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Progress in Tropical Cyclone Predictability and Present Status in the North Indian Ocean Region

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Abstract

Tropical cyclone (TC) is an important research area since it has a significant impact on human life, properties and environment. The researchers all over the world have been studying fundamental and advanced processes to better understand and thereby predict the genesis and evolution of TCs. This review chapter provides a brief overview on TC climatology, their basic characteristics, movement and intensification, research on structure analysis and prediction of these fascinating storms, with primary emphasis to North Indian Ocean (NIO). The role of ocean and atmosphere in determining the genesis and intensification of TCs is discussed. This chapter reviews the past and current research activities including inter-annual and intra-seasonal changes in TCs, current status of TC research using numerical weather prediction, gaps identified and relevant measures taken by the meteorological and government agencies in this direction, along with future directions in order to improve the understanding and predictability over the NIO region.

Keywords: tropical cyclone, cyclogenesis, predictability, North Indian Ocean, WRF

1. Introduction

A tropical cyclone (TC) is a cyclonic disturbance that originates over warm tropical oceans with anticlockwise (clockwise) winds around a centre of low barometric pressure in the Northern Hemisphere (Southern Hemisphere) [1]. It creates strong winds and intense precipitation in the regions around the system. There are seven global basins that conceive TCs, viz. North Atlantic Ocean, eastern and western parts of North Pacific Ocean, south-

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western pacific, south-western and south-eastern Indian Ocean and North Indian Ocean (NIO) region. The cyclonic storms are often known as hurricanes and typhoons in the Atlantic and northwest Pacific, whereas TCs in other Ocean basins. The average frequency of occurrence, season and intensity of TCs vary from basin to basin. NIO basin shows bi-modal TC season with maximum frequency during post-monsoon period (October–December) and are comparatively stronger than pre-monsoon ones. Though the size of the TCs is relatively smaller and their intensity is comparatively less over NIO basin as compared to the other global basins, this region is quite important in view of the densely populated rim countries with poor socioeconomic conditions. Hence, loss of life and property is quite significant in this region. Based on the intensity, TCs formed over NIO basin can be classified into (i) depression if the associated 10-m maximum sustained wind (MSW) is in between 17 and 33 kt; (ii) cyclonic storm (CS) if MSW is in between 34 and 47 kt; (iii) severe cyclonic storm (SCS) if it has MSW of 48–63 kt; (iv) very severe cyclonic storm (VSCS) if the MSW is within the range 64–90 kt, and extremely severe cyclonic storm (ESCS) if the MSW is in range of 91–119 kt; and (v) super cyclonic storm (SuCS) if it has MSW of 120 kt or more (http://www.rsmcnew-delhi.imd.gov.in). This classification may differ from those over other global basins including that of the widely used Saffir-Simpson hurricane wind scale or SSHWS (http://www.nhc.noaa.gov/aboutsshws.php). Both types of classifications, that is, the earlier one from India Meteorological Department (IMD) and the SSHWS consider the tropical low-pressure system as a depression if MSW is <34 kt. The consideration of CS and SCS lies in the tropical storm category (MSW lies in the range 34–63 kt) of SSHWS. The VSCS category over NIO basin is similar to that of the category 1 hurricane (MSW lies in the range 64–82 kt) type. The category 3 (MSW lies in between 96 and 112 kt) and category 4 (MSW is within the range 113-136 kt) major hurricanes are comparable to ESCS over NIO basin. The IMD classification categorizes MSW above 120 kt as super cyclonic storm (SuCS), whereas SSHWS considers the desired wind speed above 137 kt for category 5 hurricane. However, the basic structure of NIO TCs is similar to hurricanes and typhoons.

Having a prolonged coast line, about 96 districts (lying within 100 km from the coast) of India are vulnerable to the occurrence of TCs with varying intensity [2]. Out of these 96 districts, ~59% are at least highly vulnerable. The number of CS and SCS with a core of MSW (between 34 and 63 kt) crossing different countries of the NIO region is found to be 504 during 1891–2015 (derived from the available IMD data at http://www.rmcchennaieatlas.tn.nic.in). Out of these, about 328 (>65%) crossed the Indian coasts, whereas 127 (>25%) have crossed the east coast of India between Gopalpur and Kolkata. In general, the proneness to TCs is quite high for the coastal districts of West Bengal, Odisha, Andhra Pradesh, and Tamil Nadu [2, 3]. In view of these, TCs over NIO basin can be considered as quite lethal and expensive natural disaster as they bring widespread destruction in these regions. The consequent loss of human life and properties impacts the economy of a country. Therefore, it is important to forecast the evolution of TCs by using numerical models as the frequency of such storms is increasing in several basins of the world in the present warming period [4]. Therefore, it is attempted to put forward the recent developments in understanding the related meteorological characteristics, their predictability, climatological aspects and the gaps identified in the area of TC research.

