one of the worst stricken regions concerning tropical cyclones. It is the weakest because of its 4,670-mile coastline, which is home to a large population. Cyclones typically develop in the North Indian Ocean from April to November per year. Normally, there is a preliminary peak in November and May.

The favourable basins for the development of cyclone are shown in the figure below:

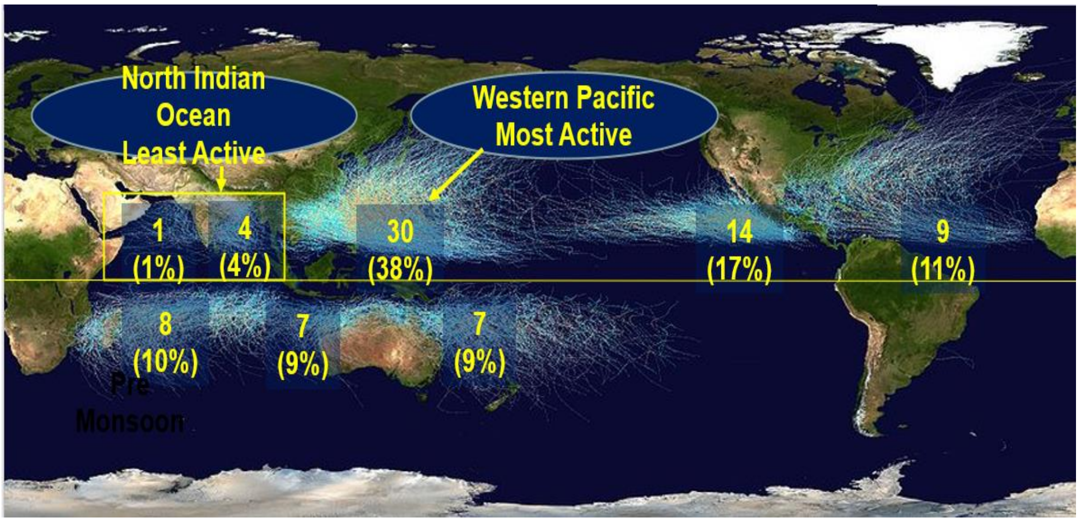


Figure 1.1: Occurrence frequency of tropical cyclones

Throughout the late summer months (July–September in the Northern Hemisphere and January–March in the Southern Hemisphere), storms hit areas as far apart as the Gulf Coast of North America, north-western Australia, and eastern India and BangladeshThe North Indian Ocean consist of two basins, the Bay of Bengal, and the Arabian Sea - creates about 7% of the world's tropical cyclones. More cyclones form in the Bay of Bengal than in the Arabian Sea. (Mandal and Gupta, 1981) i.e., Tropical cyclogenesis is most common in the northern regions of the Indian Ocean in and throughout the Bay of Bengal.

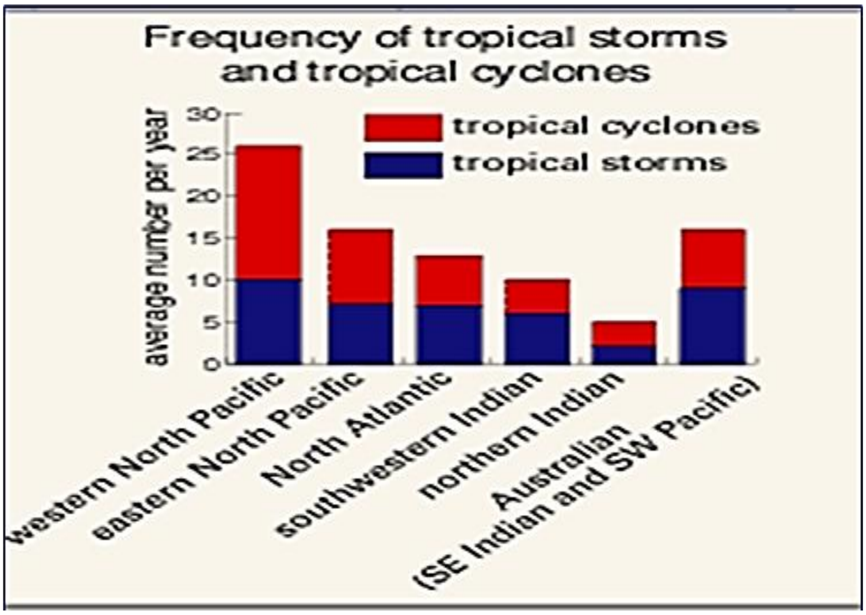


Figure 1.2: Frequency of tropical storms and tropical cyclones

India’s western coast, neighboring this calmer Arabian Sea, rarely encounters cyclones; these primarily affect Gujarat and, less often, Kerala and sometimes Odisha. However, their influence is relatively significant and destructive, particularly when they hit the East Indian and Bangladesh shores adjoining the North Bay of Bengal because of the vast population density throughout the low-lying regions near these coastlines. The depressions and deep depressions in the Bay of Bengal commonly do not intensify to cyclonic storms because of the reduced vertical wind shear throughout the peak summer monsoon season.

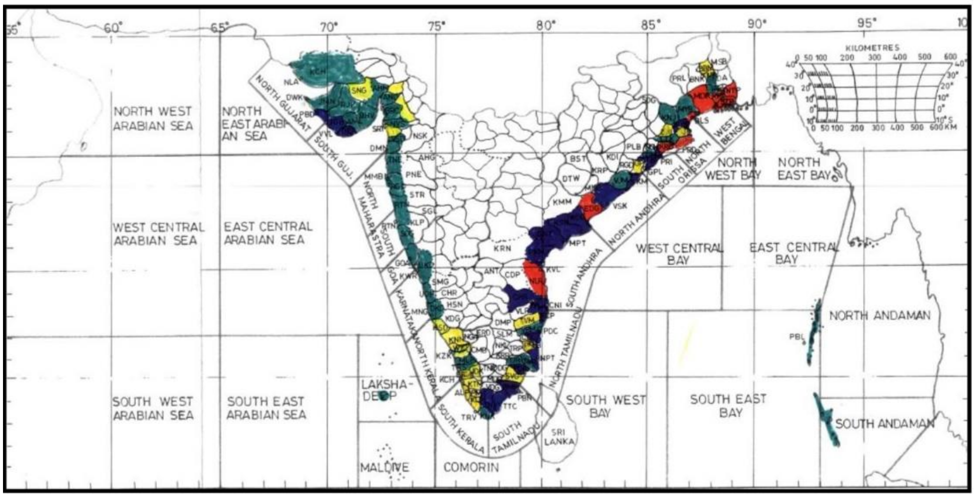


Figure 1.3: Cyclone risk districts in India (source: NDMA, IMD)

On average, approximately 5–6 TCs develop in the Bay of Bengal and the Arabian Sea each year, of which 2–3 TCs becomes the severe stage. Over the years, there have been several most destructive TCs that have hit the Indian land.

A few of the most remarkable TCs in India during recent history:

Tropical cyclone Bhola is one of the most devastating natural calamities ever reported in India. The cyclone formed in the Bay of Bengal in November 1970 and made entered in East Pakistan before making its way into West Bengal. At the peak, the storm created wind speed of 115 mph, damaging the coastal areas it run into. It is anticipated that 300,000 to 500,000 people loss life during the calamity, which turned into a recorded tropical cyclone. Another destructive storm that developed over the BoB was the 1991 Bangladesh cyclone. While it entered the land in Bangladesh and eastern India, it created winds of up to 155 mph, making it one of the very strongest in history. In addition, the cyclone generated a worst storm surge that was 20 feet in height. It washed ashore, killing at least 138,866 people. Operation Sea Angel was carried out by several countries in the storm's fallout by the largest military relief operation ever recorded. The 1999 Odisha cyclone was the very powerful TCs ever reported in the North Indian Ocean. However, unfortunately, it was also one of the highly calamitous in the state. At its peak, wind speeds of up to 160 mph were recorded, a record low pressure. About 10,000 people died, causing an estimated $ 4.44 billion in damage as it affected the Indian state of Odisha, as well as Thailand, Myanmar, and Bangladesh.

As the world struggles to deal with the Covid-19 during the Pandemic, the seasons and what they bring with them continue to affect us. This has been clear in the last few months as TCs have already started touching the Indian coast. By mid-May 2020, we witnessed a super cyclone, the Amphan raging Ganga delta, and Nisarga, a severe cyclone hitting the Indian state of Maharashtra. Both TCs had serious repercussions in regions of the country. However, Amphan was the worst cyclonic storm in the area ever since 2007 and the first 'super' storm ever after the 1999 Odisha cyclone. This super cyclone destroyed 84 people in West Bengal and Bangladesh. As the storm made landfall close to the city of Kolkata, 14 million people lost electricity and troubled. The cyclone is estimated to have caused more than $ 13 billion in destruction, with windspeed of up to 160 miles per hour. In early June 2020, cyclone Nisarga was formed in the Arabian Sea. As the cyclone started to gain strength, experts worry about that it would affect the city of Mumbai. Typically, TCs occur across the Arabian Sea, generally heading west into Oman. At that moment, Mumbai was the most infected city in India, affected by Covid 19. It is among the most populous cities of India, with over 20 million. Fortunately, the eye of the cyclone lost Mumbai a little.

TCs are one of the fascinating weather events in the tropics. TCs have a significant impact on the weather and climate of tropical countries. Global Warming has a prominent effect on the north Indian Ocean Cyclones, and its consequence will seriously disrupt the life and livelihood across India. Any variation in the number and intensity of tropical cyclones in the Bay of Bengal and the Arabian Sea will have far-making socio-economic effects for India and its neighboring nations. For example, every year, tropical disturbances on the eastern seaboard of India, Myanmar, and Bangladesh cause massive socio-economic loss of life and property because of the storms in the Bay of Bengal. Due to the vast inhabitants and the dramatic rise in infrastructure plans in India's seaside areas. However, the death toll from cyclones has dropped in recent years due to advances in science and technology and the evacuation of many humans and animals before landfall. The recent cyclone Phailin of October 2013 and cyclone Hudhud of October 2014 are two examples that made landfall on the eastern seaboard of India. On October 11, 1999, near Gopalpur at around 2130 IST and at Visakhapatnam on October 12 at approximately 1330 IST. Thanks to the inclination of the 1999 Odisha Super Cyclone, the death toll from both the cyclones has dropped significantly. Tens of thousands of people died; However, the economic damage of buildings and infrastructure has dramatically risen. For example, cyclone Hudhud near Visakhapatnam in 2014 exceeded Rs 4,000 crore, while the total loss from the cyclone was over Rs 36,000 crore.

Tropical cyclones usually do not attain high intensities over the Arabian Sea because of adverse wind shears, dry air supplies from the Thar Desert, and comparatively low SST. Yet, the Arabian Sea has created intense cyclonic storms, primarily noticed in recent years. According to the India Meteorological Department, the ratio of cyclonic storms in the Arabian Sea, over which the cyclone Nisarga developed in June 2020, and the Bay of Bengal, cyclone Amphan formed in May 2020, is typically 1: 4.

Tropical storms of about 1.7 (0.9 in the post-monsoon) formed in the Arabian Sea each year from 1979-2015 with the strongest surface wind ≥ 17.5 m s−1, just around 2% of the cyclone frequency globally ESCS Nilofar, Chapala, and Megh throughout the post-monsoon in the years 2014 and 2015, recognized as tropical storms by the World Meteorological Organistion, by a maximum wind speed of 46 m s^{-1}, were first examined over the Arabian Gulf Sea, forming extensive destruction. Extremely severe cyclones are increasing, especially during the post-monsoon season (October-December). The average number of observed

TCs is two per year between 1998-2019 in the Arabian Sea. The unusually high number of TCs over the Arabian Sea, some highly severe with wind speeds higher than 167 kmph, results from warming seas and sea surface temperature distribution changes. (Murakami et al., 2017)

The main aim of my study includes:

1. To study frequency variation of Tropical storms during the post-monsoon season in the Arabian Sea.
2. To know the role of Indian Ocean Warming on the cyclone frequency and intensity.
3. To identify the role of different cyclogenesis potential parameters in capturing the observed variability.

This study presents a comprehensive analysis of changes in tropical cyclone data in the Arabian Sea over the recent four decades (1980-2019). It examines the possible consequences of climate change on tropical storms' number and severity on Indian seaboards throughout the post-monsoon season and variations in Indian Ocean SSTs and circulation systems. Thus, their frequency and intensity trend in the North Indian Ocean is significant for South Asia's maritime regions. Therefore, knowledge of the changes in cyclone count and severity of North Indian Ocean Cyclones will be helpful for better coastal hazard and coastal zone management.

REVIEW OF LITERATURE

CHAPTER 2

REVIEW OF LITERATURE

Tropical cyclones are one of the most energetic and destructive extreme weather phenomena in the atmosphere. It is formed mainly in warm ocean regions with favorable climatic conditions for organized convection activity. Several studies have suggested that the sea surface threshold value of sea surface temperature should be high, with which TCs are not forming below 26.5ºC. [Palmen,1948; Gray,1968] TCs follow the track with warm ocean areas and weaken as they move over cold water. [Fisher 1958]. Every year, the coastal areas of the Indian subcontinent are affected by the developing tropical cyclones in the North Indian Ocean, a region very favorable for cyclone formation. It accounts for about 5% of the global annual total TCs. Although cyclones formed in the northern Indian Ocean are relatively weaker than those developed in the Atlantic or the Pacific Ocean, they are highly destructive.

The North Indian Ocean has been experiencing a minimum of one severe cyclonic storm each year. Over the past several decades very severe cyclonic storms have affected the coastal areas along the east coast of India, for example 1977 Diviseema cyclone formed in BoB, 1999 Orissa cyclone etc. had devasted the low-lying regions with associate strong storm surges. The massive wave of sea water creates lot of damages in coastal regions. Thus, studies on cyclones are very important as it will directly affect the seaside environment and its surrounding areas. The extreme weather events such as cyclones, storm surges, heavy rains, floods, thunderstorms greatly influence the socio-economic factors of India and are increasing due to the effect of climate change over globally. Especially east-coast of India had good fertile lands which produce maximum food grains from these regions. During cyclones, most of the time total yield was lost due to rains and flooding. Since TCs are one of the significant geophysical sources of loss of life and property, it is essential to know whether there is some variation in the frequency and intensity of TCs due to anthropogenic climate change.

From 2017-2018 around 12 cyclonic events have occurred in either basin of the north Indian Ocean. The frequency and intensity of cyclones are upticks when compared to past years. IPCC considers 0.25-0.5ºC rise in warming over tropical ocean over past two decades due to increase in greenhouse gas concentration over past 5 decades. The main concern about climate change is its consequences on tropical cyclones' rate, strength, and span. Nearly all the intense storms of the North Indian Ocean develop during November throughout the post-monsoon season and May in pre-monsoon, which will hit the coastal region of India and Bangladesh. Observational and modeling studies indicate that tropical cyclone wind would be increasing ocean temperature. (Sankar et al., 2010) The recent cyclone activity in the North Indian Ocean has gained considerable notice from the people and the research society. For example, in May 2008, cyclone Nargis developed in the BOB and caused landfall near Myanmar. Cyclone Gonu, which developed over ARB in June 2007, was the initial Category 5 cyclone to hit the coast, wreaking havoc near Oman, causing the country's greatest natural calamity. Evan & Camargo (2011) described a significant rise in the number of TC days each year, i.e., the number of days persisting in the tropical storm basin over the ARB during 1992-2008 correlated to 1979-1991. The trend presents a relative increase in the number of TC origin in the following period (1.8 TC per year) compared to the previous one (0.8 TC per year). Accumulated cyclone energy (ACE; Bell 2003) is the sum of the squares of the highest stable wind speed per cyclone, which almost quadrupled during 1998-2008 compared to 1979-1997. These recent severe TCs have promoted a general concern in the connection between TCs and climate change, as both theories (Emmanuel 1987), including modeling (Knutson et al. 2010), imply that TC intensities rise in hot weather (Solomon et al. 2007).

A tropical cyclone is a large swirling mass of moist air that has low pressure through the system. In other words, the whole area surrounded by tropical cyclones is low atmospheric pressure. The intensity of the cyclone is determined by the reduction in pressure at the center. The horizontal rate of pressure drop from the periphery to the middle is gentle. The frequency of cyclones is higher in the Bay of Bengal than in the Arabian Sea, with a proportion of 4: 1. Most storms in the Bay of Bengal lose their strength on land, and the number of migrations to the Arabian Sea is reduced. In addition, the sea surface temperature in the Arabian Sea is lower than in the Bay of Bengal. Of the six tropical cyclones, 2-3 severe hurricanes intensify into a hurricane phase. (Gray et al., 1968) There are two main seasons for their formation on both sides of India: March-May (pre- monsoon) and October to December (post-monsoon).

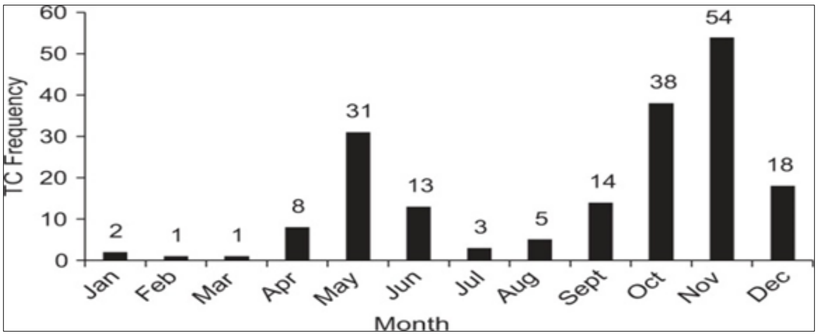


Figure 2.1: Pre-monsoon and post monsoon cyclone in North Indian Ocean

North Indian Ocean basin exhibits a dual peak with the secondary peak throughout March to May before the onset of Monson and a primary peak during October to December after the beginning of monsoon. Since SST are above 27ºC during the post-monsoon season, TCs weakening due to cooler SST does not arise. Instead, it is found that variations in environmental parameters are accountable for the noted raises in TC strength. The increased SST also the higher ocean heat content caused the ocean to be more conducive to TC intensity. At the same time, the better convection instability produces the atmosphere extra conducive to its maturity. Thus, significant changes in the atmosphere and ocean occur in the northern Indian Ocean. These differences are part of the positive linear trends, symbolizing that the magnitude of post-monsoon TCs may grow in the future.

2.1 Structure of a tropical cyclone

When a TCs at its mature stage, a few structural elements can be identified, which are common to all tropical cyclones and could form a conceptual model.

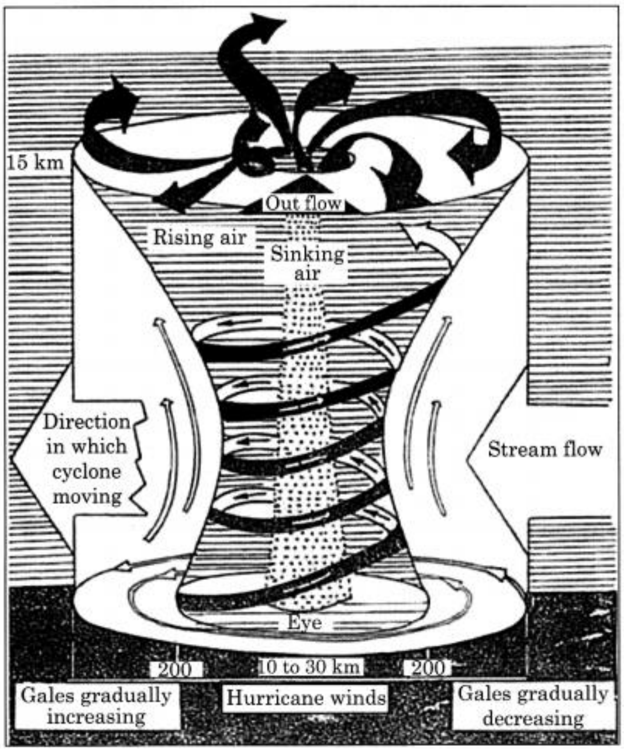


Figure 2.2: Formation and structure of a cyclone (Source: IMD)

1. **Inflow layer-** Up to 3 km high, and the bottom layer, generally named as the inflow layer, is accountable for driving the cyclone.
2. **Eye-** The clear central eye is a relatively light windy area. The fair weather seen in the middle of a severe tropical cyclone will gradually appear from the satellite.

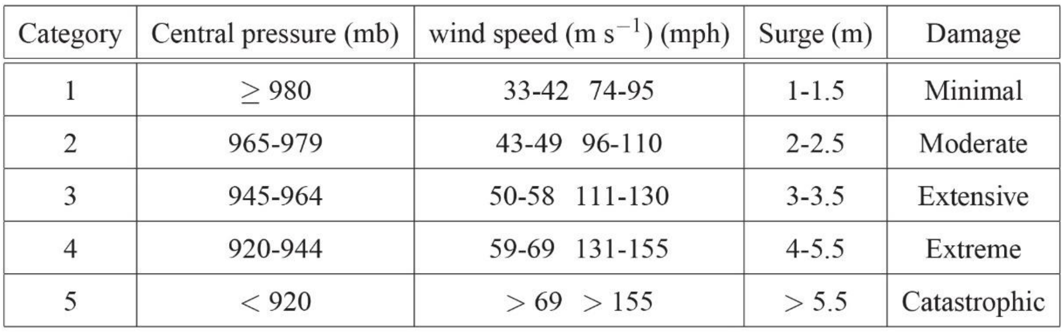
3. **Eye wall-** The tropical storm surrounds the eyewall with an approximately circular circle of deep convection, the highest surface wind area. Therefore, the highest winds are also blowing in the eyewall area.
4. **Cirrus shield-** A large shield of cirrus and cirrostratus usually accompanies the high-altitude outflow of cyclones. These can produce underlying rain bands, which are sometimes difficult to see even with the naked eye in satellite photographs.
5. **Rain bands-** In addition to the deep convection cells around the eye, secondary cells are arranged in bands around the center. These bands are called rainbands and spiral to the center of the storm.
6. **The upper-tropospheric outflow-** This is over 7 km and can be seen in all tropical cyclones. The largest outflow is seen at 12 km and beyond. The flow of air in this area is anticyclonic.

2.2 Categories of tropical cyclones (Sankar et al., 2010)

The India Meteorological Department (IMD) has formulated the following criteria based on the ability to damage, which categorizes low-pressure systems in the Bay of Bengal and the Arabian Sea, which the WMO has approved.

- Low-pressure (wind speed less than 17 knots)
- Depression (wind speed between 17-27 knots)
- Deep Depression (wind speed between 28-33 knots)
- Cyclonic storm (wind speed between 34-47 knots)
- Severe Cyclonic Storms (wind speed between 48-63 knots)
- Very Severe Cyclonic Storms (wind speed between 64-119 knots)
- Super Cyclonic Storm (wind speed equal to or greater than 120 knots)

Tropical cyclones can be further classified in terms of wind speed using the Saffir-Simpson scale (Simpson and Riehl, 1981) which ranges from category 1: the least intense, to category 5: the most intense.