2. Life cycle of tropical cyclones

This section describes the general understanding about life cycle of TCs. The description includes a brief overview about their genesis, structural evolution, propagation and dissipation.

2.1. Cyclogenesis

The TC research has evolved over several decades and researchers use observations as well as numerical models for this purpose. For example, some observational studies [5–7] discuss about TC formation and evolution. The pioneering works by Gray [8, 9] have shown that the formation of TC at any location depends on six factors: (i) appropriate Coriolis parameter 'f' that is practically effective 5° away from the equator in both the hemispheres, (ii) low-level positive relative vorticity (ζ_r), that is, existence of initial disturbance, (iii) low tropospheric vertical wind shear (S_z), (iv) ocean thermal energy (E) signified by sea surface temperature (SST), that is, SST should be ≥26.5°C within vertical extent of 60 m, (v) atmospheric instability measured in terms of difference in equivalent potential temperature (θ_e) between the surface and 500 mb or $\Delta\theta_e$ and (vi) mid-tropospheric relative humidity 'RH'. Some of these aspects are discussed explicitly over the years using observations and numerical models [7, 10]. The first three parameters produce a dynamic potential ($f\zeta_r/S_z$), while the remaining three parameters yield a thermal potential ($E\,\Delta\theta_e\,$RH). And, the product of dynamic and thermal potentials provides the seasonal genesis frequency.

Cyclogenesis do not occur spontaneously even if all the environmental conditions are met. Further, only about 10% of all cyclonic disturbances intensify into TCs. These low-pressure systems gradually form from a pre-existing (or initial) disturbance that consists of wind vortex and organized clouds. Thus, the necessary conditions for tropical cyclogenesis must be supported by the deep convection in the presence of a low-level absolute vorticity maximum and the initial convection must survive for sufficient time. The survival ability of the initial convection depends on 'ζ_r', 'f' atmospheric stability (defined by Brunt Vaisala frequency 'N') and depth of the system (H). This ability is defined by the Rossby radius of deformation 'L_R' typically for a large tropical cyclonic system (www.meted.ucar.edu):

$$L_R = \frac{NH}{\zeta_r + f}$$

(1)

The average life expectancy of a TC is about 1 week, whereas it is found that few cyclones remain active for more than 4 weeks (exact time frame may change from basin to basin) as seen in case of a hurricane, provided the system must be able to stay over the warm tropical waters. In most of the TCs, the Coriolis and centripetal forces oppose the pressure gradient force [11]. In the lowest kilometres near the surface, the frictional force destroys the gradient balance and consequently, air spirals inward towards the storm centres. The primary circulation (horizontal axisymmetric) during tropical cyclogenesis gains latent heat through the process of evapora-

tion and exchange of sensible heat with the underlying ocean as it spirals towards the storm centre [12]. Consequently, it gains large angular momentum and kinetic energy because of the acceleration towards the low-pressure centre. The evaporation of sea spray provides the necessary moisture supply. Because of the high velocity demanded by the quasi-conservation of angular momentum, the air may not penetrate beyond some small radius. To conserve the angular momentum, the air spirals upward in the eyewall forming intense ring of cumulus cloud and a calm eye at the centre and brings in the latent heat it acquired during the upward motion in the boundary layer to the free atmosphere. Due to the cooling of this rising air, latent heat releases into the atmosphere to add more energy to the storm. Across the top of the boundary layer, the turbulent eddies generated by the mechanical mixing due to the prevailing strong winds cause a significant downward flux of sensible heat from the free atmosphere through subsidence (**Figure 1**).
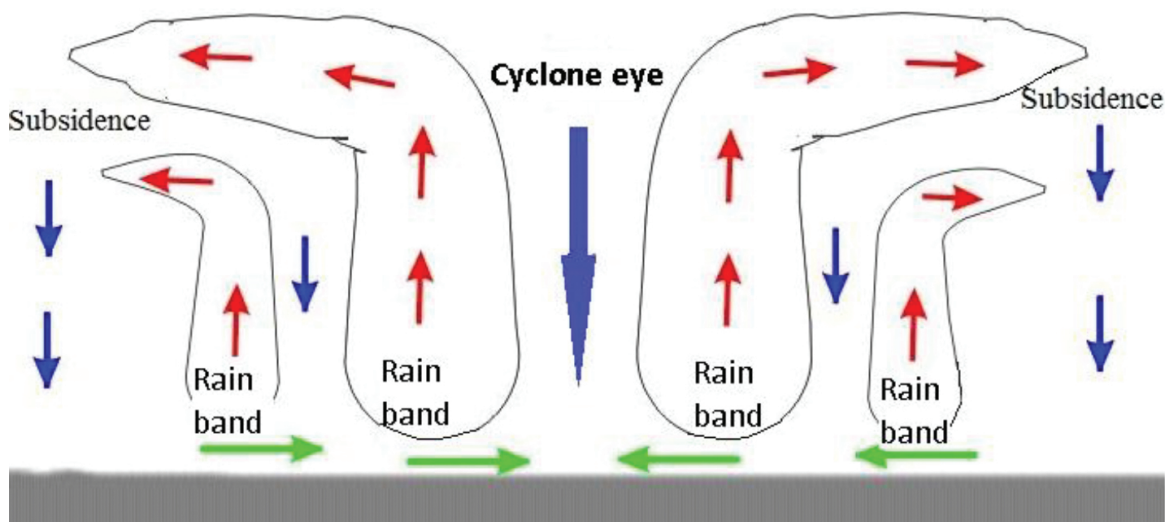