Category	Central pressure (mb)	wind speed (m s^{-1}) (mph)	Surge (m)	Damage
1	≥ 980	33-42 74-95	1-1.5	Minimal
2	965-979	43-49 96-110	2-2.5	Moderate
3	945-964	50-58 111-130	3-3.5	Extensive
4	920-944	59-69 131-155	4-5.5	Extreme
5	< 920	> 69 > 155	> 5.5	Catastrophic

Table 2.1: Saffir-Simpson Hurricane scale (Pielke and Pielke, 1997)

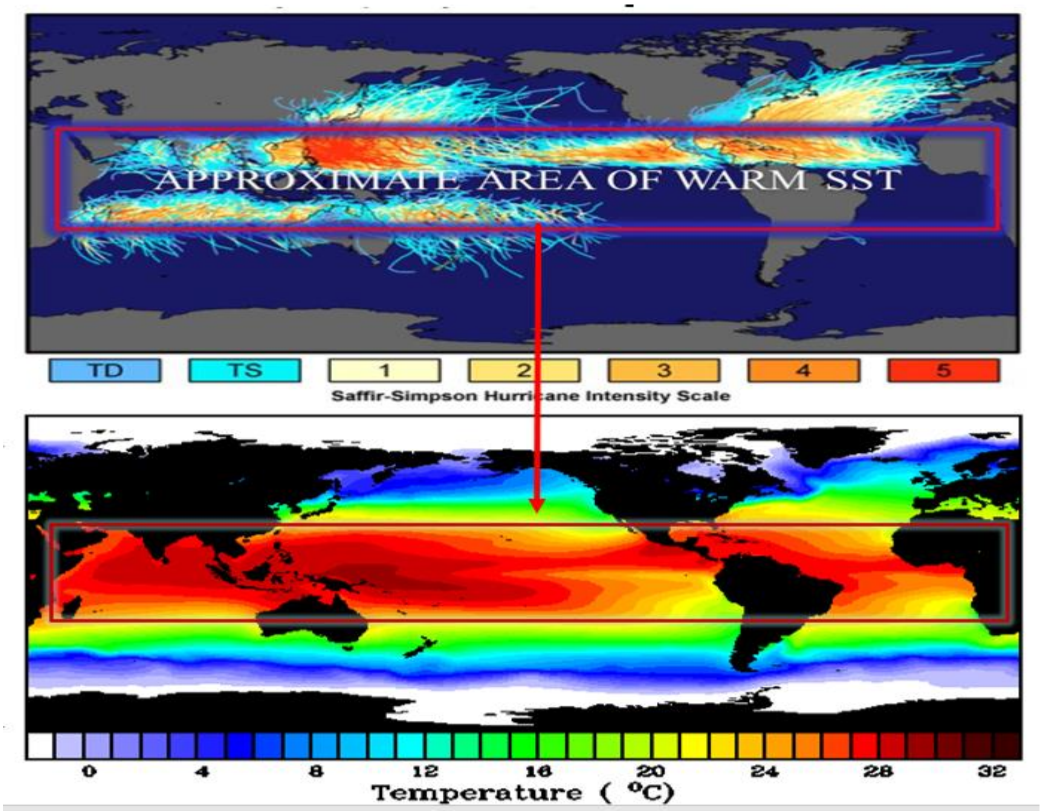


Figure 2.3: Saffir-Simpson scale (Pielke and Pielke, 1997)

2.3 Conditions Favouring Formation of Tropical Cyclone (Gray, 1968)

Seasonal tropical cyclone number is correlated to the combination of some specific physical parameters; these will henceforth be called the primary Genesis parameters. Willian M. Gray (1975, 1979) recognized the three dynamic and three thermodynamic parameters (recognized as Gray parameters) that favored the origin of TCs:

I. **Dynamical factors-**

a) **Low-level relative vorticity-** Low-level disturbance should be anticipated in the form of eastern wave disturbance in ITCZ. Small-scale local variations in the temperature of the sea water also cause the air to create several low pressure centers of narrow size. Because of the extra moisture across oceans, the thunderstorm strengthens and absorbs in the air faster—a weak cyclonic rotation forms throughout these regions. Then, a genuine cyclonic whirlwind may mature very quickly due to the rising warm, humid air. Because of the Coriolis force a vortex is created, the air in the atmosphere is blown away and distorted. Nevertheless, hardly a few of those storms develop into cyclones. Instead, due to centripetal acceleration, the air in the cyclone is driven to create a calm region termed the eye in the center of the storm. As a result, the interior side of the cyclone develops eyewall, the most powerful area of the storm. According to McBride (1974), a low-level vortex-developing cloud cluster doubles as an undeveloped disturbance. Therefore, tropical cyclones require constant low-level imports of mass, water vapor, and speed. The intensity of the import of this quantity in the boundary layer, or at an altitude of 1 km above the surface, is significantly related to the Ekman type frictional wind shear force. Across the tropical seas, it is found (Gray, 1972) that this friction of the wind averages within 10-15°.

b) **Coriolis force:** There are no cyclones over the equator due to the zero Coriolis force (Coriolis force is zero), but it increases at latitude. The Coriolis force at 5° latitudes is sufficient to create a vortex. Around 65% of cyclone movement happens within 10° and 20° latitudes. This parameter is connected to the first parameter of Frank (1977) to the absolute cyclone.

c) **Weak vertical wind shear (VWS)-** Windshear is the difference within wind speeds at various altitudes. Tropical cyclones originate while the wind speed is the same. Due to the weak vertical wind shears, cyclone origin activities are confined to the latitudinal equatorial wards of the subtropical jet stream. In temperate zones, strong winds are more likely to be due to westerly winds, which prevents the formation of convection cyclones. Vertical wind shears are the strongest for tropical cyclones. Vertical wind shear is a change in wind direction and velocity as altitude increases in the atmosphere. Vertical wind shears are associated with the reaction of large-scale tropical circulation obstruction. This factor is a large-scale parameter that plays a crucial part in the origin and strengthening of tropical cyclones. When there is deep vertical wind shear, the top of a tropical storm can blow down hundreds of miles. In this case, the storm will become very unbalanced or tilted vertically and will begin to relax as it draws in dry air and/or obstructs the flow of hot and humid air throughout the storm. The stronger the tropical cyclone, the more subtle the phenomenon. As the tropical cyclone intensifies, the phenomenon becomes more subtle. The stronger the tropical cyclone, the more subtle the phenomenon. Since the latent heat generated during the convection process does not escape from the circulatory system, low wind shears are conducive to the formation of turbulence to develop. Tropical cyclones generally require a calm atmosphere to develop, maintain intensity, and/or continue to intensify.

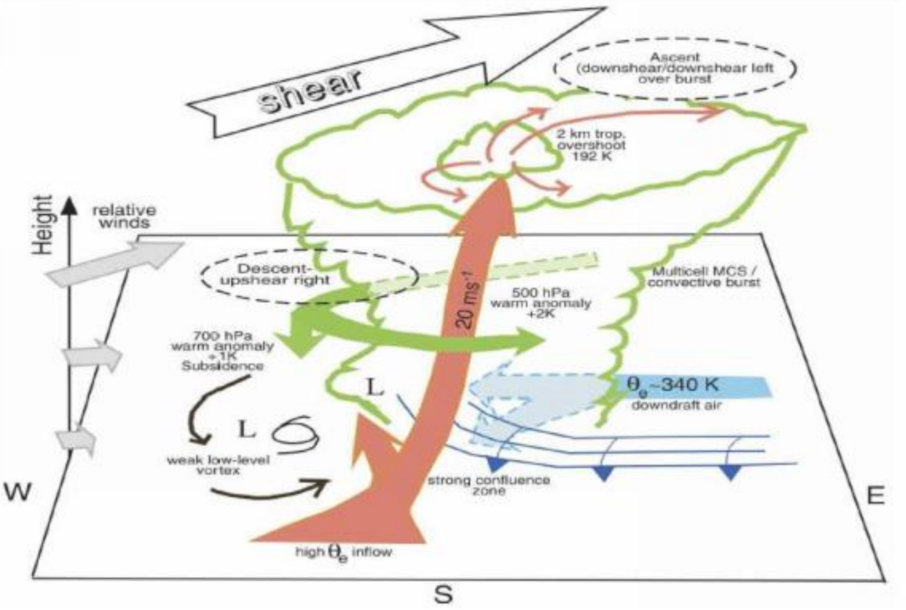


Figure 2.4: Schematic on the influence of vertical wind shear on a tropical cyclone (Heymsfield et al., 2006)

As this continues, the rising mass of air begins to spin faster and faster. The more air rises, the lower the pressure, the faster the air tries to restore it, creating higher winds. Although some tropical cyclones can form and strengthen even in moderate winds, such storms are often unlikely to rupture or develop at first. Moreover, for the duration of the formative stage, if the disturbance comes under the divergent portion of an upper air trough and when the low-level convergent region is superimposed by the upper-level divergence associated with the trough, it gets intensified. The surface low tends to deepen. The disturbance tends to spin up. On the other side, when the disturbance is under a high level of convergence field, it will weaken and eventually dissipate. Wind turbulence significantly limits the formation of hurricanes during the monsoon.

II. Thermodynamical factors

a. **Sea surface temperature (SST)-** Elevated SSTs play a vital role in the formation of the storm in the north Indian Ocean (Yokoi 2010; Chowdhury et al. 2020; Kotal et al. 2009). The threshold value of the SST, below which TCs do not form, is 26.5℃, and a deep thermocline is needed. The high SST increases the movement of heat fluxes from the ocean to the atmosphere, facilitating better convection and providing favorable requirements for the genesis of cyclones. For example, warm SSTs (30–31 C) in the Arabian Sea increased heat flux transfer from the ocean to the atmosphere before the onset of cyclone Gonu. This enhanced the storm into a severe cyclonic storm (Krishna and Rao 2009). The condensation of moisture distributes sufficient latent heat of condensation to enhance the cyclone. Since cooler temperatures prevail in the Southeast Pacific and South Atlantic, no storms form in these regions. It is estimated that the magnitude of the sea to the airflow of sensible heat plus latent heat in the average cyclone is about 712.21Watts/m2 /d in the inner 80 km. Tropical cyclones can profoundly influence the ocean's temperature across which they move. The altered ocean temperature, in turn, can feedback and modify the nature of the cyclone. The depth of the warm water should be 60-70 m from the sea surface in such a way that the deep convection currents in the ocean do not combine with the hot water near the sea surface and the cold water below. These conditions occur, particularly in western tropical seas. The warm waters currents flowing from the east towards the west develop a thick layer of water with temperatures greater than 27°C. This releases sufficient moisture into the cyclone. The cold currents reduce the sea surface temperatures of the eastern parts of the tropical oceans, making them inadequate for developing storms.

b. **Conditional instability-** In the early stages of growth, a low pressure is formed above the ocean, and a cluster of vertically developed clouds is formed, because the vertical currents are caused by the converging wind. These cumulonimbus clouds produce thunder. During thunderstorms, the vapor converts to a liquid form and distributes the latent heat as it falls as rain. Due to heat loss, the air column heats up and the surface pressure decreases. As the pressure decreases, more winds converge toward the center of the depression and more clouds form. The second type is a cycle of development called conditional instability (CISK), which explains hurricane development.

c. **High relative humidity (RH) in the lower and middle troposphere-** This is an essential parameter for tropical cyclone formation. The dry mid-troposphere is unsuitable for the genesis and persistence of extensive convective activity. Cyclones avoid developing where the seasonal amount of mid-tropospheric relative humidity is low. Enough middle-level relative humidity (a minimum threshold of 40%) is necessary for cyclone formation (Gray, 1968, 1975). A high RH level in the middle troposphere from 3 to 6 km (1.8 to 3.7 miles) in altitude is more conducive to the generation of deep cumulonimbus convection and hence to deeper upward coupling in the troposphere. Firstly, the convective clouds beginning in the boundary layer are consumed by the entrainment of dry air as they rise within the middle troposphere. Secondly, much of the mass convergence takes place in tropical cyclones over the boundary layer. Dry middle-level air means less condensation convergence in the column and less latent heat release. Even Though intense cumulonimbus convection happens nearby middle latitude land regions in low, mid-tropospheric relative humidity conditions, cumulonimbus convection does not usually happen over the sea areas when mid-tropospheric relative humidity is less than 50-60%. Over tropical sea, large mid-tropospheric vapor content is a potent enhancer rather than an inhibitor of deep cumulus convection.

Although those parameters are not enough for cyclogenesis, TC genesis may progress in areas and seasons when the product of the parameters discussed above is maximal (Gray, 1975). Climate-friendly formation zones are well-suited to the post-monsoon seasonal trough location, and depression intensifies as a hurricane in this region. Numerous tropical lows develop as simple waves in the easterlies of the Trades, e.g., monsoon depressions of the head Bay of Bengal in South Asia or tropical waves off the west coast of Africa. Such regional waves or depressions generally move W/WNW/NW wards and account for sizable rainfall in the tropical lands. Tropical cyclones may originate from a cyclonic eddy traveling westwards in the tropical belt; or form in situ, starting as a thermal low over the warm waters of tropical seas, where land and sea are in good juxtaposition. The circumstances are favorable for developing cyclones in the western parts of tropical oceans, where prevailing moist air is general conditionally unstable. The warm moist air over tropical waters, having sea surface temperature (SST) around 28.3º C (83º F) in October, 27.8º C (82º F) in November and 26.7 C (80 F) in December elsewhere over the ocean, produces a steep lapse rate of temperature there and, therefore, favors strong convection and fall of pressure locally.

2.4 Formation and Development of Tropical Cyclones

TCs have a thermal origin and development in the tropical oceans in late summer. In these areas, the main local convection currents gain a cyclonic motion due to the Coriolis force. Once developed, these storms continue until they attain a weak point in the trade wind belt. While there are desirable requirements, numerous thunderstorms are developing in the tropical seas. These lightning bolts combine to form an intense low-pressure system. In thunderstorms, the air rises as there is heat and light. Due to the lapse rate and the adiabatic lapse rate at fixed altitudes, the air temperature reduces, and the humid air condenses. Condensation releases condensed heat, creating hot air. This results in significantly less weight and more lifting. This area is covered with clean moist air. Condensation happens in this air, and when moisture is applied the cycle continues. Due to the excess moisture in the tropical oceans, thunderstorms become stronger and more rapidly absorbed into the air.

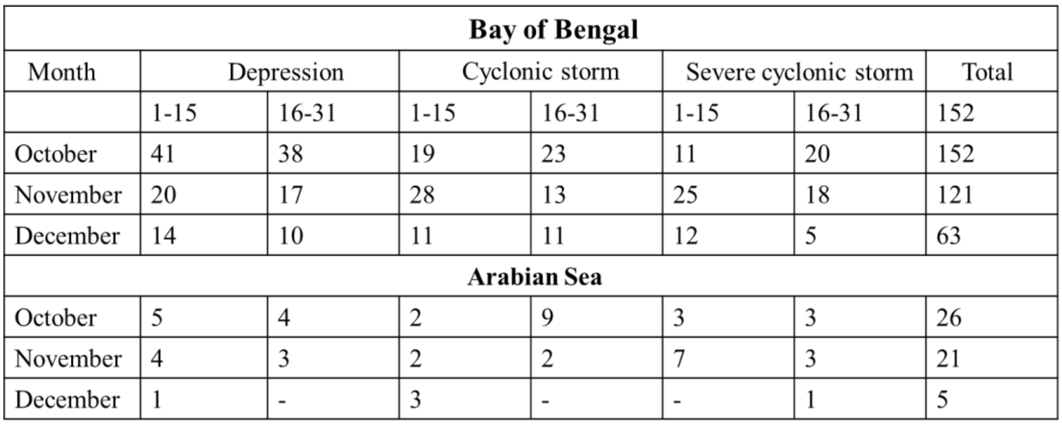
Cyclone Coriolis is a force that causes the surrounding air to rise and fall. Due to the centrifugal force, the air in the cyclone is forced to form a calm position in the center of the cyclone, known as an eye. The inner surface of the cyclone creates the ivory, a very violent area of the TCs. Every wind that carries it upwards absorbs its moisture and expands to cool and intense. It falls to the surface along the cylinder eye area and through the edge of the vortex. Continuous moisture from the oceans is the most important driving force behind each cyclone. As it moves to shore, the moisture supply is interrupted, and the hurricane disperses. If the sea can give more further moisture, the storm will attain maturity. At this point, the cyclone movement of the wind develops multiple convection cells with continuous calm and violent locations. Areas where cumulonimbus clouds grow is called rain band, and below that receive severe rainfall. The rising air will lose humidity in certain areas and fall back to the surface across the quiet areas between the two rain bands. The formation of clouds is in the middle. The area of the cloud contracts from the center to the outside. Rain bands are chiefly formed up of cumulonimbus clouds. The marginal clouds are Nimbostratus and Cumulus clouds. Cirrus clouds form a dense covering at the top of the troposphere, usually containing hexagonal ice crystals. Dry air flowing through the dense middle cloud layer falls around and around the eye area.

2.5 Track of tropical cyclones

TCs start with a westward motion but turn north at a latitude of 20. They rotate north-east around 25 ° latitude and then east around 30 latitudes. They then deplete and deplete the energy. They then deplete and deplete the energy. TCs go through a parabolic path, their axis remains parallel to the isobars. Coriolis force, east and west winds change the course of tropical cyclones. TCs melt at 30 latitudes due to calm seawater and westerly winds.

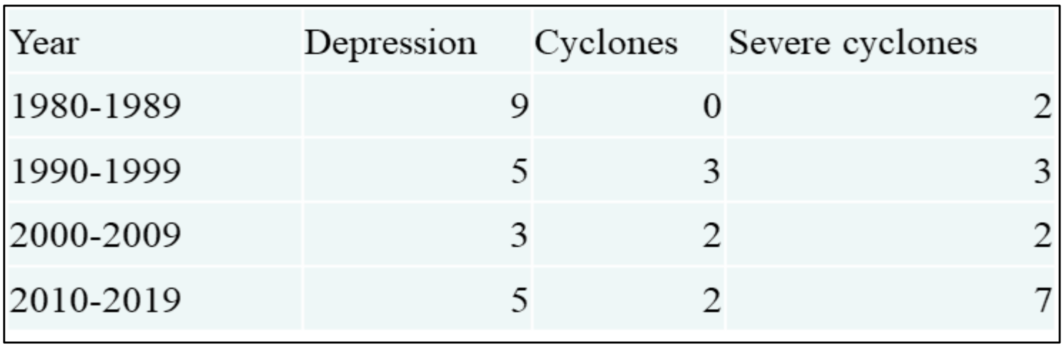
2.6 Storms and Depressions in Arabian Sea during post-monsoon season

As well as intense convective activity, the warm weather season is characterized by the TC activity in the Indian Ocean. TCs are bimodal across the North India Ocean, with a primary peak in November and a secondary rise in May, i.e., one in post-monsoon and in the pre-monsoon season. Very rarely cyclones develop in the Indian Ocean from January to March. The Indian Ocean develops 5-7 cyclones per year, accounting for 7% of the global total (about 890). They are short-lived, smaller in size, and less intense than their counterparts in the other tropical oceans. However, they are deadlier when they cross the coast nearby the North Bay of Bengal. This is mainly due to severe storm surge problems in these regions. They develop from April to mid-June during the pre-monsoon season and from October to mid-December in the post-monsoon; these stages of storm activities in the Indian Oceans are recognized as the ‘Storm Season.’ In the table given below, numbers of depressions, cyclonic storms, Severe cyclonic storms for 86 years (1877 – 1972) while the post-monsoon season.



Bay of Bengal							
Month	Depression		Cyclonic storm		Severe cyclonic storm		Total
	1-15	16-31	1-15	16-31	1-15	16-31	152
October	41	38	19	23	11	20	152
November	20	17	28	13	25	18	121
December	14	10	11	11	12	5	63
Arabian Sea							
October	5	4	2	9	3	3	26
November	4	3	2	2	7	3	21
December	1	-	3	-	-	1	5

Table 2.2(a): Depressions/Cyclonic Storms/Severe cyclonic storms 1877 – 1972 (86 years) over Bay of Bengal and Arabian Sea.



Year	Depression	Cyclones	Severe cyclones
1980-1989	9	0	2
1990-1999	5	3	3
2000-2009	3	2	2
2010-2019	5	2	7

Table 2.3(b): Depressions, Cyclonic Storms, Severe cyclones 1980-2019 over the Arabian Sea throughout post monsoon season.

The initial peak of the tropical cyclones in the Indian Ocean is seen in November. From the above table, the following features are revealed.

- In October, the more significant number of tropical cyclones and depressions, and December has the fewest
- Maximum number of cyclones originates throughout November. The number of cyclonic and severe cyclonic storms is higher in the first half of November than in the latter half.
- Thus, the earlier half of the post-monsoon season creates a primary cyclonic season for India.
- The number of cyclones and low pressures in the Arabian Sea is relatively small compared to the Bay of Bengal.
- In October, the number of depressions was higher than the number of cyclones and depressions. In the months that followed, storms were more likely to cause depression.

2.7 Place of origin

There are two seasons of tropical cyclone formation in the North Indian Ocean between 5-15 ° latitude. During post-monsoon season:

October-

In the Arabian Sea, the development is in the Eastern Half to the west of Longitude 70° E between 12° N and 17° N.

November-

Depressions develops over SE of Arabian Sea. Yet, their strengthening is much spread out (8° N to 13° N)

December-

Throughout December, their number is negligible.

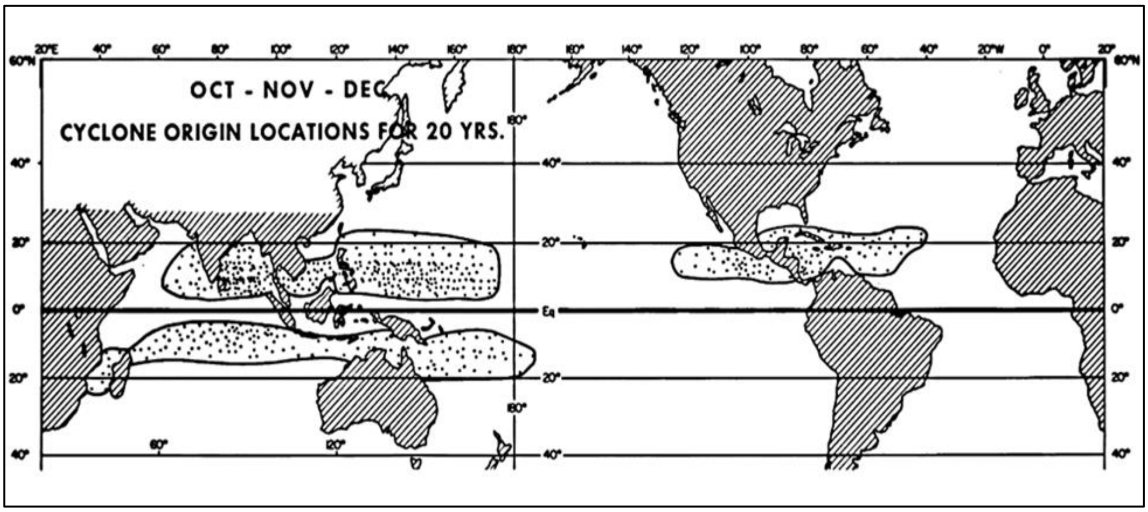


Figure 2.5(a): The spots on Figs. 2.5 show post-monsoon cyclone formation points for all tropical cyclone formations over a 20-year period from 1952-1971. (Source: Gray et al.,1975)

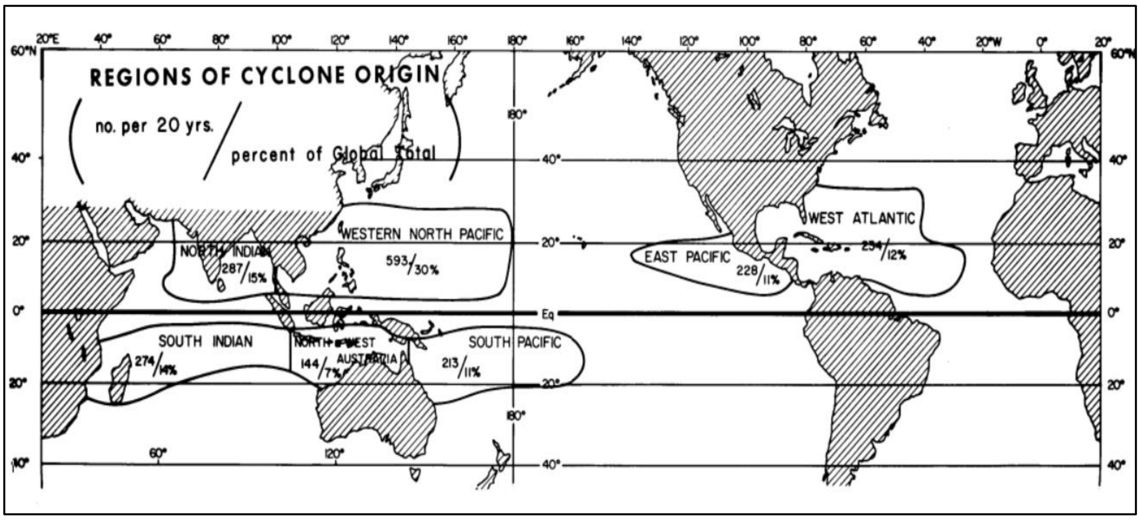


Figure 2.5(b): The figure depicts cyclone origin areas and provides information on local genesis frequency over the 20 years from 1952-1971.

(Source: Gray et al.,1975)

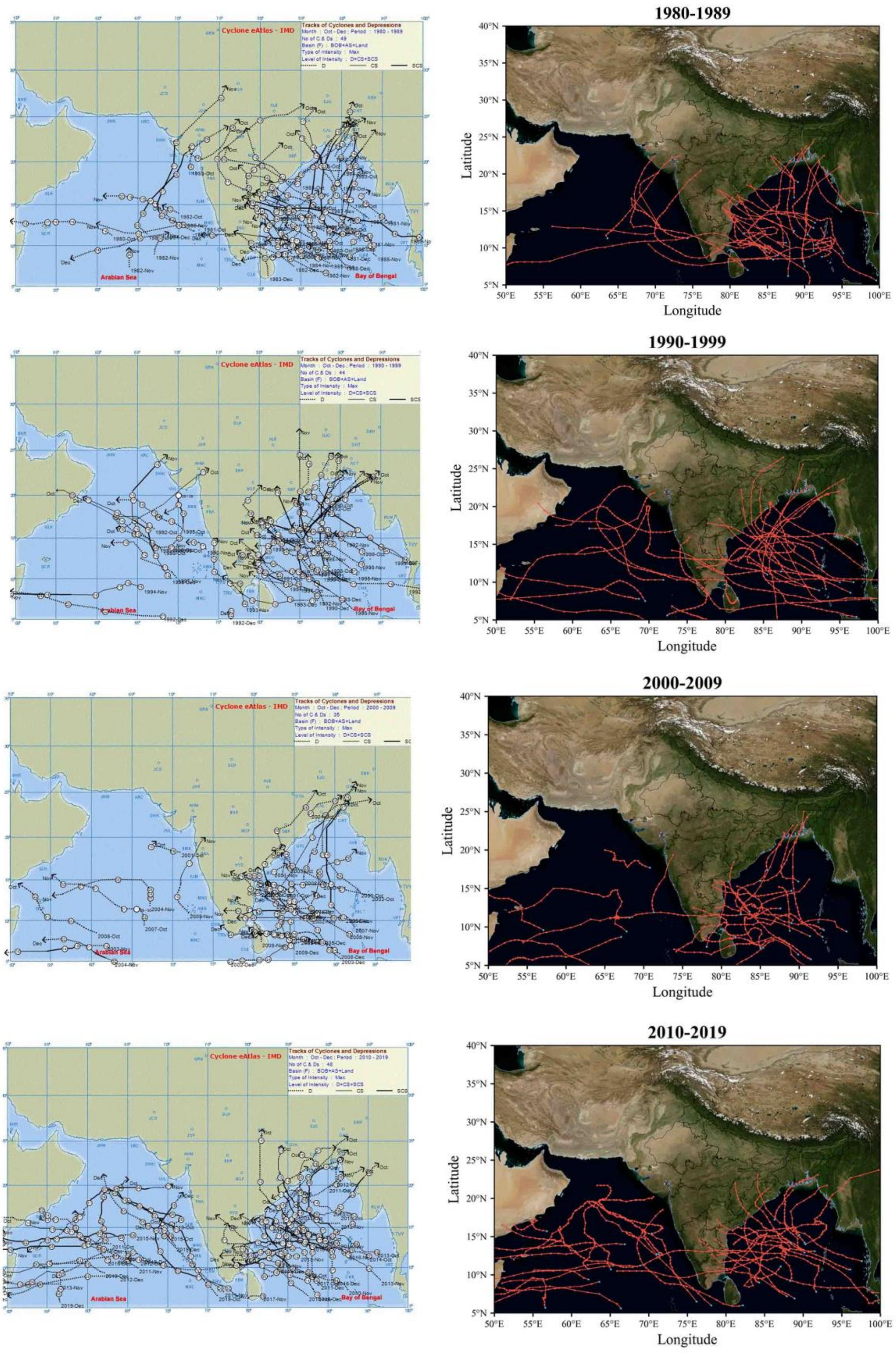


Figure 2.6: Place of origin and track of storms during post monsoon season, 1980-2019

2.8 Movement of Storms and Depressions

Around 60-70 percent of the post-monsoon cyclones reach the Indian shore. Cyclones make their way along the coast of the Indian subcontinent along certain characteristic tracks. Thus, the probable path of a cyclonic storm can be calculated to some degree of confidence according to the climatology of storm tracks. Nevertheless, pre-monsoon storms and post-monsoon storms exhibit significant fluctuations in their path. Most of the instabilities (60-70 percent) that develop across the BOB throughout October and November hit the east coast of India. Although, throughout December, barely around 20 percent of them move to the Indian coast. In this period, half of them dissipate over the ocean as they migrate north or recurve eastwards. With the progress of the season, the cyclones hit the east shore at a more southerly latitude. In October, more than 80 percent of the storms make landfall on the east coast north of latitude 14º N, about 70 percent of the coast within November 10º N and 16º N. In December, 80 percent of the south coast of latitude 14º N. Some of the storms in the Bay of Bengal, are likely to move south Peninsula and intensify again into cyclonic storms across the Arabian Sea. About 20-25% of the storms that form in the Arabian Sea strike the western seashore of India. Most of the cyclones affect the Gujarat – North Maharashtra seaboard between 18º N and 23º N. The storms that develop across the Arabian Sea in November recurve N to NNE wards. The possibility of recurvate is highest in December for the Bay of Bengal and the Arabian Sea cyclones. In October, the systems move more towards the west than to the north. Also, it is evident that in the east coast of India, north Tamil Nadu – South Andhra Coast and Gujarat coast in the west coast are most exposed regions from storms threat during the post-monsoon season.

2.9 Impact of climate change on tropical cyclones

According to a research paper published in Nature Geosciences, future predictions based on the theory and high-resolution dynamic models consistently show that climate change will turn the average strength of TCs around the world into a powerful storm and develop in intensity by 2-11% 2100. Current theories suggest a 6-34% decrease in the global average frequency of TCs. High-resolution modeling studies generally expect a significant increase in the frequency of the most intense cyclones, with a 20% increase in rainfall within 100 km of the storm center. Recent global climate models continue to predict future drops in overall TC numbers. Yet, it does indicate an increase in the intensity of hurricanes and an increase in rainfall. Further studies indicate that Category 4 and 5 cyclones will double and heavy rainfall is expected by the end of this century. Globally, the consensus forecast is a 5-30% decrease in TC numbers, a 0-25% increase in the frequency of Category 4 and 5 storms, a 0-5% increase in the maximum intensity of normal lifetime, and an increase of 5-20% in TC rainfall. Recent high-resolution modeling research suggests that the frequency of the most severe cyclones correlated with widespread physical impact is likely to rise significantly in some basins under the heat of the 21st century, with moderate confidence in TC rainfall levels increasing everywhere.

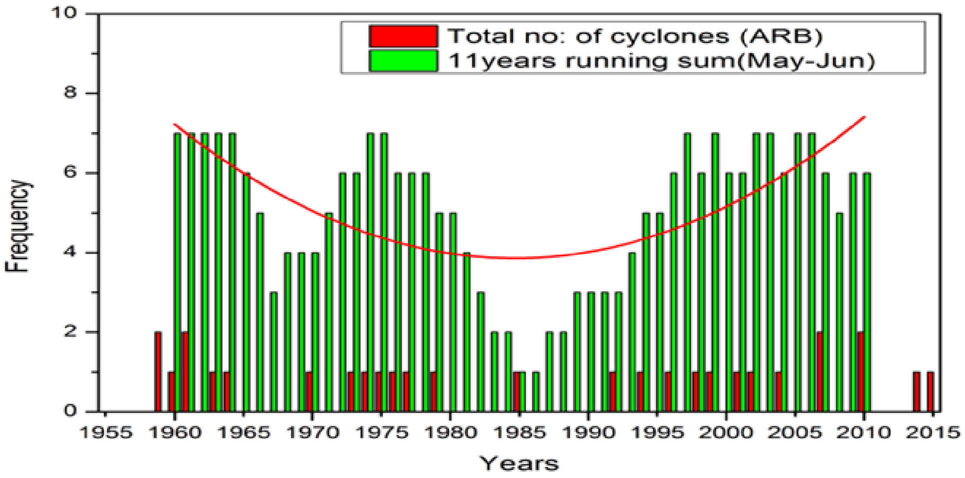


Figure 2.7: Number of cyclones over the Arabian sea throughout pre-monsoon season (Baburaj and Abhilash, 2018)

Epochal variability in the frequency of cyclonic storms during the pre-monsoon season over the Arabian Sea. Recent CS Gonu, Ashoka, Sagar, Mekanu are examples.

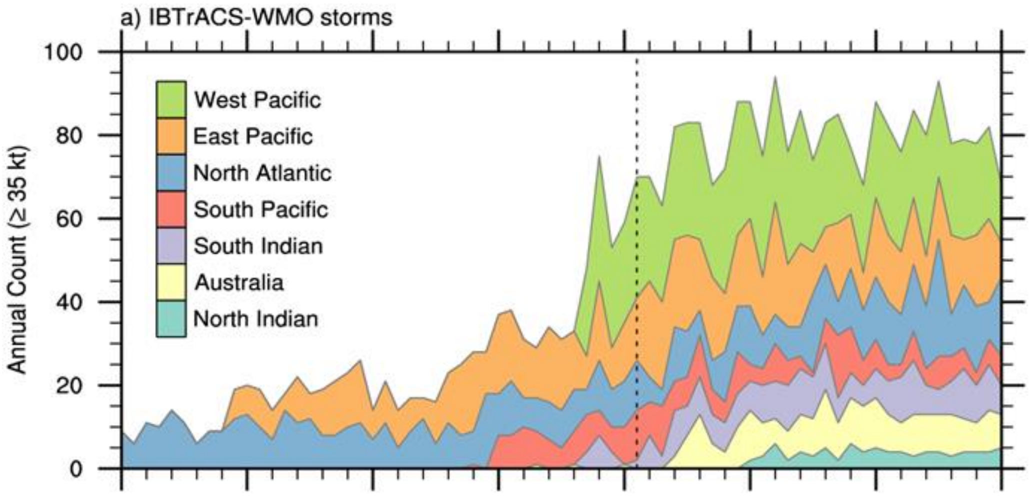


Figure 2.8: Number of extremely severe cyclones over the Arabian sea during post-monsoon season (Murakami et al., 2017)

Recent observations of ESCS, Nilofar, Chapala, Megh, and recent Ockhi in the Arabian Sea after the monsoon are clear evidence of these findings. (Murakami et al.,2017) In 2014, cyclone Nilofar, the first ESCS with a maximum wind speed of 46 m s 1, was recorded in the Arabian Sea during the post-monsoon period (Vinodhkumar et al. 2021). Two more post-monsoon ESCSs, Chapala and Megh, were observed in the Arabian Sea in the following year. It was found that natural variation plays a small role in the enhanced frequency of the ESCS. Therefore, sustainable anthropogenic forces will increase the risk of cyclones in the Arabian Sea and the resulting socio-economic repercussions. (Murakami et al.,2017) Prior to 1998, no satellite data was available. Therefore, the storm's intensity can be reduced due to the oblique view of the adjacent moons. ESCSs were not identified after 1998 and in the post-monsoon season until 2014, indicating that change in the amount of ESCSs was associated with anthropogenic warming. Various studies consistently state that anthropogenic global warming has raised the average storm severity. Cyclone Ockhi in 2017 was the fourth-strongest hurricane to hit the Arabian Sea in the last 28 years.

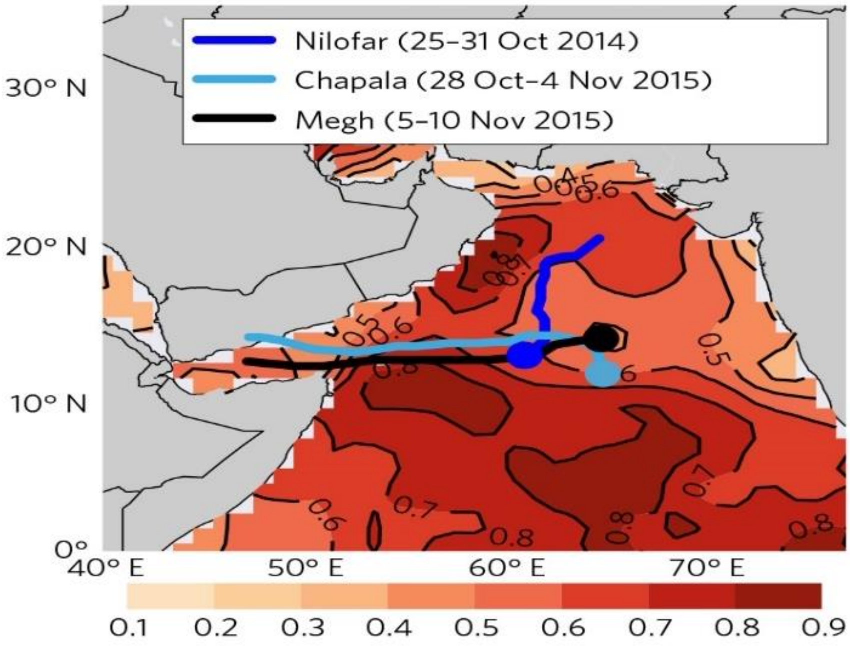
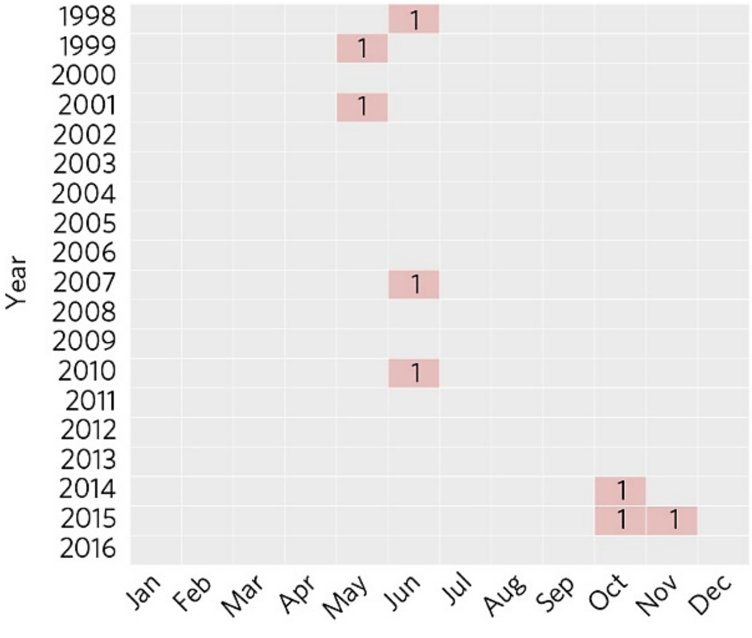


Figure 2.9: Extremely severe cyclonic storms Nilofar (blue), Chapala (light blue), and Megh (black) during the post-monsoon season in 2014 and 2015, along with the observed linear trend in SST.



Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1998						1						
1999					1							
2000												
2001					1							
2002												
2003												
2004												
2005												
2006												
2007						1						
2008												
2009												
2010						1						
2011												
2012												
2013												
2014											1		
2015										1	1	
2016												

Table 2.4: Observed number of ESCSs over the ARB for each month for the period 1998–2016. (Murakami et al.,2017)

The rate of Ocean Warming over Arabian Sea is More compared to other regions, over the box shown in the figure, it is warmed by around 0.450C in 4 Decades (1982-2017). Arabian Sea is warmed by more than 1.3 0C in the last 117 years. (No Satellite Date before 1980) The Indian Ocean has warmed higher than the global mean. A recently published IPCC report claimed Red Alert and issued the strongest warning about global warming. It says the Indian Ocean is warming up faster than other oceans. Sea surface temperatures in the Indian Ocean increased by a normal of 1 ° C during the period 1951-2015, compared with the global average of 0.7 C.

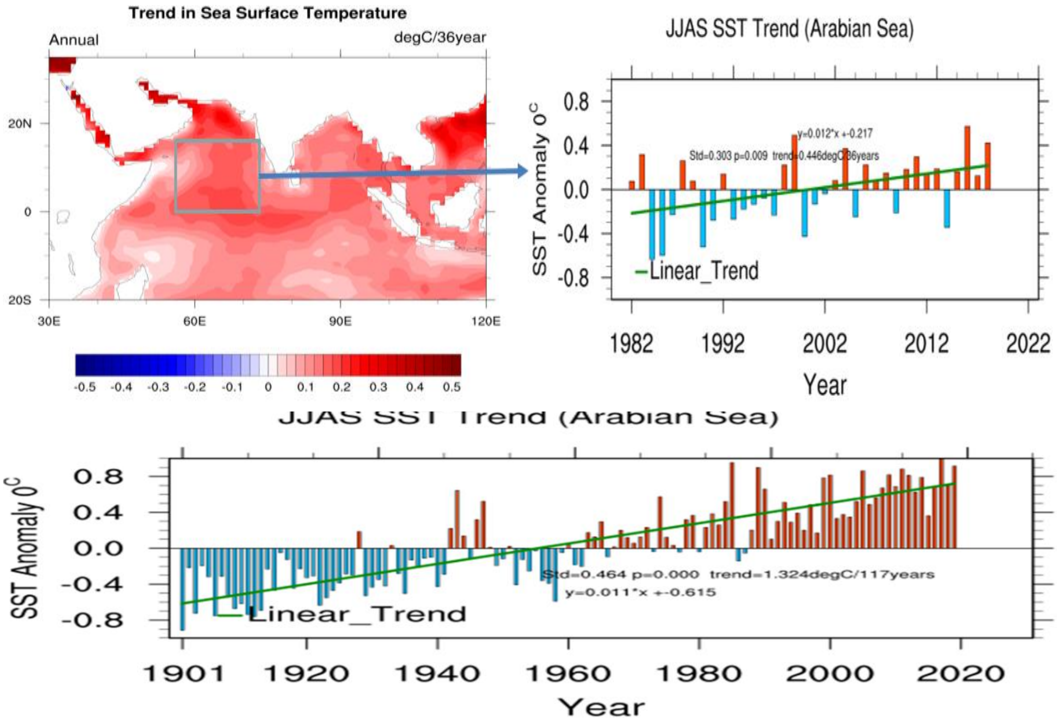
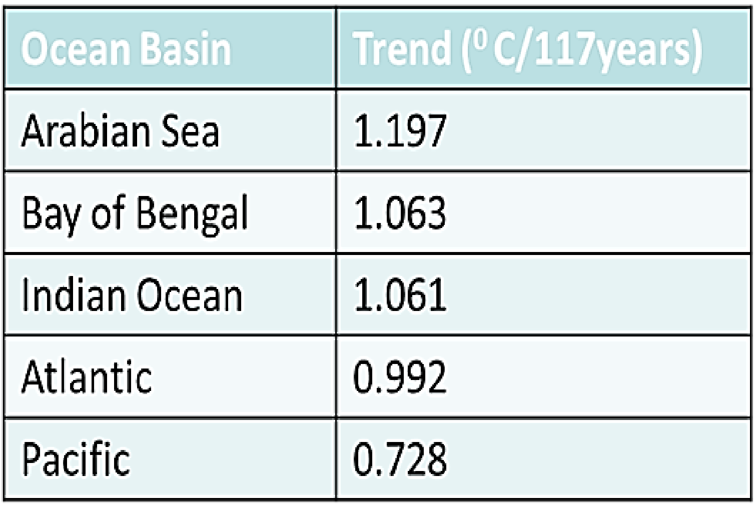


Figure 2.10: Increasing Sea surface temperature over Arabian Sea during pre-monsoon season during 1900-2022 (Abhilash et al)**.**

Other than the Indian Ocean, the western equatorial Pacific Ocean has too warmed more rapidly. Tropical oceans get much heat, according to Swapna Panickal, a researcher at the Indian Institute of Tropical Meteorology. In the case of the northern Indian Ocean, the northern hemisphere is warmer as the reservoir is surrounded by the northern South Asian continent. In contrast, the Atlantic Ocean is open to the North Pole, letting hot and cold water to spread. Another possible reason: the southwest monsoon cycle, which contributes to the warming of the northern Indian Ocean to the south, has weakened in recent decades. It may have allowed more heat to accumulate in the northern Indian Ocean. Sea level in the Indian Ocean raised from 1.06–1.75 mm between 1874 and 2004 and 3.3 mm between 1993 and 2015. It is similar to the global average sea-level rise. However, relative sea levels were observed to have developed faster. Relative sea levels indicate the level of the sea with land. For instance, the sea level in the Bay of Bengal-West Bengal and the northern coast of Bangladesh has been observed to rise by 5 mm or more per year (compared to the overall 3.3mm in the north Indian Ocean). This is because the Bengal Delta is sinking, which is increasing the impact of sea-level rise. In many parts of Asia, especially in the deltas, landslides occur due to natural and developmental factors. Parts of Jakarta, for instance, parts of Jakarta sink up to 10 cm every year.



Ocean Basin	Trend (^{0} C/117years)
Arabian Sea	1.197
Bay of Bengal	1.063
Indian Ocean	1.061
Atlantic	0.992
Pacific	0.728

Table 2.5: Rapid Ocean warming (Abhilash et al., 2018)

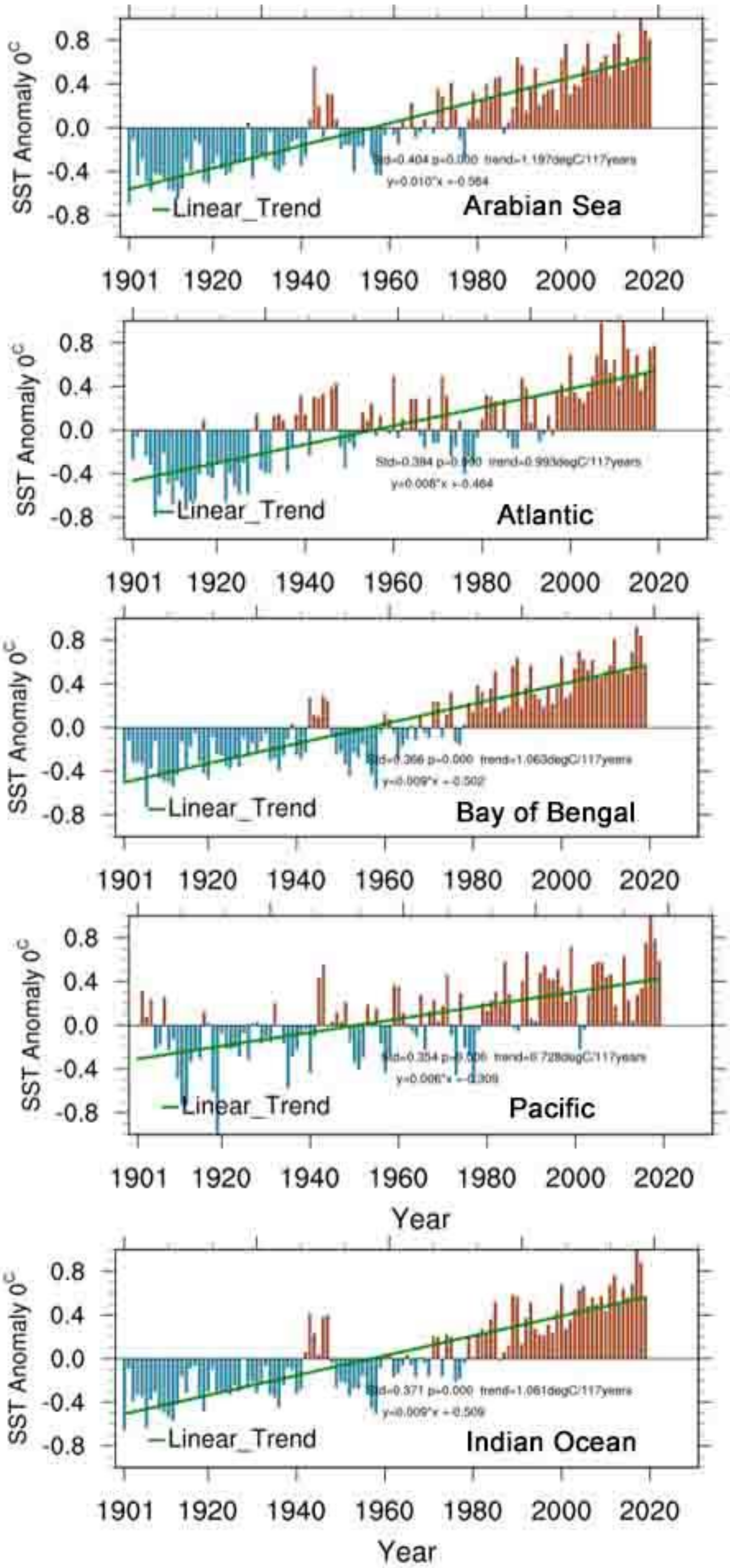


Figure 2.11: Rapid Ocean warming (Abhilash et al., 2018)

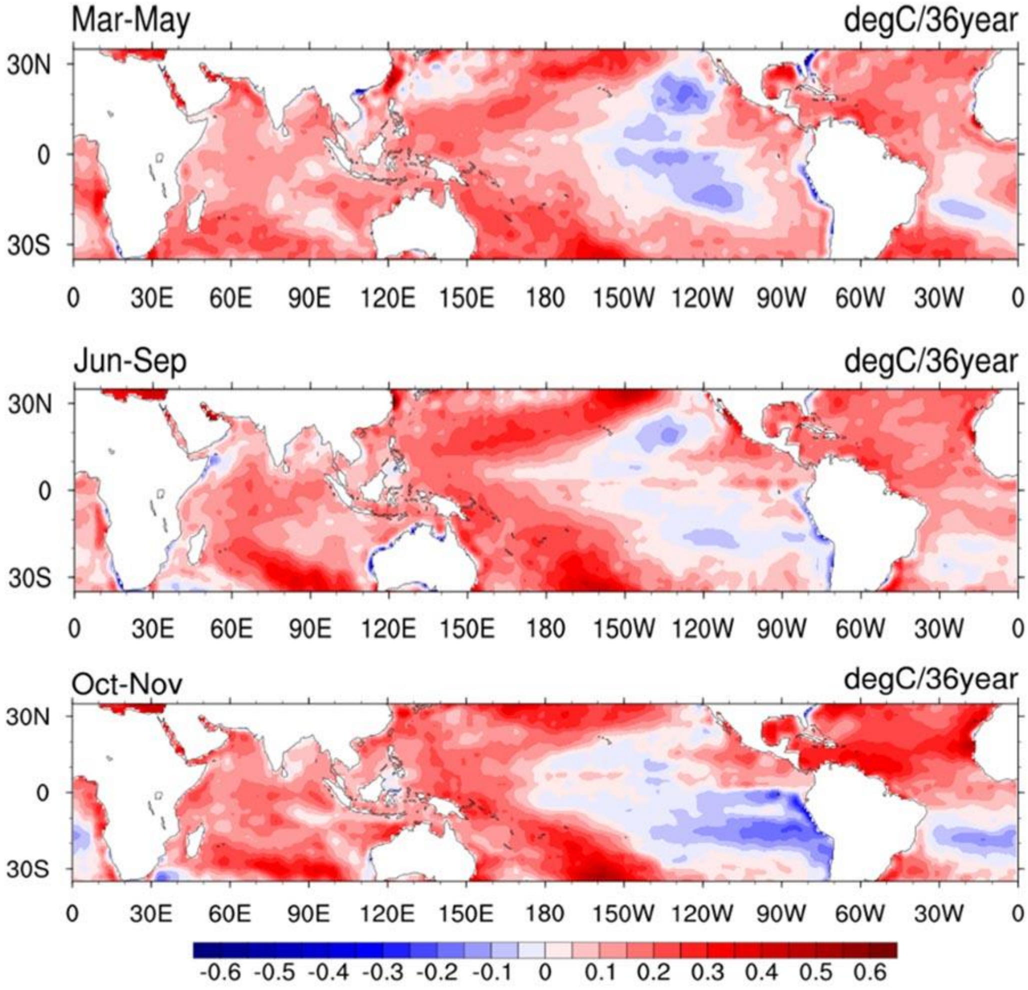


Figure 2.12: Global status of seasonal dependence of ocean warming: SST trend (Abhilash et al.)

If the Indian Ocean warms faster than the global average, sea levels will rise rapidly. Unlike some oceans, most of the sea level in the Indian Ocean is the consequence of global warming — because the water expands with warming — and not by the melting of glaciers and the melting of ice sheets. Nevertheless, there is uncertainty regarding the melting of ice sheets such as the Greenland ice sheet, which is causing global sea-level rise. The impact of global warming on cyclones in the northern Indian Ocean has been studied, and the results indicate the occurrence of storms and cyclones does not exhibit a significant increase in spite of a significant rise in sea surface temperature in the Bay of Bengal. From

1951-2007 compared to 1901-1951. The frequency of storms is related to changes in two atmospheric parameters over the northern Indian Ocean during global warming. Even with a small drop of surface pressure over the ocean cyclonic circulation sets in, and the air starts spiralling up around the low-pressure centre. Numerous Cumulus, cumulonimbus clouds develop, and cumulonimbus gives showers, releasing latent heat of condensation. The latent heat energy donates further to the cyclonic gyration of the air. Tropical cyclone form from pre-existing disturbances containing much deep convention. Pre-existing disturbance should acquire warm core through the troposphere. Prior to the genesis, the lower troposphere vorticity increases over a horizontal area of 1000-2000 km.

Subsequent periods (1951–2007) markedly significant depletion of mid-tropospheric humidity in the Bay of Bengal. The correlation among SST over the Bay of Bengal and the highest wind of cyclonic systems is complex, and the likelihood of a cyclone or severe cyclone forming in the northern Indian Ocean is limitless. (Ramesh et al., 2010). Danard and Murty (1989) and Yu and Wang (2009) noticed that double-CO2 increases tropical cyclone frequency and potential intensity in the world. On the other hand, observational studies have shown a significant decrease in the frequency of tropical cyclones (depression or above) during the monsoon season in the Bay of Bengal (Rajeev et al., 2000) or throughout the Bay of Bengal (Patwardhan, Bhalme 2000); Rajendra Kumar and Dash, 2001; Jadav and Munoth, 2009) Xavier and Joseph (2000) argue that despite the increase in SST in recent decades, the frequency of recent declining tropical cyclones will depend on vertical wind shear. Mandake and Bhide (2003) extended the research to show a potential relationship between atmospheric parameters and reducing tropical cyclone number after the 1980s.

Dash et al. (2004) further discussed the weakening of the parameters favorable for the formation of tropical cyclones in recent years. Pattanaik (2005) analyzed the oceanic and atmospheric parameters at high and low frequencies of tropical cyclones. Chan (2007) concluded that large-scale atmospheric circulatory variability was the primary cause other than SST, which makes a variation in tropical cyclone activity. Srivastava and Sinha (2000) conducted the Mann-Kendel test to find long-term trends in hurricane activity. The period is divided into four phases, for which a special test is applied to define the trends on a short time scale. The results show a significant decrease in the number of hurricanes during the period 1891-1997. Singh, Khan, and Rahman (2001) used linear trends by means of least square method with the help of pentad running through frequencies of the storm to compute the general trend. The study also determined the strength by means of the number of tropical depressions turning into intense cyclones. The study found the increasing rate and intensity of TCs in the months of May and November even though the annual frequency registered a declining trend. Mrutyunjay, Srivastava and Geetha (2015) analysed118 year statistics on cyclonic activity. The study found dissimilar decadal variability with maximum in 1921-30 and minimum in 1981-90. The long-term linear trend for cyclones exhibited a declining trend. It has also been seen that the frequency of decrease in occurrence is maximum in Monsoon season. Though the sea surface temperature has been increasing it has been found to have no influence in the frequency or intensity of cyclones. Deo and Garner (2013) analyzed pre-monsoon and post-monsoon cyclone duration, storm frequency, and storm days. In addition, the inequality of different energy components, such as accumulated cyclone energy (ACE) and power dissipation index (PDI), is calculated. It was found that the duration of the entire hurricane tends to increase.

MATERIALS AND METHODOLOGY

CHAPTER 3

MATERIAL AND METHODOLOGY

The study, entitled "Changes in the Frequency of Tropical Cyclones in the North Indian Ocean in Response to the Warming of the Tropical Indian Ocean" from 1980-2019. This chapter details the study area, data, and methods used in the study.

3.1 Area of the study

Changes in tropical cyclone frequency in the northern Indian Ocean were studied based on 40-year Arabian hurricane data frequency. Between latitude 12.2502 ° N and longitude 64.3372 E, the Arabian Sea is an area of the northern Indian Ocean bordered by Pakistan, Iran, and the Gulf of Oman is surrounded on the west with the Gulf of Aden and the Guardafui Channel. And the Arabian Peninsula, southeastern Laccade Sea, southeastern Somalian Sea, and eastern India. The surface area of the Arabian Sea is 3,862,000 km2 (1,491,000 sq mi), with a maximum depth of 4,652 m (15,262 ft).

India accounts for about 10% of the world's tropical cyclones. Five to six tropical cyclones on average produce each year, two of which can be devastating. The western part of the Arabian Sea is cooler and, therefore, not favorable for the development of storms. Gujarat is the chief pocket threatened by cyclones in the Arabian Sea and witnesses about 70% of the storms. 10% of them hit the Maharashtra coast while the rest drift to Oman or Pakistan. Although the death toll has dropped significantly, India suffers huge economic losses with each cyclone. According to a UN report, Hurricane Amfan cost $ 14 billion. RMSI, a global consultancy firm operating on natural disasters, estimates the damage caused by Hurricane Toukte at Rs 15,000 crore.

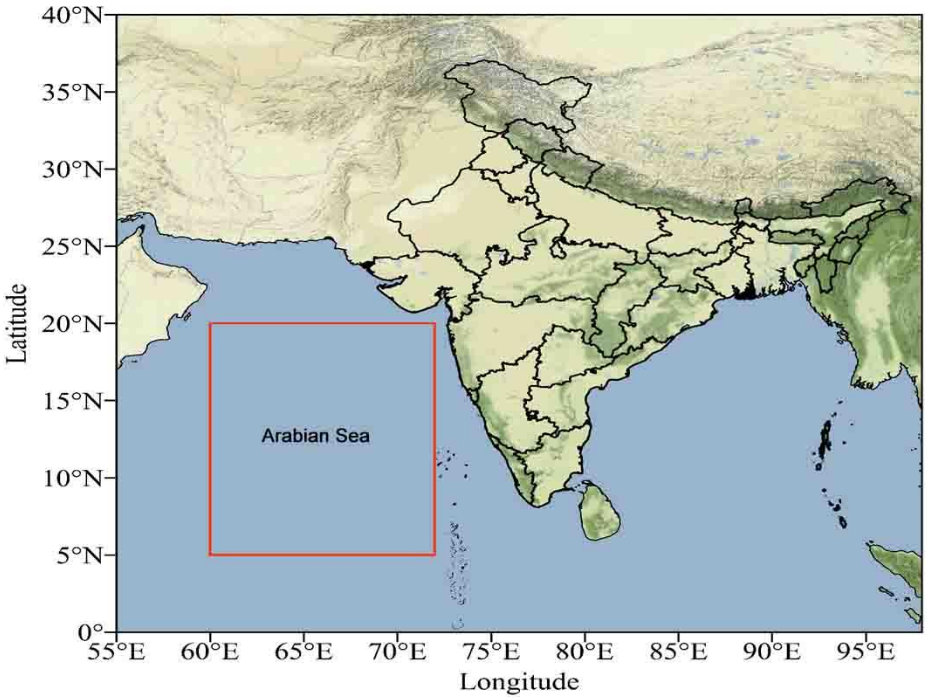


Figure 3.1: Area of Study

3.2 Observed database

3.2(a) Arabian Sea cyclone

The frequency of tropical disturbances in the Arabian Sea from 1979-2019 (40 years) was considered for this study. The dataset used to analyze frequency tropical disturbances was obtained as annual and monthly data from the cyclone eAtlas, developed by the Meteorological Department of India (IMD), New Delhi, to generate tracks and statistics on maps, charts, and tables on different features of cyclones and lows in the Indian Ocean.

Best track data of tropical cyclonic storm was downloaded from IMD best track (https://rsmcnewdelhi.imd.gov.in/report.php?internal_menu=MzM=). The Joint Typhoon Warning Center (JTWC) used best track data in this study for tropical cyclones in the Arabian Sea from 1980-2019.

3.2(b) Sea Surface Temperature

The Extended Reconstructed Sea Surface Temperature (ERSSST) dataset is a worldwide monthly SST dataset obtained from the International Comprehensive Ocean-Atmosphere Dataset (ICOADS). Enhanced space with ERSST statistics is ideally on the 2° × 2° grid. This monthly assessment began in January 1854 and continues to this day, including estimates of meteorology for the months 1971-2000 can be downloaded from www.ncdc.noaa.gov. The latest version of ERSST, version 5, uses new data sets from ICOADS Release 3.0 SST.

3.2(c) Vertical wind shear

Vertical wind data (i.e., 850, 200 hPa) from the National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) at 2.5° × 2.5° longitude/latitude resolution (Kalney et al., 1996) were retrieved from the monthly revision dataset. In the current case, a vertical windshield variable (S) of approximately 200 to 850 hPa is calculated over an area of 2.5 radii in the center of the cyclone system.

3.2(d) Relative humidity, vorticity, and tropospheric instability

Data related to RH, vorticity, and tropospheric instability is downloaded from NCEP/NCAR Reanalysis 1, (2.5° × 2.5° lat./long) dataset from 1979–2019.

3.2(e) Kotal genesis potential index

Kotal et al. (2009) developed a Genesis Potential Parameter (GPP) and further evaluated (Kotal et al., 2013; Nath et al., 2013), which is used by the Meteorological Department of India (IMD) in New Delhi to classify cyclogenesis potential zones over the northern Indian Ocean. The IMD maintains KGPP with the scale range value of up to 30, with higher KGPP values showing the potential area of cyclogenesis. KGPP is based on atmospheric parameters such as a relative humidity, vertical windshield, and thermal instability. GPI (Genesis Potential Index) is calculated using an equation explained by Kotal (2009). If Kotal GPI shows positive values, a more significant number of cyclones will form. Although the ocean has an essential function in the origin and intensity of storms (Sadhuram et al., 2004; Lin et al., 2009; Maneesha et al., 2015), no ocean parameters are included. The vorticity of 850 hPa, middle-level relative humidity, tropospheric instability, and vertical wind shear variables are used to obtain GPP. Therefore, the specific GPI is defined as:

$$\mathrm{GPI} = \frac{\xi_{850}}{S} \times \mathrm{M} \times I \quad \text{if } \xi_{850} > 0,\ \mathrm{M} > 0 \text{ and } \mathrm{I} > 0$$

$$= 0 \text{ if } \xi_{850} \leq 0,\ \mathrm{M} \leq 0 \text{ and } \mathrm{I} \leq 0$$

Where, ξ_{850} is the low-level relative vorticity at 850 hPa in 10^{-5} S^{-1}

S is the Vertical wind shear between 200 and 850 hPa in m s^{-1}

Mid tropospheric relative humidity, $\mathrm{M}= \frac{[\mathrm{RH}-40]}{30}$

Where, RH = mean relative humidity between 700 and 500 hPa

I is the mid tropospheric instability $(T_{850}-T_{500})$ ˚C

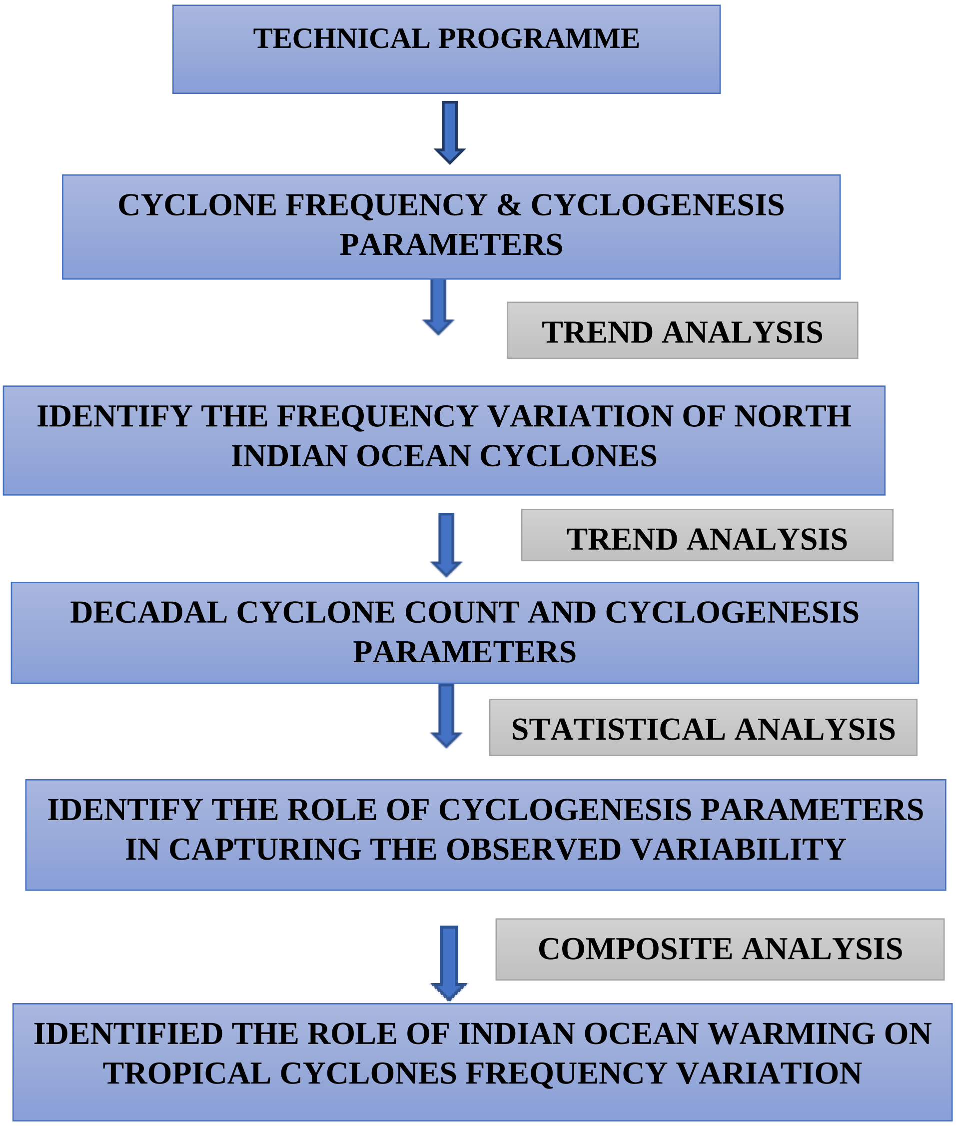
To calculate the GPP value, each of the four variables is calculated by averaging all the grid point values within a circle with a radius of 2.5 around the center of the cyclonic system.

3.2(f) New genesis potential index

It is found that, with proper scaling and modification of the individual cyclogenesis parameters, the new index better captures the decadal cyclone frequency, intensity, and track distribution. We have taken integrated temperature over 850 to 500 and the vertical wind shear term is modified and scaled to SQRT (1 +0.1SH). The NGPP is more useful for describing the decade-long frequency variation of post-monsoon tropical cyclones in the warming baseline of the Arabian Sea.

3.3 Technical program

The study focusses on trend detection, a linear trend of depression, cyclone, and severe cyclonic storm during the period 1979-2019 are explicitly expressed. Decadal trends of frequency Arabian Sea cyclones and cyclogenesis parameters were analysed. To understand the influence of physical parameters (such as sea surface temperature, vertical wind shear, relative humidity, vorticity, tropospheric instability,) trend analysis and composite analyses were carried out.



To understand physical parameters that drive behind the cyclonic years' correlation have been computed between decadal cyclone count and cyclogenesis parameters. In this research, we analyzed Kotal GPI (Kotal et al., 2009; Zhang et al., 2016) with a new GPP that includes mid-tropospheric instability ranging from 850 to 500° C for the post-monsoon (October-December) season utilizing data from the period 1980-2019. Composite analysis Kotal GPI and NGPI were carried out. Systematic representation of technical program is shown above.

3.3 (a)Trend analysis

For the study, trend analysis was used to analyse the variation in cyclone counts and role of different cyclogenesis parameters in the observed variation. Monthly sea surface temperature data was collected from Extended Reconstructed Sea Surface Temperature (ERSST) - version 5 was used to analyse SSTData associated to different atmospheric parameters (i.e., 850, 200 hPa, RH 500 hPa, 500-hPa geopotential altitude, and mid-tropospheric instability) were obtained from the National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) monthly reanalysis dataset. With the collected data of cyclogenesis parameters, the standardised anomaly was calculated. For the analysis, the calculated value was plotted using Microsoft excel. Analysis is done by linking the thermo dynamical parameters and dynamical background state with variation of cyclone number and intensity and thereby identifying the role of Indian ocean warming on tropical cyclones.

3.3 (b) Decadal analysis

To capture decadal variability in cyclone frequency, Thermo dynamical and dynamical background state is analysed with respect to the decadal variation of cyclone number and intensity and thereby identified the role of Indian ocean warming on tropical cyclones frequency variation.

3.3 (c) Composite Analysis

Spatial plot of each cyclogenesis parameters was plotted using Open GrADS. To get the composite anomaly of individual parameter, first take the average of the variable taken over specific time. Then subtract the above average with the climatology (1980-2019) of the variable gives the composite anomaly of each variable.

3.3 (d) Correlation analysis

Statistical technique is used to compute the role of cyclogenesis parameters on variability tropical cyclone. Correlation between cyclogenesis parameters and cyclone count is measured using software R. It is a free software environment for statistical computing and graphics.

3.4 Software Used

Software used in the study includes Open GrADS, Ferret, R and Microsoft Excel. The Grid Analysis and Display System (GrADS) is a bilateral desktop tool used to access, manipulate, and visualize the earth data. Composite anomalies of weather parameters are drawn using GrADS software. Statistical tools such as correlation, standard deviation was done in using R and Microsoft Excel respectively. Line graph and bar graph were drawn using Microsoft Excel.

RESULT

CHAPTER 4

RESULT

Tropical cyclones, particularly near the eastern coasts of India, Bangladesh, and Myanmar, have caused significant socio-economic loss of life and property. From 1980 to 2018, they were responsible for almost half of the global disasters, causing a total of $ 2111 billion in damage. Important statistical parameters like Mean (M) and Standard Deviation (SD) of cyclone frequency and cyclogenesis parameters was computed for the period 1980 to 2019.

4.1 Data analysis

Frequency analysis of depression, cyclonic storm, and severe cyclonic storm

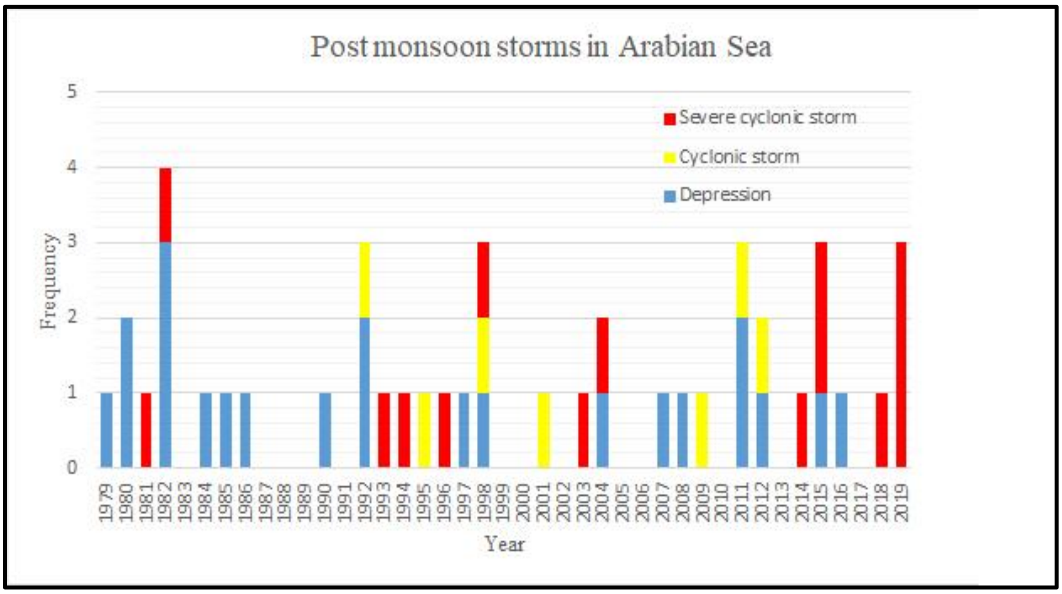


Figure 4.1(a): The figure shows total number of depressions, cyclones, and severe cyclonic storms during 1979-2019.

Tropical cyclone during the post-monsoon season in the Arabian Sea has produced several most destructive cyclones reported in the history. The above figure shows the frequency of depression, cyclonic storm, and severe cyclonic storm over Arabian Sea. The blue, yellow and the red lines represent the depression, cyclonic disturbance, and severe cyclonic storm respectively during 1980 to 2019.

Here it is shown that the strength of most cyclones with wind greater than 49 ms^{-1} in the post-monsoon Arabian Sea increased during the recent decade. For better understanding, trend analysis of severe cyclonic storm from 1980 to 2019 is given below. For example, recent cyclones Nilofar in 2014, Chapala and Megh in 2015.

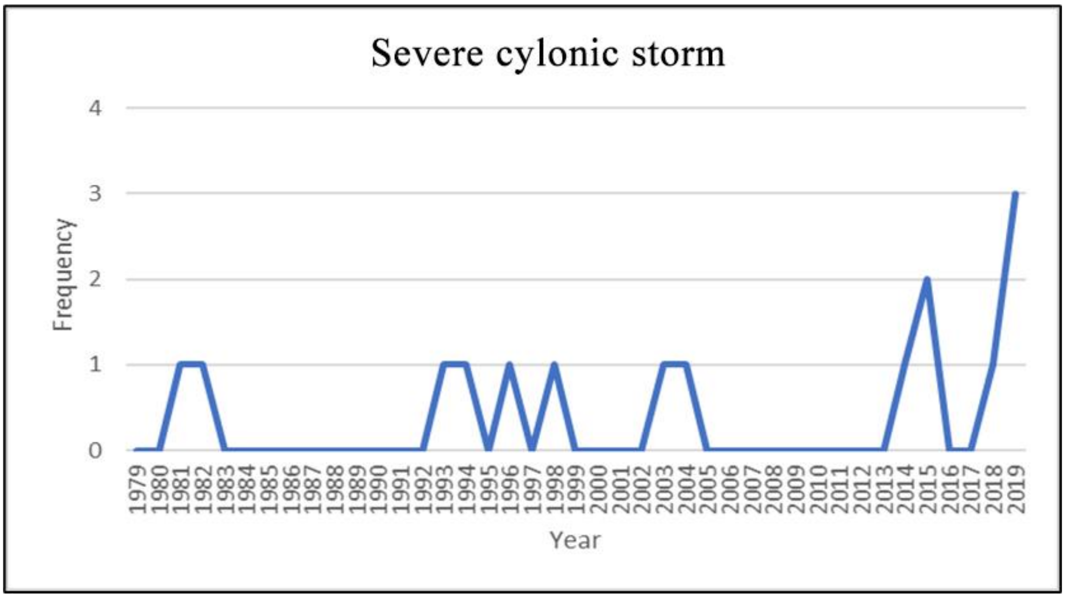


Figure 4.1 (b): The figure shows the increasing frequency of severe cyclonic storms during 1979-2019.

Variations in environmental factors have been found to contribute to the observed increase in TC intensity. The elevation of the SST and the high heat content of the ocean caused the sea to be more conducive to TC strengthening. In contrast, the increased convective instability produced the atmosphere extra conducive to the development of TCs. The most notable variations in the weather and sea happened in the Arabian Sea. These variations are part of the positive linear trends, which indicates that the strength of the post-monsoon Arabian TC may increase in the future. Observation-based studies have generally shown no significant change in the overall number of TCs and depressions, but a rise in the number of severe TC events in the Arabian Sea throughout the recent decades. By analysing different atmospheric parameters over Arabian Sea during last four decades will enable to know the change in frequency of tropical cyclones. The observed increase in intensity since 1980s has been related to increasing SST in the Indian Ocean, which provides more energy to fuel cyclones.

4.2 Trend analysis of cyclogenesis parameters

I. Analysis of SST

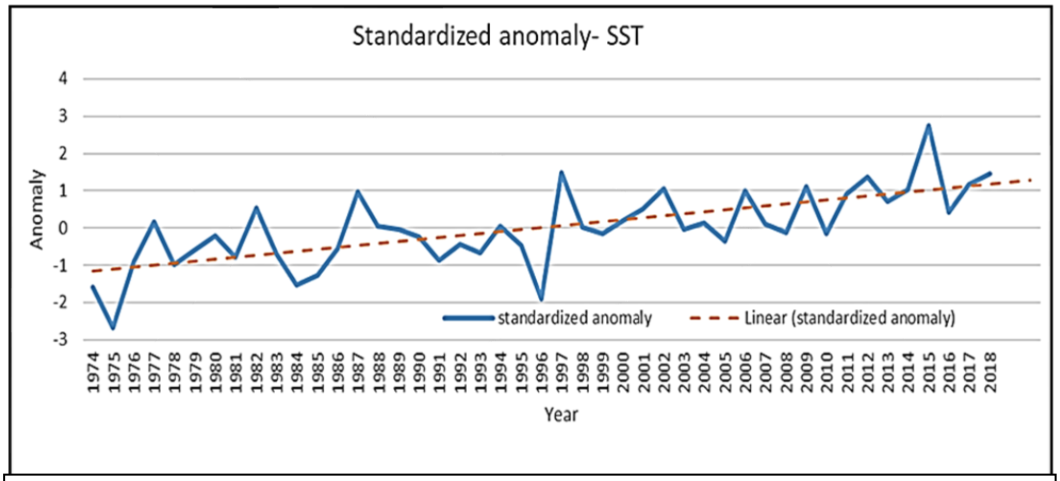


Figure 4.2: The figure shows the standardised anomaly of SST over Arabian Sea during 1979-2019.

The above graph shows standardized anomaly of SST over Arabian Sea, which shows an increasing pattern from 1974-2018. According to a recent study, sea surface temperatures in the tropical Indian Ocean rose by an average of 1ºC between 1951 and 2015. Ocean warming at 700 m is on the rise compared to 1955. At present, the average value has risen to 4.2% from the temperature increase. In November 2015, the SST deficit reached 2.7 degrees, breaking the 1.4°C record set in November 1997. The average annual SST in the Arabian Sea has increased by 0.36 C over the last 19 years. It is clear that SST anomalies were positive throughout El Nino throughout the Arabian Sea, while La Nina has seen negative anomalies over the years. SST anomalies decreased in 1983–1984, 1988–1989, 1998–1999, 2000–2001, 2008–2009, 2010–2011, 2016–2017; This is because of the La Nina incident. From 1980 to 2019, there will be a steady increase in sea surface temperature over the Arabian Sea. According to several studies, the Arabian Sea is constantly warming, and its warm pool is growing, especially in recent decades. This Indian Ocean warming can be linked to global warming, ocean warming, and ENSO (Roxy et al. 2014; Rao et al., 2012), reducing land-ocean temperature variation. The impact of global warming on the Indian Ocean is minimal.

II. Analysis of vertical wind shear

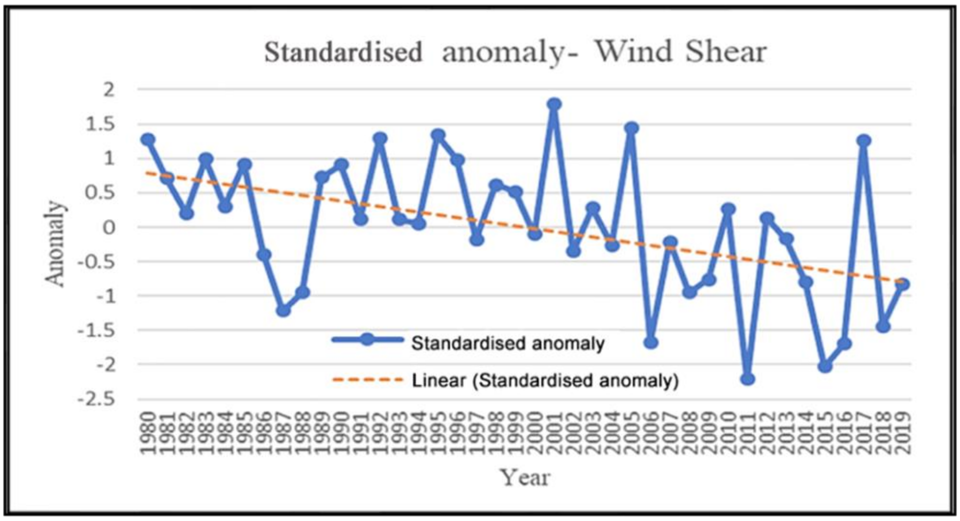


Figure 4.3: The figure shows the standardised anomaly of wind shear over Arabian Sea during the period 1979-2019.

The above figure indicates the standardized anomaly of the wind shear in the Arabian Sea between 1980 and 2019. VWS is a large-scale parameter that performs an essential role in the origin of TCs and their strengthening. Low VWS favors the origin and development of TC (Gray, 1968; DeMaria, 1996; Maloney and Hartmann, 2000; Zehr, 2003). The trend of wind shear fell dramatically, though there was a great deal of fluctuation within this fall. Clearly, reduction in wind shear is a bigger problem in the formation of storms in the 20th century than it was before. If the reduction in wind shear is likely to increase, the chance of intensity and frequency of tropical storms will also increase.

III. Analysis of relative humidity

The graph shows the standardized anomalies of mid-tropospheric relative humidity between 1980 and 2019. The dry mid-troposphere is detrimental to the onset and stability of extensive convection activity. Mid-tropospheric RH (at least 40%) is required for cyclogenesis (Gray, 1968, 1975). The relative humidity level increases: Thus, RH contributes to the formation of TCs.

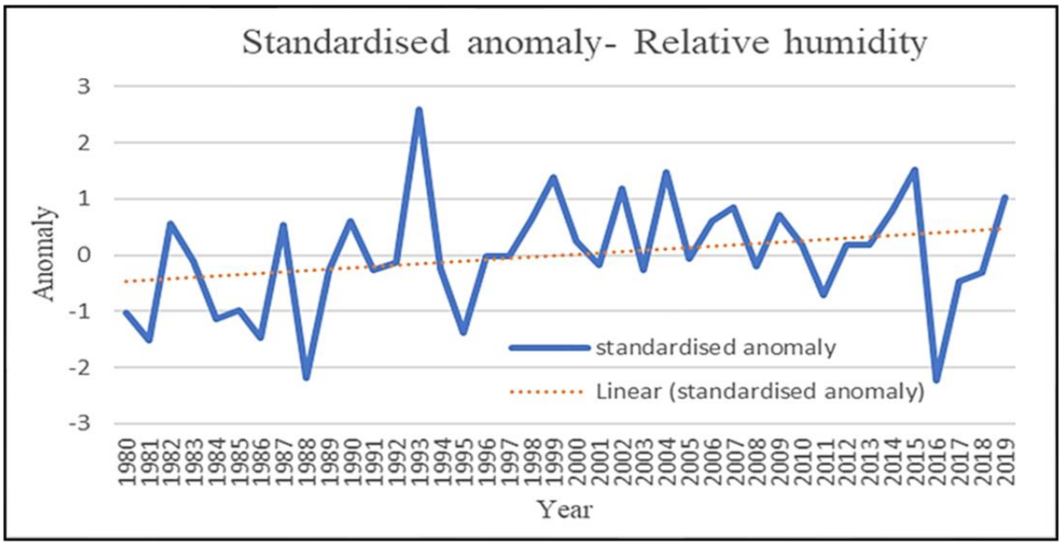


Figure 4.4: The figure shows the standardised anomaly of relative humidity over Arabian Sea during 1979-2019.

IV. Analysis of vorticity

The given graph displays Vorticity's standardized anomaly between 1980 and 2019. Relative vorticity at high and low levels favours the formation of TCs. The image shows that the magnitude of the low-level vorticity is increasing; Thus, the high low-level relative vorticity contributes for the development of cyclonic disturbances.

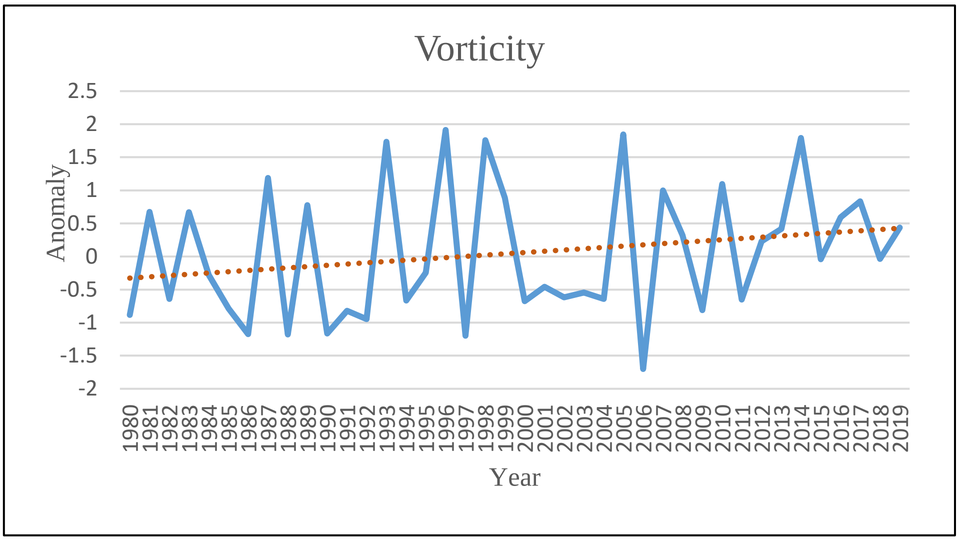


Figure 4.5: The figure shows the standardised anomaly of vorticity over Arabian Sea during the period 1979-2019.

V. Analysis of tropospheric instability

The graph below displays the standardised anomaly of tropospheric instability between 1980 and 2019. Conditional instability through a deep atmospheric layer is needed for the formation of TCs. The magnitude of tropospheric instability is increasing; thus, tropospheric instability contributes for the formation of TCs.

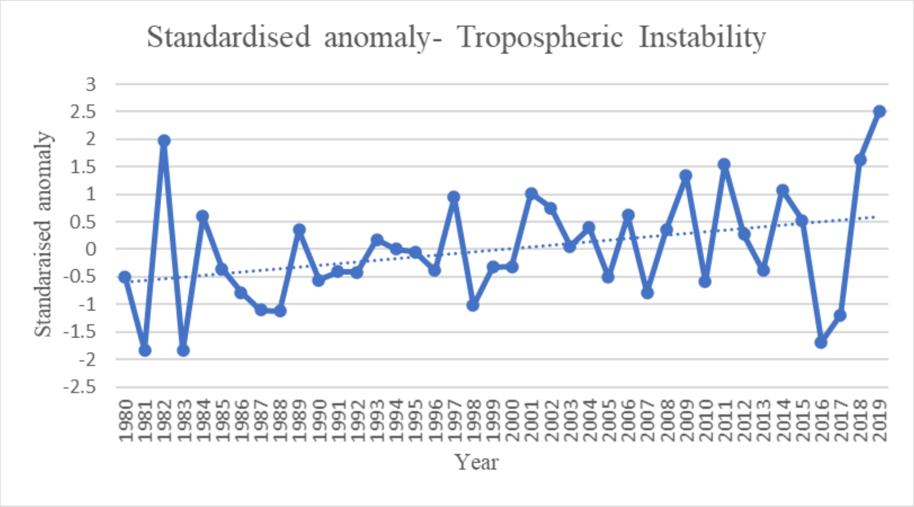
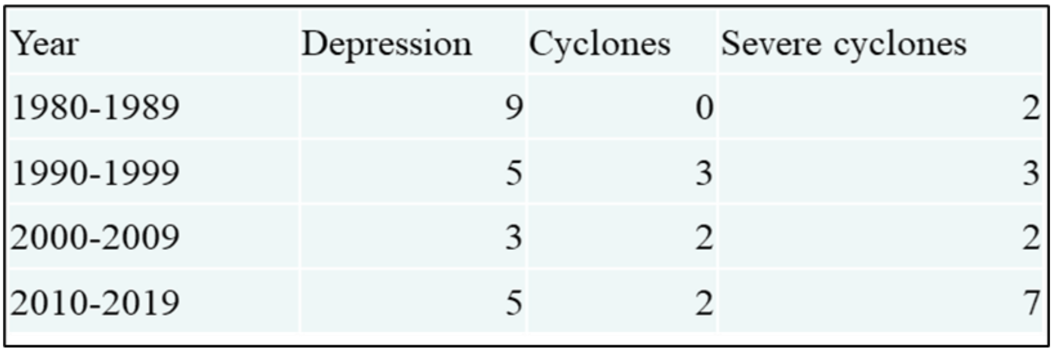


Figure 4.6: The figure shows the standardised anomaly of tropospheric instability over Arabian Sea during the period 1979-2019.

4.3 Decadal frequency analysis of tropical disturbance

To understand the Arabian cyclone trend in each decade (1980-1989, 1990-1999, 2000-2009, 2010-2019), decadal analysis was carried out. The table clearly shows that severe cyclonic storms in the Arabian have increased in the recent decade during the post-monsoon season.



Year	Depression	Cyclones	Severe cyclones
1980-1989	9	0	2
1990-1999	5	3	3
2000-2009	3	2	2
2010-2019	5	2	7

Table 4.7: Depression, cyclones, and severe cyclones over Arabian Sea during the period 1979-2019.

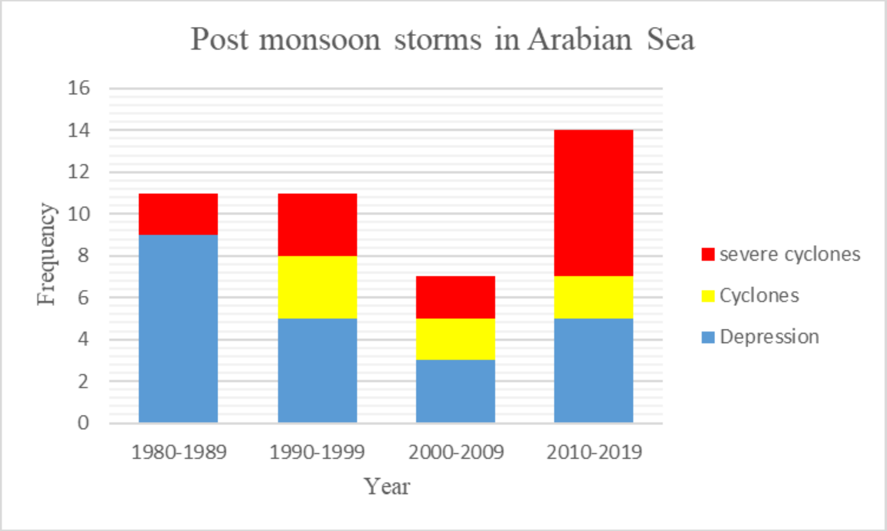


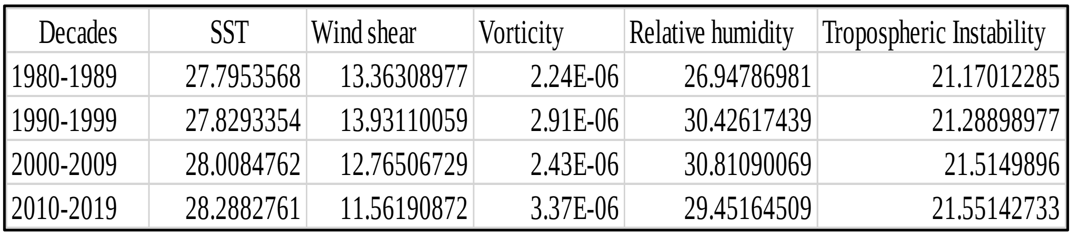
Figure 4.8: Post monsoon, decadal frequency analysis of TD, CS and SCS over ARB.

The long-term decadal frequency analysis of tropical disturbances in the Arabian Sea for 40 years has been presented in Figure.

The blue, yellow, and red color represents tropical depression, cyclonic storm, and severe cyclonic storms respectively. Figure 1 shows that there is a generally increasing trend in the decadal frequency of cyclonic storms during the period 2000-2009.

4.4 Decadal analysis of cyclogenesis parameters

To understand decadal variability in cyclone frequency, cyclogenesis parameters is analysed with respect to the decadal variation of cyclone number and thereby identified the role of Indian ocean warming on tropical cyclones frequency variation.



Decades	SST	Wind shear	Vorticity	Relative humidity	Tropospheric Instability
1980-1989	27.7953568	13.36308977	2.24E-06	26.94786981	21.17012285
1990-1999	27.8293354	13.93110059	2.91E-06	30.42617439	21.28898977
2000-2009	28.0084762	12.76506729	2.43E-06	30.81090069	21.5149896
2010-2019	28.2882761	11.56190872	3.37E-06	29.45164509	21.55142733

Table 4.2: Decadal values of cyclogenesis parameters.

I. Analysis of SST

Figure shows the SST variation during last four decades. Maximum temperature and increase in number of severe cyclonic storm is observed in the recent decade, 2010-2019. The hottest six years in 2016, 2019, and 2020 were after 2015. The changes in the average global temperature during the three hottest years, 2016, 2019, and 2020, are indistinguishable. Therefore, SST contribute for the enhanced cyclonic activity in the recent decade.

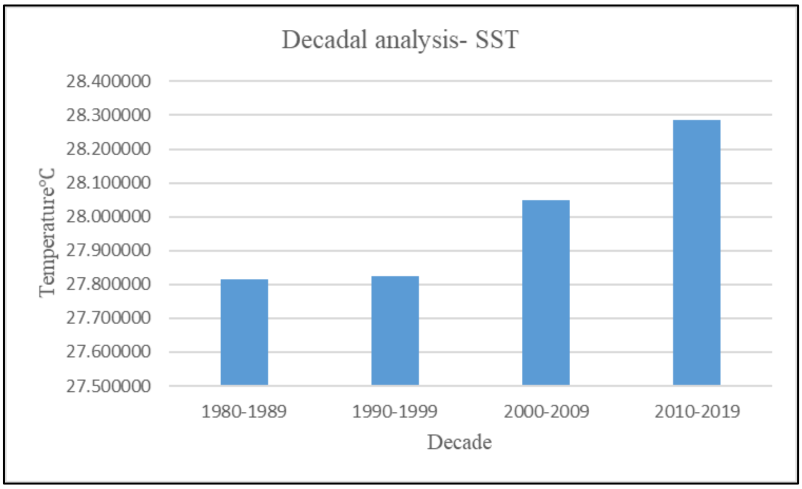


Figure 4.9: Decadal variation of SST

II. Analysis of vertical wind shear

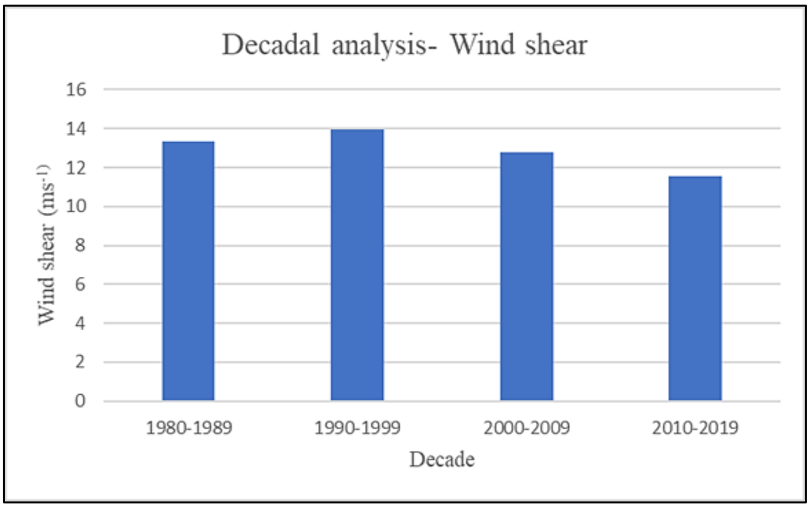


Figure 4.10: Decadal variation of wind shear

The change in vertical wind shear in different decades during OND is shown in figure 4.19. the figure shows a decreased vertical wind over the Arabian Sea. The minimum vertical wind shear is favorable for the formation of tropical disturbances. Decreasing vertical wind shear during recent decade may contribute for the formation of tropical disturbance.

III. Analysis of vorticity

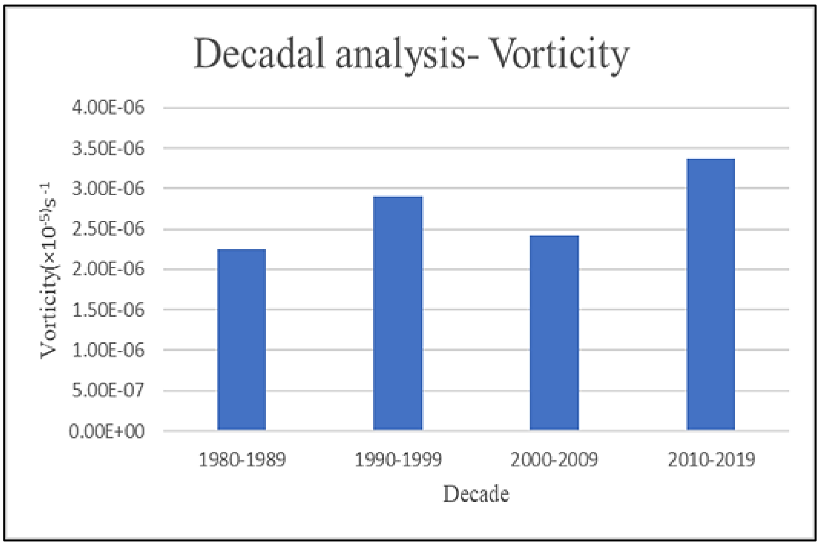


Figure 4.11: Decadal variation of vorticity

The above figure shows the variability in low-level vorticity in recent decades. Vorticity shows an erratic pattern from 1980-2019. During the last decade, the value of vorticity was high. Therefore, a high low-level is needed for the formation of the cyclone. On the other hand, during the last decade, the number of cyclonic disturbances was also increased, which means high low-level vorticity contributes to the formation of cyclones.

IV. Analysis of tropospheric instability

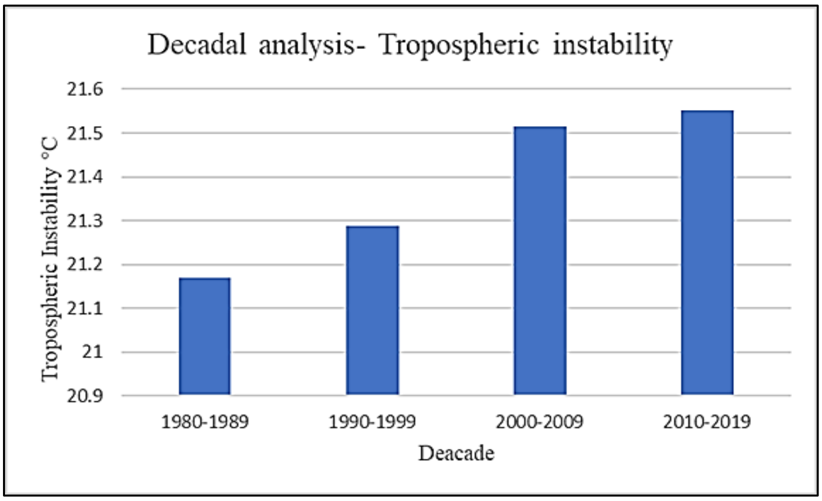


Figure 4.12: Decadal variation of tropospheric instability

Conditional instability through a deep atmospheric layer will favour the formation of cyclones. It is clearly visible from the figure that the tropospheric instability is increasing in each decade. Among all decades, 2010-2019 shows the biggest figure of tropospheric instability. Hence high tropospheric instability will influence the formation of cyclonic disturbance.

V. Analysis of relative humidity

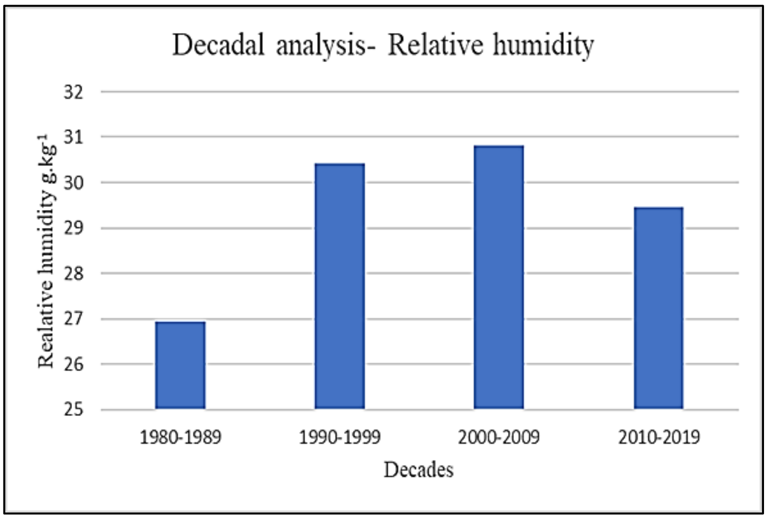


Figure 4.13: Decadal variation of relative humidity

High relative humidity tends to the release of latent heat, which is necessary for the development and intensification of tropical storms. During the last decade, relative humidity decreased compared to other decades. However, the cyclone count was high in the recent decade. On the other hand, the high relative humidity value was seen during 2000-2010, while cyclone count was less. Therefore, relative humidity contributes less to the cyclone formation during 1980-2019.

4.5 Statistical analysis

Correlation analysis between cyclogenesis parameters and decadal cyclone number was performed to find each cyclogenesis parameter's contribution to the formation of cyclonic disturbances.

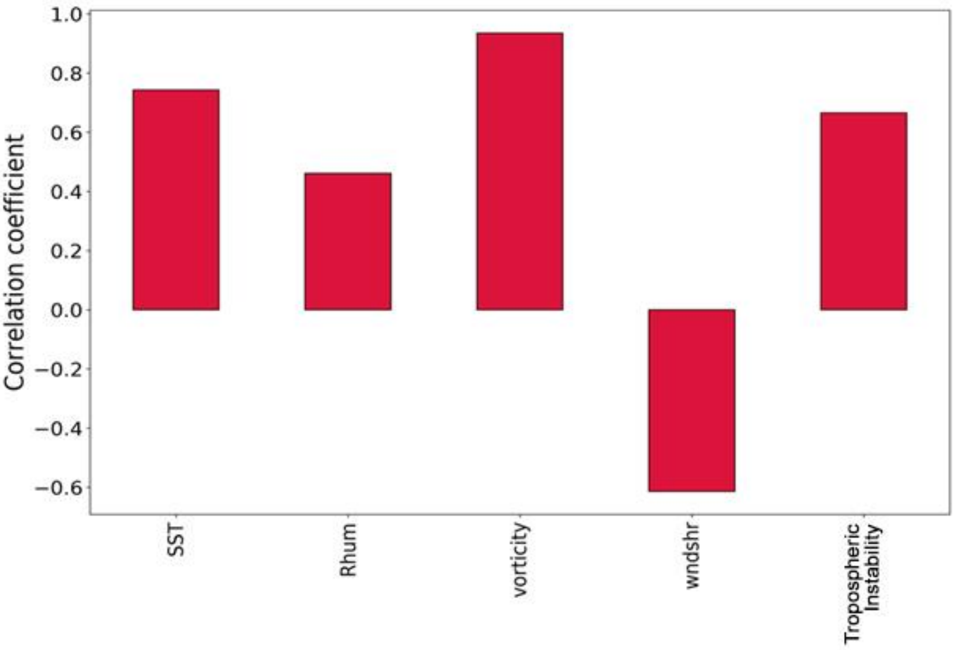


Figure 4.14: Correlation between cyclone count and cyclogenesis parameters

The above figure shows the correlation analysis between cyclogenesis parameters and decadal cyclone number. The result of correlation analysis indicated that the enhanced cyclonic activity in the recent decade is primarily triggered by increasing sea surface temperature, thermal instability, relative vorticity, and reduction in the vertical wind shear while relative humidity contributes much less.

4.6 Composite analysis

Composite anomaly of vorticity, wind shear, mid tropospheric relative humidity, thermal instability, Kotal genesis potential index (Kotal GPI) and New GPI were plotted for the period 1980-1989, 1990-1999, 2000-2009, 2010-2019.

I. Vorticity anomaly

The composites of vorticity over the past four decades have been shown in the figure. The vorticity has been examined to be high in the above-normal tropical cyclone years, while it is low in the below average cyclonic years.

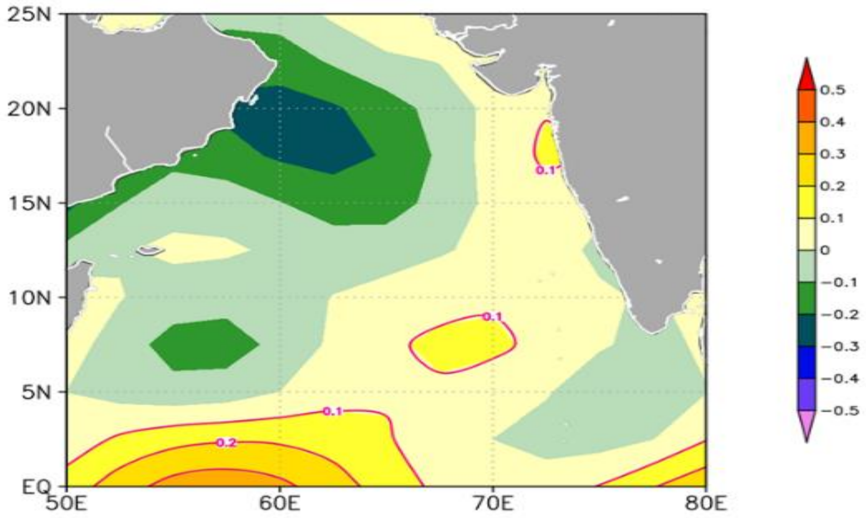


Figure 4.15(a): Composite anomaly of vorticity (1980 – 1989)

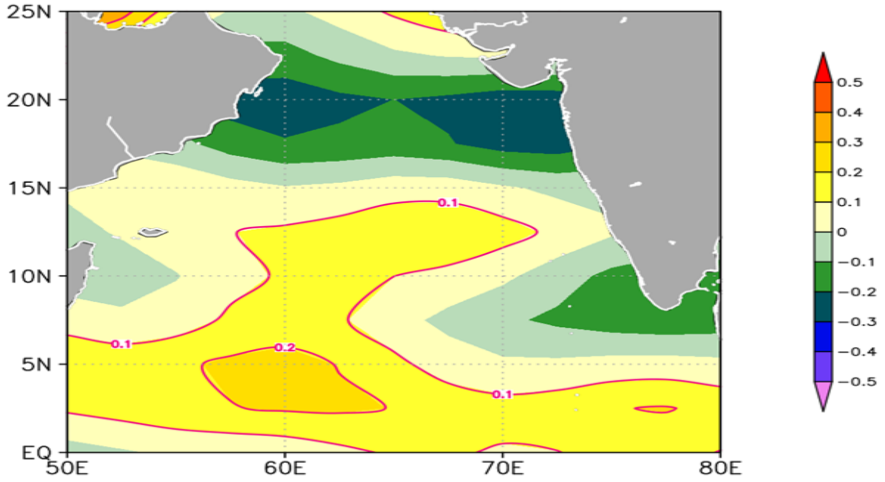


Figure 4.15(b): Composite anomaly of vorticity (1990 – 1999)

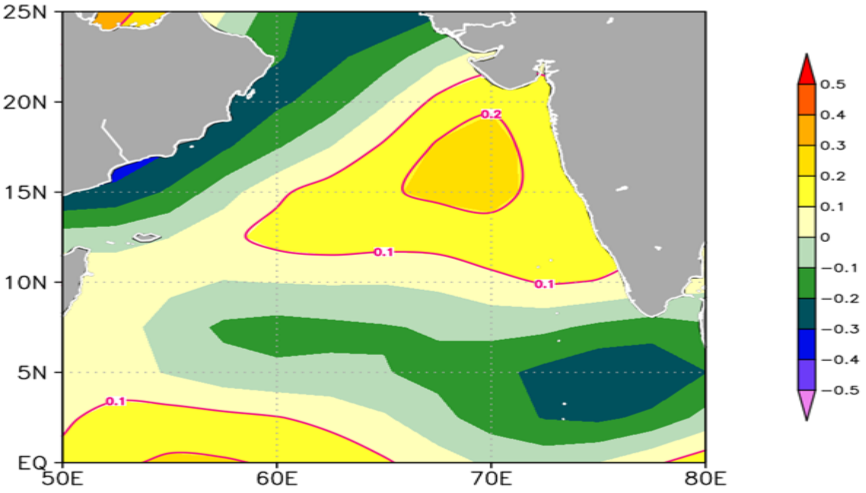


Figure 4.15(c): Composite anomaly of vorticity (2000 – 2009)

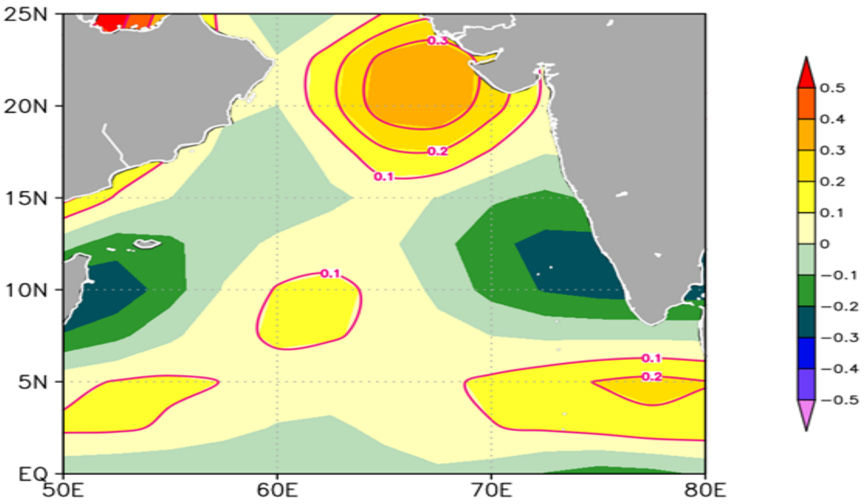


Figure 4.15(d): Composite anomaly of vorticity (2010 – 2019)

II. Wind shear anomaly

Figures represent the anomaly of VWS over the past four decades have been shown in the figure. The wind shear has been examined to be high in the above-normal tropical cyclone years, while it is low in the below average cyclonic years that prevailed over the Arabian sea during the recent four decades. It is evident that more depressions, cyclones, and severe cyclones are formed when wind shear shows negative values. While during positive anomalies, fewer number of storms are formed.

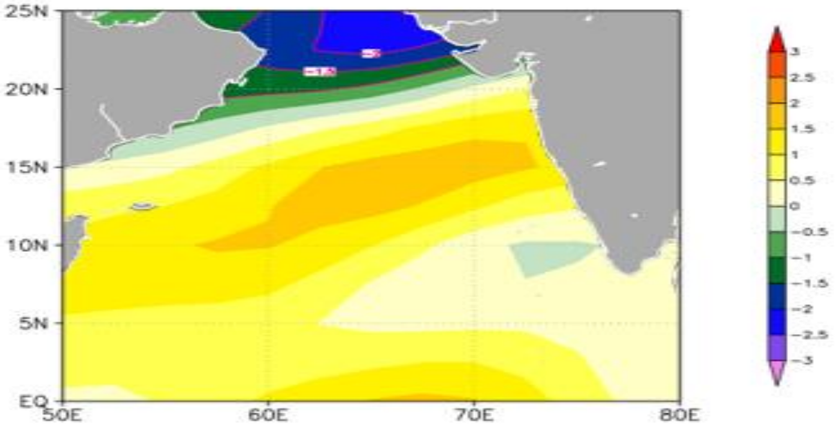


Figure 4.16(a): Composite anomaly of wind shear (1980 – 1989)

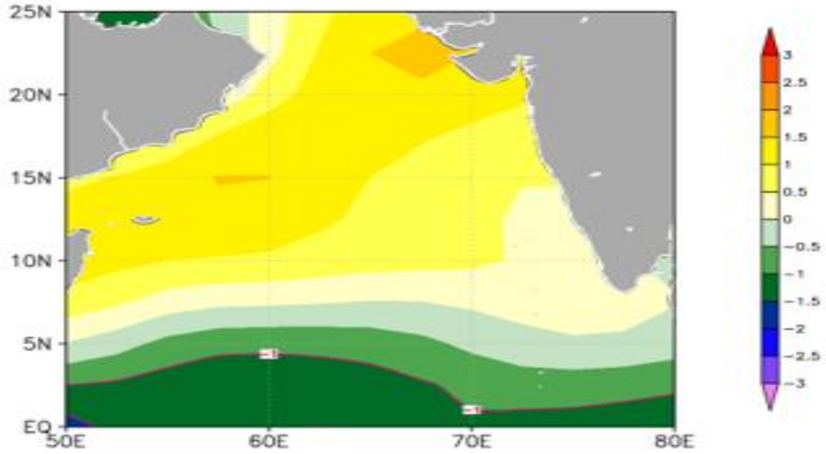


Figure 4.16(b): Composite anomaly of wind shear (1990 – 1999)

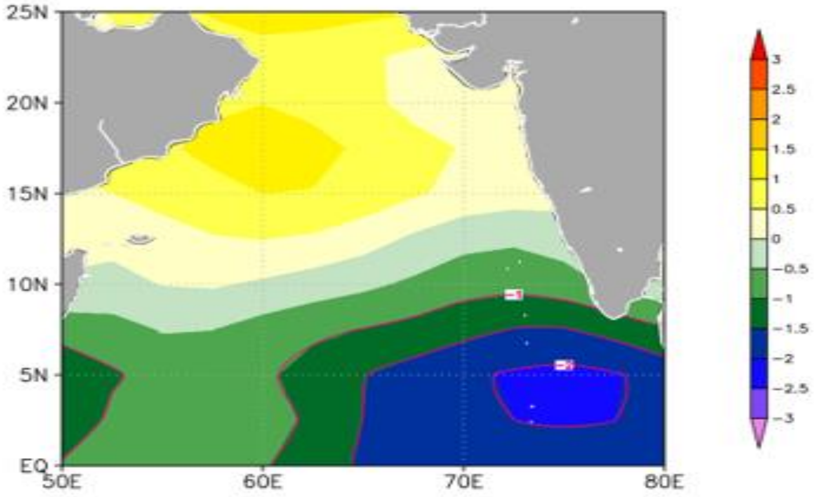


Figure 4.16(c): Composite anomaly of wind shear (2000 – 2009)

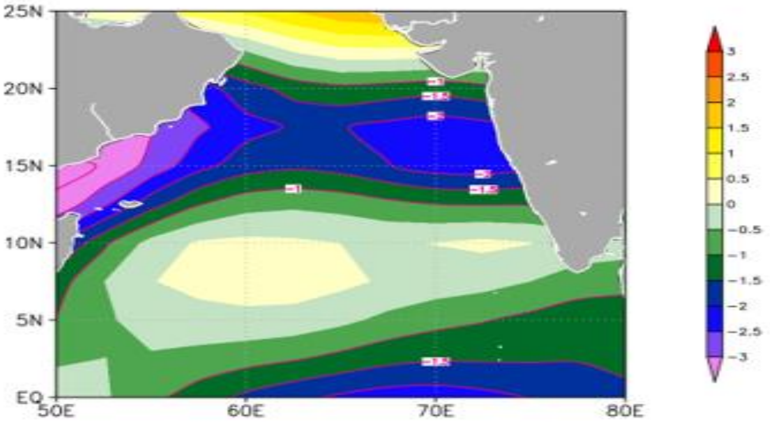


Figure 4.16(d): Composite anomaly of wind shear (2010 – 2019)

III. Mid tropospheric relative humidity anomaly

This figure shows the mid tropospheric relative humidity at 700 – 500 hpa anomalies. The anomalies are negative in most of the areas in all four decades. And thus, Relative humidity contribute less to the formation of TCs. Mid tropospheric relative humidity is calculated using the following formula:

$$\mathbf{M}=\frac{[\mathbf{RH}-\mathbf{40}]}{\mathbf{30}}=\textbf{Mid tropospheric relative humidity}$$

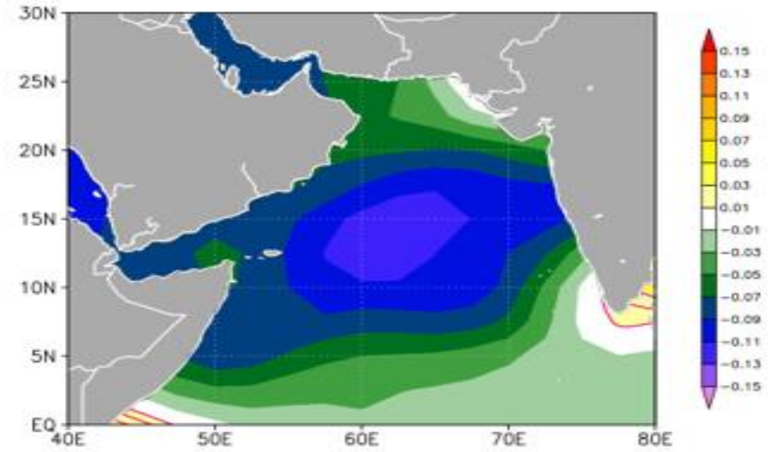


Figure 4.17(a): Composite anomaly of mid tropospheric relative humidity (1980 – 1989)

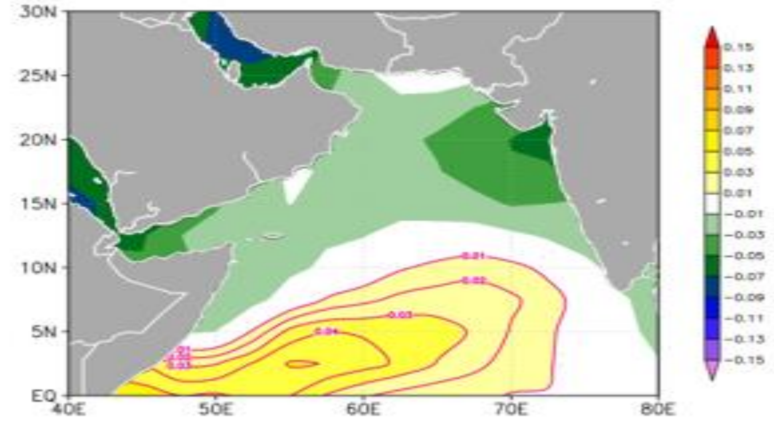


Figure 4.17(b): Composite anomaly of mid tropospheric relative humidity (1990 – 1999)

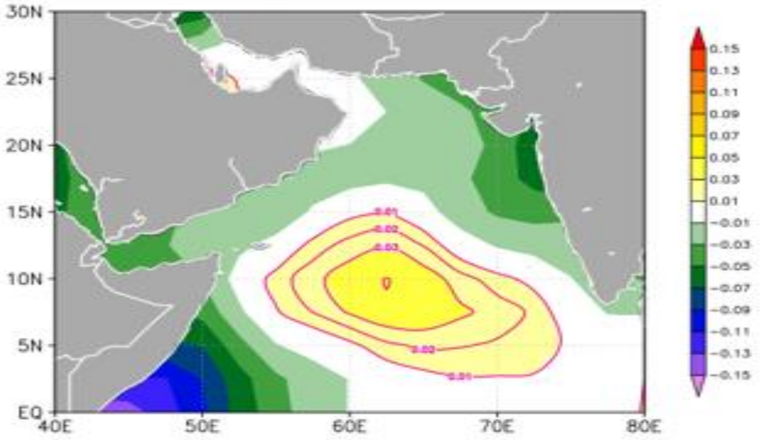


Figure 4.17(c): Composite anomaly of mid tropospheric relative humidity (2000 – 2009)

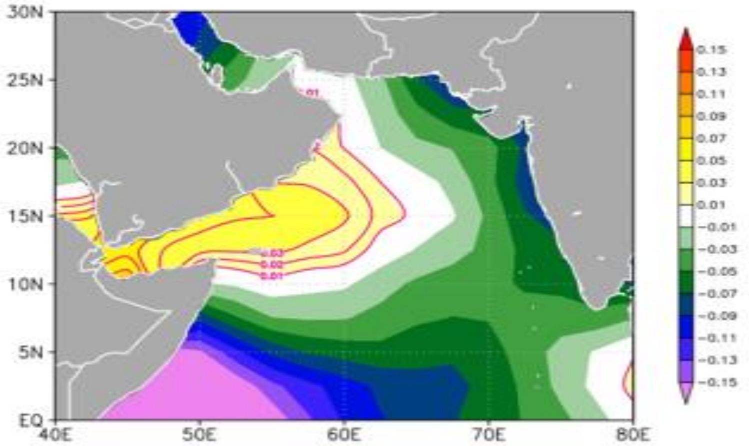


Figure 4.17(d): Composite anomaly of mid tropospheric relative humidity (2010 – 2019)

IV. Thermal instability anomaly

The figures represent the thermal instability anomaly (T850 - T500). It is evident that more depressions, cyclonic storms, and severe cyclonic storms are formed when Thermal instability shows positive values. While during negative anomalies, fewer number of storms are formed. Middle tropospheric instability I is calculated using the following formula:

Middle tropospheric instability I = (T850-T500) C (temperature difference between 850 and 500 hPa)

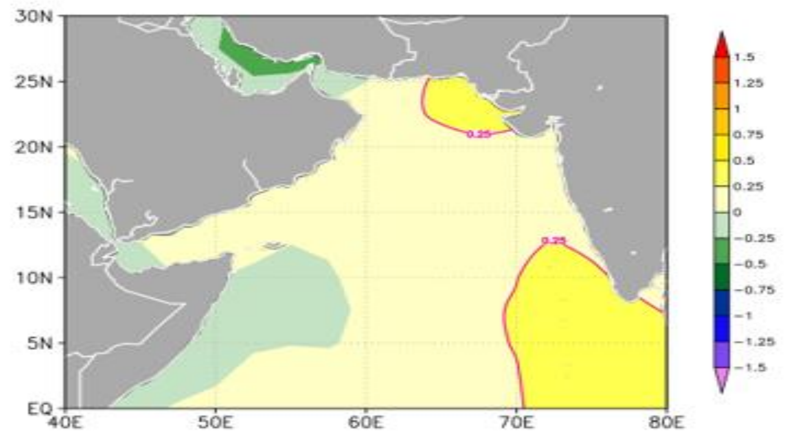


Figure 4.18(a): Composite anomaly of thermal instability (1980 – 1989)

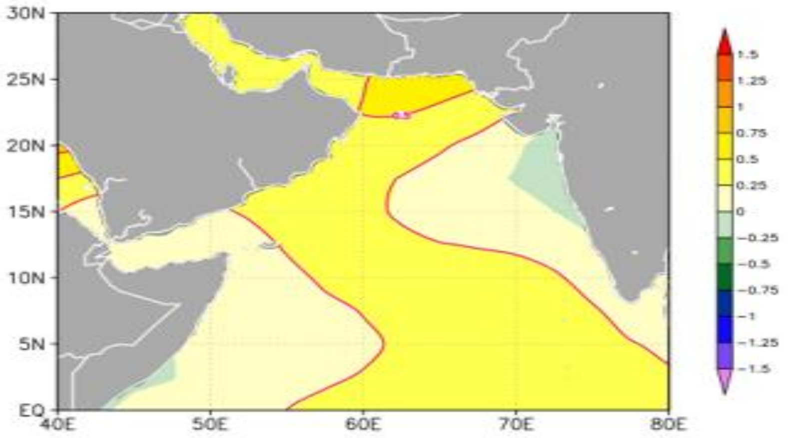


Figure 4.18(b): Composite anomaly of thermal instability (1990 – 1999)

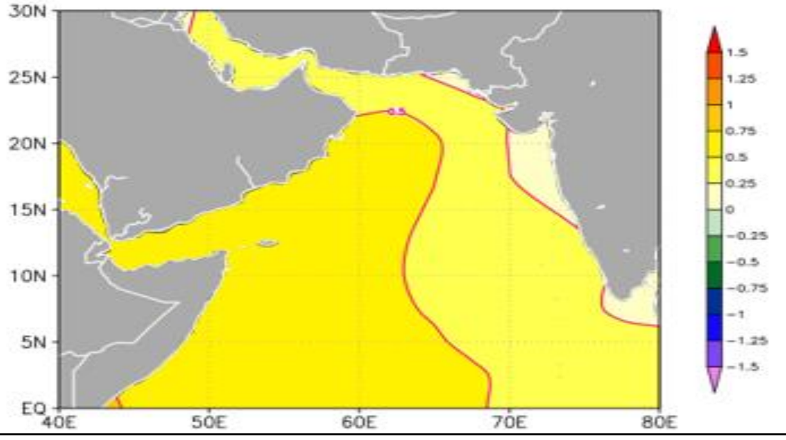


Figure 4.18(c): Composite anomaly of thermal instability (2000 – 2009)

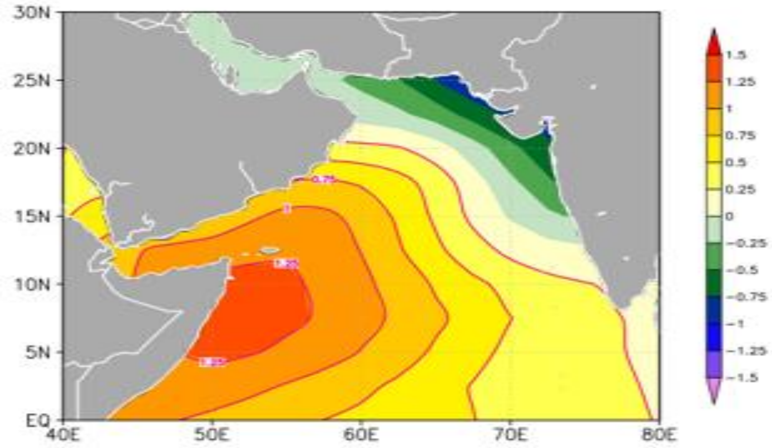


Figure 4.18(d): Composite anomaly of thermal instability (2010 – 2019)

V. Kotal GPI Anomaly

Figures represent Kotal GPI (genesis potential index) anomaly. More number of cyclones are formed when Kotal GPI shows positive values. While during negative anomalies, fewer number of storms are formed. Kotal GPI anomaly shows positive values during recent decade in almost all regions over the Arabian Sea, which means a greater number of cyclones are formed during the recent d

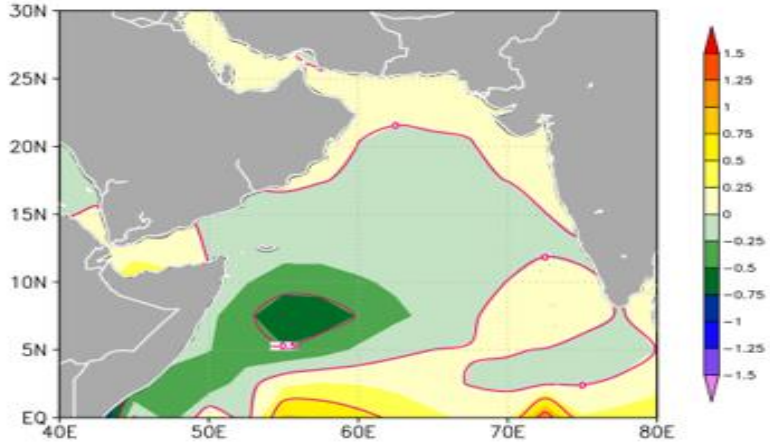


Figure 4.19(a): Composite anomaly of Kotal GPI (1980 – 1989)

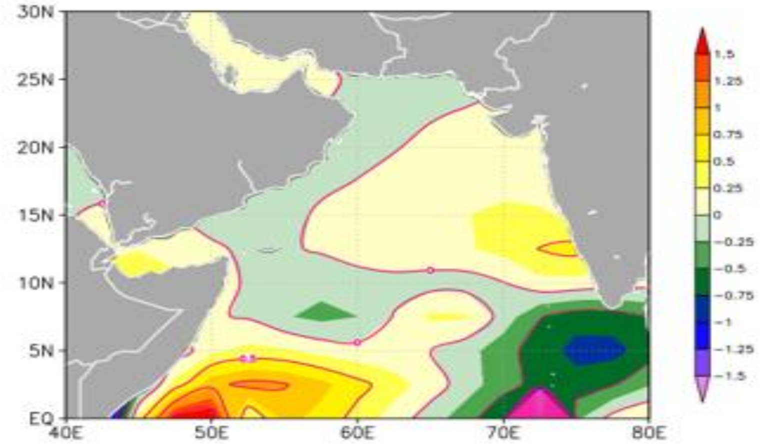


Figure 4.19(b): Composite anomaly of Kotal GPI (1990 – 1999)

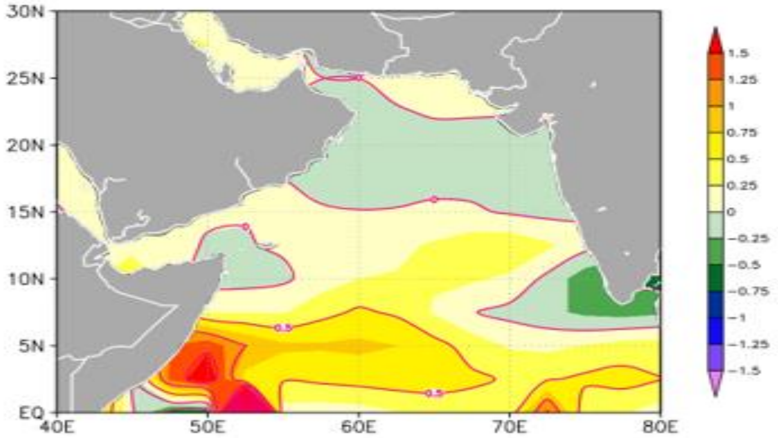


Figure 4.19(c): Composite anomaly of Kotal GPI (2000 – 2009)

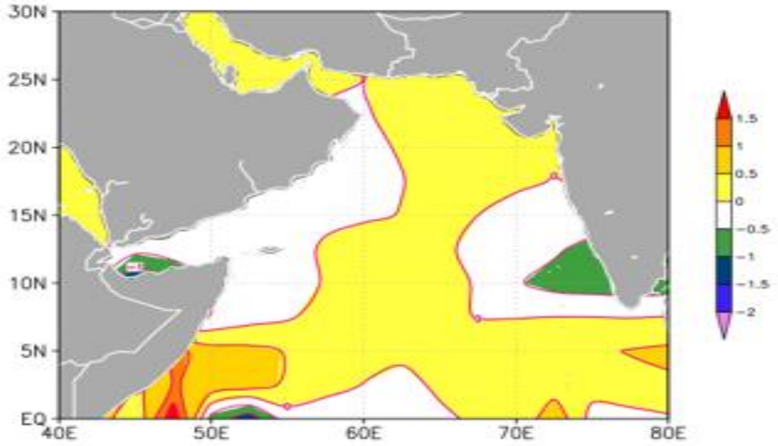


Figure 4.19(d): Composite anomaly of Kotal GPI (2010 – 2019)

VI. New GPI Anomaly

Anomaly of New GPI (genesis potential index) is shown in the figures. The NGPP is more useful for describing the decadal frequency variation of post-monsoon tropical cyclones in the warming baseline of the Arabian Sea. More number of cyclones are formed when New GPI shows positive values. While during negative anomalies, fewer number of storms are formed.

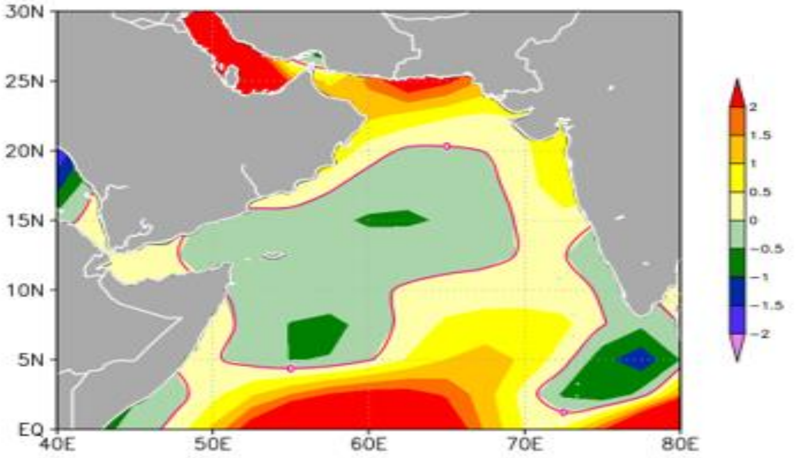


Figure 4.20(a): Composite anomaly of new GPI (1980 – 1989)

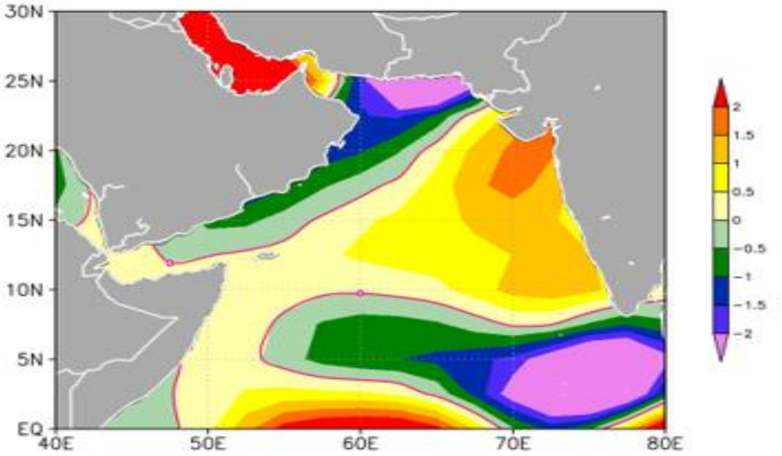


Figure 4.20(b): Composite anomaly of new GPI (1990 – 1999)

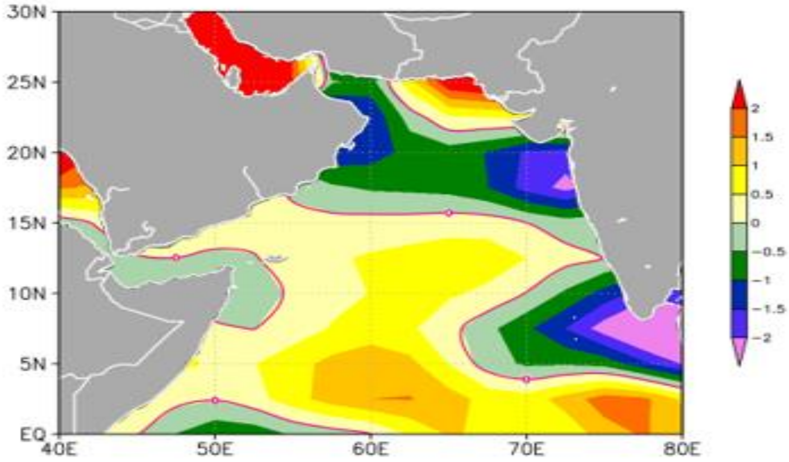


Figure 4.20(c): Composite anomaly of new GPI (2000 – 2009)

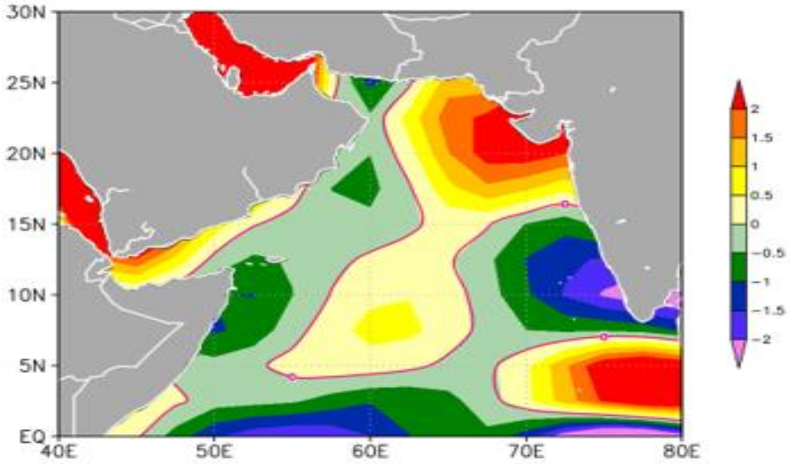


Figure 4.20(d): Composite anomaly of new GPI (2010 – 2019)

DISCUSSION

CHAPTER 5

DISCUSSION

Cyclones are intense low-pressure systems in the atmosphere that form over warm tropical ocean waters, with a substantial rotating mass of moist air in the form of a rotating disc. The associated winds often exceed 200 kmph and sucking up vast quantities of water will produce the worst of all, torrential rains, and flooding, resulting in significant loss of life and property damage. Tropical cyclones form in the oceans at low latitudes of all oceans except the South Atlantic and Southeast Pacific. Over 80 tropical cyclones occur over Earth: about two-thirds of cyclones form in the northern hemisphere. They are also known as hurricanes or typhoons at speeds of up to 119 kilometers per hour, depending on where they originate. Webster et al. (2005) described a steady rise in severe tropical cyclones in all basins from 1970-2004. Elsner et al. (2008) demonstrated the increased strength of the intense tropical cyclones worldwide during the satellite period (1981–2006). The analysis of NIO tropical cyclone trends, especially in the Bay of Bengal and the Arabian Sea individually, is inadequate. Around 7% of total tropical cyclones occur in the northern Indian Ocean.; moreover, many cyclones develop in the Bay of Bengal than in the Arabian Sea, around four times higher (Dube et al., 1997). On average, nearly 5–6 tropical cyclones develop over this basin every year (Singh et al. 2001) in the two cyclone seasons, namely pre-monsoon season (March-May) and post-monsoon season (October–December). Tropical cyclones are the most potent weather events on Earth, according to NASA. Rising sea levels can exacerbate cyclones and make them more deadly and devastating. Thermodynamic and dynamic parameters are considered to be responsible for the origin of tropical cyclones. Palmen (1948) showed that hurricanes form in areas where the SST is above 26 C. In addition to SST, other necessary parameters for the formation of TCs are large Coriolis force, high low-level relative vorticity force, weak vertical wind shears, humidity in the mid-troposphere, and convection instability (Gray 1975). Gray (1978) defined the genetic component of a tropical cyclone as the result of three thermodynamic and three dynamic factors. The three thermodynamic parameters are the relative humidity of the middle level troposphere and the vertical gradient of equivalent temperature at depths up to 60 m SST above 26ºC. The three kinetic factors are the Coriolis force, the inversion of the vertical windshield, and the relative vortex.

5.1 Arabian Sea cyclone trend (1980-2019)

In general, studies on the number and intensity of tropical cyclones in the northern Indian Ocean are limited, taking ARB and BoB activities individually. In some research, satellite information is illustrated in the study, which is inaccurate (Klotzbach 2006), and in other analyzes, recent data (after 2010) are not added. Utilizing information from 1980-2018, Murakami et al. (2020) identified variations in worldwide distribution and tropical cyclone formation and its spatial patterns. Global tropical cyclone numbers have not declined, but the upward trend in the South Indian Ocean, northeastern Pacific, northeastern coast of Australia, ARB, Central Pacific, and the North Atlantic Basin is declining. IMD's director-general Dr. M Mohapatra and team reported a gradual rise in the trend of cyclones' number over the Arabian Sea, causing the coastal areas to be highly exposed.

More than 90 % of the heat generated by greenhouse gases soaks up the oceans, causing water temperatures to rise. As tropical cyclones draw energy from hot water, rising temperatures make cyclones more common. The SST of the Arabian Sea is rapidly rising (Roxy et.al. 2019). An average of two or three cyclones a year are usually weak in the Arabian Sea. However, the Arabian Sea has experienced more severe cyclones than the Bay of Bengal off the east coast of India. But global warming is changing the temperature of the water. As a result, therefore, of more storms and cyclones in the tropics, especially in the Arabian Sea, because of ocean heat and rapid ocean warming Chan and Chan (2012) explain that the bigger size of Western Pacific storms is probably correlated with the elevated SSTs and that the intensity of cyclones affects the spatial range of the cyclone-produced cooling (Pun et al. 2018). The Indian Ocean is warming rapidly

(Roxy et al. 2019), and over the past 20 years, ocean temperatures have risen by more than 25% globally. (Lee et al. 2015; Cheng et al., 2017).

Floods become a major problem due to high tides. In addition, an increase in the number of extreme weather events, such as hurricanes in western India, may increase the cost of building infrastructure projects in the region. The increasing intensity of extreme cyclones with significant socio-economic impacts is due to atmospheric parameters such as intense mid-level relative humidity, positive low-level relative vorticity, low magnitudes vertical wind shear, and warm sea surface temperature. Relative humidity, relative vorticity, and vertical wind shear are distinct through the pre-monsoon season of La Niña, which favors the genesis of severe cyclone formation over this region. However, environmental factors such as SST, wind streamlines, Vertical Velocity, and Specific Humidity exhibited similar contributions to cyclone formation during El Niño and La Niña phases. This symbolizes the role of global warming in causing about this rising trend. The strength of tropical disturbance in the Indian Ocean is expected to rise with warmer climates. (Mittal et al. 2019; Reddy et al. 2021; Bhatia et al. 2018; Knutson et al. 2020).

5.2 Six primary cyclogenesis parameters

Tropical cyclones develop in warm oceans, with high SST above 26 C, weak vertical wind shear, low relative cyclone, large amounts of Coriolis force and middle level relative humidity. The increasing number of cyclones over the ARB is mainly associated with a rise in sea surface temperature (Deo et al. 2011; Rajeevan et al. 2013), and a reduction in wind shear (Evan et al. 2011; Deo et al. 2011; Rajeevan et al. 2013). Surface temperatures in the Arabian Sea have risen dramatically during the past decades because of global warming. The increasing temperature is also allowing the Arabian Sea to provide sufficient energy for the intensification of cyclones. Evan et al. (2011) demonstrated that the drop in wind shear is attributed to a immediate rising trend in human caused black carbon and sulphate particles. The Arabian Sea is also contributing favorable wind shear for storms. For example, a higher-level easterly wind made the depression of Cyclone Ockhi from the Bay of Bengal to the Arabian Sea.

Many studies were carried out to determine the association between El Nino phenomena and Tropical Cyclone activity (e.g., number, origin, path, and strength). The mean lifetime, occurrence, and power of Tropical Cyclones tend to develop while intense El Niño episodes across the eastern, central, and Western North Pacific. (Clark and Chu, 2002; Chan, 1985; Chen and Huang, 2006; Camargo and Sobel, 2005; Chu and Wang, 1997; Wang and Chan, 2002; Chen et al., 2006;). The two strongest El Ninos of the 20th century were those of 1982/83 and 1997/98, which had the highest SST. The El Nino of 2015/16 is in the same class as those of 1982/83 and 1997/98, and it set a record has the warmest year ever recorded on Earth. El Nino variability is generally monitored using indices calculated from average sea-surface temperature (SST) over the regions marked on the map. In 2015, during the post-monsoon season, depression and two severe cyclones, namely, Chapala and Megh were formed over the Arabian Sea, whereas during 1997, only depression was found. This is due to the positive IOD negating the effect of El Nino in 1997. Following a period of cold SST in 1996, it was anomalously high in 1997, yet a severe cyclone formed in 1996. This prompted the conclusion that the occurrence of cyclones is associated to the variations in SST over the north Indian Ocean. The formation of some atmospheric parameters, such as La Nina, positive IOD, changes the pattern of increasing frequency of TCs with response to the rise in SST.

SUMMARY AND CONCLUSION

CHAPTER 6

SUMMARY AND CONCLUSION

With about 6 percent of the worldwide storms, the Indian subcontinent is one of the most dangerous cyclone-striking areas of the world. In addition, about 8 percent of the total land area is vulnerable to tropical cyclones, particularly along the eastern and Gujarat coast. More cyclones form in the Bay of Bengal than in the Arabian Sea. Similarly, the east coast is more prone to storms, affecting 80 percent of the total cyclones created in the north Indian Ocean off the eastern coast of India.

Knowledge of the variations in number and strength of North Indian Ocean Cyclones will be helpful for better coastal hazard and coastal zone management. Global Warming has a prominent effect upon the north Indian Ocean Cyclones, and its consequence will seriously disrupt the life and livelihood across India. The number of cyclones in the Arabian Sea has increased by 52 percent, and very severe cyclones increased by 150 percent. The duration of cyclone in the Arabian Sea has increased by 80 percent over the past two decades. The intensity of the cyclone in the Arabian Sea increased by about 20 percent. Although the cyclone energy in the Arabian Sea has almost tripled, there has been no significant change in the Bay of Bengal (Roxy, M. K. et al.).

This study comprehensively analyzes the changes in the recent four decades (1980–2019) of cyclonic disturbance in the Arabian Sea. It explores the implications of the tropical Indian Ocean warming for the frequency of tropical cyclones and the post-monsoon intensity off the Indian coast. For this, changes in the frequency of tropical cyclones in the Arabian Sea after the monsoon have been studied using 45 years of tropical cyclone numbers (1974-2019). An attempt has been made in this study to link different cyclogenesis potential parameters that favor the formation and frequency variation of hurricanes in the Arabian Sea. Analyzed the thermodynamic and dynamic background conditions related to the decadal variation in cyclone number and intensity and identified the role of the of the Indian Ocean warming in the frequency variation of tropical cyclones.

Changes in tropical cyclone frequency and intensity are related to changes in the cyclogenesis parameters such as thermal instability, mid-tropospheric humidity, vorticity, wind shear, and sea surface temperature. According to recent studies, the tropical Indian Ocean's sea surface temperature has been increasing. Several studies implies that the Arabian Sea is continually warming, and its warm pool is growing, notably in recent decades. The most significant variations in the atmosphere and ocean occurred in the Arabian Sea. These variations are part of positive linear trends, indicating that the strength of Arabian Sea TCs after the monsoon may rise later as well. However, the impact of the Indian Ocean warming on the local climate is moderate.

The SST analysis of the study shows that the maximum temperature and increase in maximum cyclone intensities observed in the recent decade 2010-2019. Decreased SST anomaly is observed during the years 1983–1984, 1988–1989, 1998–1999, 2000–2001, 2008–2009, 2010–2011, and 2016–2017; this is due to the occurrence of La Nina. A steady increase in sea surface temperature over the Arabian Sea can be visible from 1980- 2019. The hottest six years are after 2015, with 2016, 2019 and 2020 in the top three. In addition, the average global temperature variation for the three hottest years, 2016, 2019, and 2020, is indistinguishable. Therefore, SST has contributed to improved cyclone activity in recent decades.

Minimal Vertical wind shear is a large-scale parameter that plays a significant role in a tropical cyclone in the formation and strengthening of tropical cyclones. Minimal vertical wind shear is favourable for the formation of tropical disturbances. Decreasing vertical wind shear during the recent decade may contribute to the formation of tropical disturbance. Vertical wind shear anomalies are negative in the recent decades. More depression, cyclonic storms, and severe cyclonic storms are formed when wind shear shows negative values. While during positive anomalies, a smaller number of storms is formed.

The relative humidity with a minimum of 40 % is needed for the formation of a cyclone. However, the relative humidity anomalies show a negative value in most of the regions over the Arabian Sea, and the decadal frequency of relative humidity has decreased during the last decade. Conditional instability through a deep atmospheric layer is needed for the formation of tropical cyclones. Thermal instability anomalies show positive values and among the four decades highest value is noted during 2010-2019.

Standardised anomaly of vorticity shows an erratic pattern from 1980-2019. It has been observed that vorticity is high in the above-normal tropical cyclone years and is during below normal TCs. High low-level relative vorticity is favourable for the formation of tropical cyclone. vorticity anomalies are negative in the recent decades. Composite analysis of KGPP and NGPP shows that a greater number of cyclones are formed when KGPP and NGPP shows positive values.

Our results indicated that the enhanced cyclonic activity in the recent decade is primarily triggered by increasing SST, thermal instability, vorticity, and reduction in wind shear. Therefore, a further cyclogenesis potential index, namely Kotal Genesis Potential Parameter (KGPP), was used for the analysis. The new genesis potential parameter (NGPP), with proper scaling and modification of the individual cyclogenesis parameters, better captures the decadal cyclone frequency, intensity, and track distribution. It is also noted that the NGPP is more useful in explaining the decadal frequency variation in the post-monsoon Tropical Cyclones over the Arabian Sea in a basic warming state.

REFERENCE

Chapter 7

REFERENCES

Abhilash, S., Sahai, A. K., Borah, N., Chattopadhyay, R., Joseph, S., Sharmila, S., De, S. and Goswami, B. N., 2014a, "Does bias correction in the forecasted SST improve the extended range pre-diction skill of active-break spells of Indian summer monsoon rainfall?", Atmospheric Science Letters, 15, 2, 114-119. https://doi.org/10.1002/asl2.477.

Baburaj PP, Abhilash S, Mohankumar K, Sahai AK (2020) On the epochal variability in the frequency of cyclones during the pre-onset and onset phases of the monsoon over the north Indian Ocean. Adv Atmos Sci 37:634–651. https://doi.org/10.1007/s00376-020-9070-5

Camargo SJ, Emanuel KA, Sobel AH (2007) Use of a Genesis Potential Index to diagnose ENSO effects on tropical cyclone genesis. J Clim 20:4819–4834. doi:10.1175/JCLI4282.1

Camargo, S. J. (2013). Global and regional aspects of tropical cyclone activity in the CMIP5 models. J. Climate.

Camargo, S. J. and Zebiak, S. E. (2002). Improving the Detection and Tracking of Tropical Cyclones in Atmospheric General Circulation Models. Weather and Forecasting,17(6), 1152–1162.

Camargo, S. J., Robertson, A. W., Gaffney, S. J., Smyth, P., and Ghil, M. (2007a). Cluster Analysis of Typhoon Tracks. Part II: Large-Scale Circulation and ENSO. J. Climate,20(14), 3654–3676.

Camargo, S. J., Barnston, A. G., Klotzbach, P. J., and Landsea, C. W. (2007b). Seasonal tropical cyclone forecasts. WMO Bulletin, 56, 297–309.Camargo, S. J., Emanuel, K. A., and Sobel, A. H. (2007c). Use of a Genesis Potential Index to Diagnose ENSO Effects on Tropical Cyclone Genesis. J. Climate, 20(19),4819–4834.

Camargo, S. J., Sobel, A. H., Barnston, A. G., and Klotzbach, P. J. (2010). The Influence of Natural Climate Variability on Tropical Cyclones, and Seasonal Forecasts of Tropical Cyclone Activity. In Global Perspectives on Tropical

Cyclones: From science to mitigation, pages 325–360. World Scientific Pubslishing Co.

Chan, JCL. and Shi, J. 1996. Long-term trends and interannual variability in tropical cyclone activity over the western North Pacific. Geophys. Res. Lett. 23:2765-2767.

Chan, JCL. 2006. Comments on Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment. Science. 311, 1713b.

Danard M, Murty TS. 1989. Tropical cyclones in the Bay of Bengal and CO2 warming. Natural Hazards 2: 387–390.

Deo A.A., Ganer D.W. Variability in Tropical Cyclone Activity Over Indian Seas in Changing Climate. International Journal of Science and Research, 4, Issue 5. 2015.

DeMaria M, Knaff JA, Bernadette HC (2001) A tropical cyclone genesis parameter for the tropical Atlantic. Weather Forecast 16:219–233.

Dvorak VF. 1984. Tropical cyclone intensity analysis using satellite data. NOAA Tech. Rep. NESDIS 11, National Oceanic and Atmospheric Administration, 47p

Elser JB, Kossin JP, Jagger TH (2008) The increasing intensity of the strongest tropical cyclones. Nature 455:92-95.

Emanuel KA. 1988. The maximum intensity of hurricanes. Journal of Atmospheric Sciences 45: 1143–1155.

Emanuel, K. (2005b). Increasing destructiveness of tropical cyclones over the past 30 years. Nature, 436(7051), 686–8.

Evan,A.T. & Camargo,S.J. A climatology of Arabian Sea cyclonic storms. J.Clim. 24, 140–158(2011).

Evans JL. 1993. Sensitivity of tropical cyclone intensity to Sea Surface Temperature. Journal of Climate 6: 1133–1141.

Frank, W. M. and Young, G. S. (2007). The interannual variability of tropical cyclones. Mon. Wea. Rev., 135, 3587–3598.

Gray, W. M., 1984, “Atlantic seasonal hurricane frequency. Part II: Forecasting its variability”, Mon. Wea. Rev., 112, 1669-1683.

Gray, William M., 1968, “Global view of the origin of tropical disturbances and storms”, Monthly Weather Review, 96, 10, 669-700.

Gray, William M., 1975, “Tropical Cyclone Genesis in the Western North Pacific”, Colorado State University, Fort Collins, Deptt. of Atmospheric Science. http://hdl.handle.net/10945/32587.

Gray, William M., 1998, “The formation of tropical cyclones”, Meteorology and atmospheric physics, 67, 1-4, 37-69.

Gray WM. 1968. Global view of the origin of tropical disturbances and storms. Monthly Weather Review 96: 669–700.

Gray, W. M., 1979, “Hurricanes: their formation, structure and likely role in the tropical circulation. Supplement of Meteorology Over the Tropical Oceans”, RMS, James Glaisher House, Grenville Place, Bracknell, Berkshire, RG 12 1BX, D. B. Shaw, (ed)., 155-218.

Gupta, A. and Muthuchami, A. 1991. El Niño and tropical storm tracks over Bay of Bengal during post monsoon season. Mausam. 42:257-260.

Gupta, GR., Desai, DS. and Biswas, NC. 1991. Cyclones and depressions over the Indian seas during 1989. Mausam. 42:1-16.

Henderson-Sellers, A. et al. Tropical cyclones and global climate change: A post-IPCC assessment. Bull. Am. Meteorol. Soc. 79, 19–-38 (1998).

IMD Atlas (1979) Tracks of storms and Depressions in theBay of Bengal and Arabian Sea. New Delhi: IMD

Jadhav SK, Munot AA. 2009. Warming SST of Bay of Bengal and decrease in formation of cyclonic disturbances over the Indian region during southwest monsoon season. Theoretical and Applied Climatology 96(3): 327–336

Joseph P.V. and Prince K. Xavier., (1999), Monsoon Rainfall and Frequencies of Monsoon Depressions and Tropical Cyclones of recent 100 years and an outlook for the first decades of the 21st century., Meteorology beyond-2000, Proceedings of National Symposium Tropmet-99., 16-19 Feb 1999, Editors A.K. Bhatnagar et al., Indian Meteorological Society, Chennai Chapter., 364-371.

Karthik Balaguru, Sourav Taraphdar, L. Ruby Leung, and Gregory R. Foltz. Increase in the intensity of post monsoon Bay of Bengal tropical cyclones. Geophysical Research Letters. 2014.

Kotal, S. D. and Bhattacharya, S. K., 2013, “Tropical cyclone Genesis Potential Parameter (GPP) and its application over the north Indian Sea”, MAUSAM, 64, 1, 149-170.

Kotal, S. D., Kundu, P. K. and Roy Bhowmik, S. K., 2009, “Analysis of cyclogenesis parameter for developing and non-developing low-pressure systems over the Indian Sea”, Natural hazards, 50, 2, 389-402.

Krishna, K. M., 2009, “Intensifying tropical cyclones over the North Indian Ocean during summer monsoon-global warming”, Global and Planetary Change, 65, 1-2, 12-16.

Mandake SK, Bhide UV. 2003. A study of decreasing storm frequency over Bay of Bengal. Journal of the Indian Geophysical Union 7(2): 53–58.

Mandal GS, Neumann CJ (1976) Climatology of North Indian Ocean tropical cyclones by 2 1/2-degree latitude longitude square. Fellowship report of senior authors. New Delhi: India Meteorological Department

McBride JL (1981) Observational analysis of tropical cyclone formation. Part III: budget analysis. J Atmos Sci 38:1152–1166. doi:10.1175/1520-0469(1981)038\1152: OAOTCF [2.0.CO;2

McBride JL, Zehr RM (1981) Observational analysis of tropical cyclone Part II: comparison of non-developing and developing systems. J Atmos Sci 38:1132–1151.

Mohapatra M, Nayak DP, Bandyopadhyay BK (2012a) Evaluation of cone of uncertainty in tropical cyclone track forecast over north Indian ocean issued by India Meteorological Department. Trop Cyclones Res Rev 1(3):331–339. https ://doi.org/10.6057/2012T CRR03 .02

Mohapatra M, Nayak DP, Sharma RP, Bandyopadhyay BK (2012b) Historical global tropical cyclone landfalls. J Earth Syst Sci 122(3):589–601

Mrutyunjay Mohapatra., A. K. Srivastava., S. Balachandran and Geetha B (2015) Inter-annual Variation and Trends in Tropical Cyclones and Monsoon

Depressions Over the North Indian Ocean. In book: Observed Climate Variability and Change over the Indian Region, pp.89-106.

Murakami H, Mizuta R, Shindo E (2012) Future changes in tropical cyclone activity projected by multi-physics and multi-SST ensemble experiments using the 60-km-mesh MRI-AGCM. Clim Dyn 39:2569–2584. doi: 10.1007/s00382-011-1223-x

Murakami H, Sugi M, Kitoh A (2013) Future Changes in Tropical Cyclone Activity in the North Indian Ocean Projected by the New High-Resolution MRI-AGCM. Clim Dyn 40:1949–1968. doi: 10.1007/978-94-007-7720-0_6

Murakami H., and B. Wang. 2010. Future change of north Atlantic tropical cyclone tracks: Projection by a 20 km mesh global atmospheric model. Journal of Climate 23: 2699-2721

Murakami H, Vecchi GA, Underwood S (2017) Increasing frequency of extremely severe cyclonic storms over the Arabian Sea. Nat Clim Chang. doi: 10.1038/s41558-017-0008-6

Palmen E.N. 1948. On the formation and structure of the tropical hurricane. Geophysica., 3:26-38

Patnaik K.V.K.R.K., K.Maneesha. Y.Sadhuram., K.V.S.R.Prasad., T.V.R.Murty, and V.B. Rao. 2014. East India coastal current induced eddies and their interaction with the tropical Storms over Bay of Bengal. Journal of Operational Oceanography 7(1): 58-68

Pattanaik DR. 2005. Variability of oceanic and atmospheric conditions during active and inactive periods of storms over the Indian region. International Journal of Climatology 25: 1523–1530.

Patwardhan SK, Bhalme HN. 2001. A study of cyclonic disturbances over India and the adjacent oceans. International Journal of Climatology 21: 527–534.

Pielke, R.A. Jr., Landsea, C., Mayeld, M., Laver, J. & Pasch, R., Hurricanes and global warming, Bull. Amer. Meteorol. Soc., 86(2005) 1571–1575.

Ramesh kumar, M.R. and Sankar, S. 2010. Impact of Global Warming on Cyclonic Storms Over North Indian Ocean. Indian Journal of Marine Species 39(4), 516-520

Rao DVB, Naidu CV, Rao BS (2001) Trends and fluctuations of the cyclonic systems over north Indian Ocean. Mausam 52(1):1–8

Roy Bhowmik SK (2003) An evaluation of cyclone genesis parameter over the Bay of Bengal using model analysis. Mausam 54:351–358

Saffir RH, Simpson, B. 1974. The hurricane disaster potential scale. Weatherwise 27:169–186

Sikka DR, Suryanarayana R (1968) Forecasting the movement of tropical cyclone/depression in the Indian region by computer-oriented techniques using climatology and persistence. New Delhi, IMD 76: 268 pp

Smith, T.M. & Reynolds, R.W., Improved Extended Reconstruction of SST (1854-1997), J. Climate, 17(2004) 2466-2477.

Singh OP, Ali Kahn TM, Rahman. 2001. Has the frequency of intense tropical cyclones increased in the North Indian Ocean? Curr. Sci. 80:575–580

Singh OP (2007) Long-term trends in the frequency of severe cyclones of Bay of Bengal: observations and simulations. Mausam 58:59–66

Singh OP, Khan TMA, Rahman S (2000) Changes in the frequency of tropical cyclones over the North Indian Ocean. Meteorol Atmos Phys 75:11–20

Singh OP, Khan TMA, Rahman S (2001) Has the frequency of intense tropical cyclones increased in the North Indian Ocean? Curr Sci 80:575–580

Southern, R. L. The global socio-economic impact of tropical cyclones. Aust.Meteorol. Mag. 27, 175–-195 (1979).

SS Ganesh., Abhilash, S., S. Joseph, M Kaur, “A review of the development and implementation of a tropical cyclone prediction system for North Indian Ocean in a multi-model ensemble framework”, Earth Science and Space Science, 7, 10, **https://doi.org/10.1029/2020EA001209**

Srivastav AK, Sinha Ray KC, De US (2000) Trends in the frequency of cyclonic disturbances and their intensification over Indian Seas. Mausam 51:113–118

Xavier PK, Joseph PV. 2000. Vertical wind shear in relation to frequency of monsoon depressions and tropical cyclones of Indian Seas. Proc. TROPMET-2000, National Symp. On Ocean and Atmosphere, Cochin, India, Indian Meteorological Society, 232–245.

Yamagata T, Behera SK, Luo J-J, Masson S, Jury MR, Rao SA (2004) The coupled ocean-atmosphere variability in the tropical Indian Ocean. Earth's climate: the ocean-atmosphere interaction. Geophys Monogr 147:189–211

Yu J, Wang Y. 2009. Response of tropical cyclone potential intensity over the north Indian Ocean to global warming. Geophysical Research Letters 36: L03709,5.

Zhao, H. and Raga, G.B. (2015) On the distinct interannual variability of tropical cyclone activity over the eastern North Pacific. Atmosfera,28, 161–178.

Zehr RM (1992) Tropical cyclogenesis in the Western North Pacific. NOAA Technical Report NESDIS 61,181 pp

Zeng Z, Wang Y, Wu CC. 2007. Environmental dynamical control of tropical cyclone intensity – an observational study. Monthly Weather Review 135: 38–59.

Changes in the frequency of tropical cyclones over Arabian Sea in response to Tropical Indian Ocean Warming

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THESIS ABSTRACT

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CHAPTER 7

ABSTRACT

Tropical cyclone is an intense circular storm that originates over warm tropical oceans and is characterized by low atmospheric pressure, high winds, and heavy rain. Drawing energy from the sea surface and maintaining its strength as long as it remains over warm water, a tropical cyclone generates winds that exceed 119 km (74 miles) per hour. Accompanying these strong winds are torrential rains and a devastating phenomenon known as the storm surge, an elevation of the sea surface that can reach 6 metres (20 feet) above normal levels. Such a combination of high winds and water makes cyclones a serious hazard for coastal areas in tropical and subtropical areas of the world. This study presents comprehensive analyses of the changes in cyclonic disturbances over Arabian Sea in the recent four decades (1980–2019) and investigates the likely impacts of Tropical Indian Ocean warming on tropical cyclones frequency and intensity on Indian coasts during the post monsoon season. For this, changes in the frequency of tropical cyclones developing over the Arabian Sea during post monsoon season have been studied utilizing 45-years (1974-2019) of tropical cyclone count from IMD eAtlas. An attempt has been made in this study to link different cyclogenesis potential parameters favouring the formation of the cyclones and frequency variation over Arabian Sea. Thermo dynamical and dynamical background state is analyzed with respect to the decadal variation of cyclone number and intensity and thereby identified the role of Indian ocean warming on tropical cyclones frequency variation. Monthly data of sea surface temperature is collected from Extended Reconstructed Sea Surface Temperature (ERSST) - version 5 was used for the analysis of SST. Data related to various atmospheric variables (i.e., winds at 850 and 200 hPa, RH at 500 hPa and 500-hPa geopotential height, mid tropospheric instability) have been obtained from the National Centres for Environmental Prediction-National Centre for Atmospheric Research (NCEP-NCAR) monthly reanalysis dataset. The Joint Typhoon Warning Centre (JTWC)

best track data has been utilized in this study for the Arabian Sea tropical cyclones for the period 1980–2019.

The results show that the changes in frequency of tropical cyclone is related to changes in the cyclogenesis parameters such as thermal instability, mid tropospheric humidity, vorticity, wind shear and sea surface temperature. Our results indicated that the enhanced cyclonic activity in the recent decade is primarily triggered by increasing SST, thermal instability, vorticity, and reduction in the wind shear. Further cyclogenesis potential index, namely Kotal Genesis Potential Parameter (KGPP) operationally used by India Meteorological department (IMD) is modified to capture decadal variability in cyclone frequency over Arabian Sea. It is found that, with proper scaling and modification of the individual cyclogenesis parameters, new index better captures the decadal cyclone frequency, intensity, and track distribution. It is also noted that the new genesis potential parameter (NGPP) is more useful in explaining the decadal frequency variation in post monsoon Tropical Cyclones over Arabian sea in a warming basic state.