Figure 1. Vertical cross section of a mature cyclonic storm and associated basic characteristics (adopted from http:// www.hko.gov.hk/informtc/nature.htm).

As the convective updrafts in the eyewall ascends to the tropopause, the latent heat is converted to sensible heat through condensation in order to provide the much-needed buoyancy for lifting air from the surface to tropopause level. After reaching at the upper level, the air turns outwards and eventually spread out at high altitudes, where it forms anticyclonic circulation and eventually the cool air above the eye begins to sink into the central core (**Figure 1**). Thus, the storm can be termed as a quasi-steady thermodynamic heat engine that is primarily driven by latent heat release. This heat engine runs between a warm heat reservoir as sea that is at ~300°K and a cold reservoir located at 15–18 km up in the troposphere having a temperature ~200°K. A baroclinic structure is maintained by the latent heat release in the warm core, which is continuously converted to kinetic energy that is responsible to drive the TC.

Apart from the basic factors discussed so far, there is a significant role of Madden-Julian oscillation (MJO) and El Niño in the frequency of occurrence of TCs (see [13]). In certain scenarios, equatorial Rossby waves (ER), mixed Rossby-gravity waves (MRG), Kelvin waves

and easterly waves also influence the tropical cyclogenesis [14]. However, equatorial Kelvin waves do not appear to play a major role in tropical cyclogenesis. Several hurricanes in the North Atlantic form from African waves, MJO has a significant role in tropical cyclogenesis in North Pacific and the formation of cyclonic storms in the northwest Pacific is associated with MRG waves [13, 15]. These waves enhance the local conditions for the genesis of TCs by increasing upward motion, convection and the low-level vorticity by altering the local vertical shear pattern. The larger-scale waves, such as the MJO and ER, can also alter the mean zonal wind in large spatial and temporal scales in order to influence the mean flow.

The active phase of MJO is generally found over Indian Ocean, the maritime continent, and western pacific [13], which seem to play a major role in regulating the frequency of occurrence (usually increases) and formation of TCs in these regions. MJO increases the westerly wind which blows from west to east and its active phase through the region increases convective activity. During El Niño events, the atmospheric response to SST anomalies (SSTA) in the equatorial Pacific perturbs the Walker circulation [16]. The most common form of genesis occurs when they interact with the Asian monsoon. However, such type of interaction is still not studied well though few studies emphasized the role of El Niño or El Niño Southern Oscillation (ENSO) in TC formation over the Bay of Bengal (BOB) region indicating a decrease in the number of TCs [17].

2.2. Structural evolution

The general structure of the TC can be understood through the visualization of vertical cross-section of a mature TC as depicted in **Figure 1**, which consists of eye, eyewall and rainbands. The centre of the structure signifies the low-pressure cyclone eye, where a strong downward flow occurs indifferent to the immediate neighbouring updrafts. However, subsidence is also visible alongside the updrafts in the neighbourhood eyewall region away from the eye. The appearance of eye, its growth, intensification of eyewall and disappearance of eye are described in this section.

The life cycle of the TC is shown in **Figure 2(a)**, where the inner and outer cores of a TC are considered besides its intensification in order to depict the strengthening and weakening. **Figure 2(b)** depicts the different stages of TC life period including genesis, development, mature stage and dissipation by considering the evolution of TC Phailin (2013) in BOB region as an example to the illustration shown in **Figure 2(a)**.

In the intensification period (or phase 1), the momentum from outer core towards the inner one helps in strengthening the 700 hPa wind field and subsequently it helps in the eye wall cloud formation [18]. Prior to the appearance of eye, the intensification process is quite slow (at a rate ~8 hPa/day). The increase in maximum wind field is ~5 ms^{-1}day^{-1} and the outer core strengthens at a rate of ~2 ms^{-1}day^{-1}. Gradually, when the eye appears, the central pressure is about 987 hPa and the rate of intensification increases by ~250 times, at a rate of about 20 hPa/day. The rapidly deepening cyclone (at a rate ~42 hPa/day) supports an earlier eye formation. During the filling phase, the central pressure starts rising by drawing momentum through the outer core and strengthening the outer core's wing.
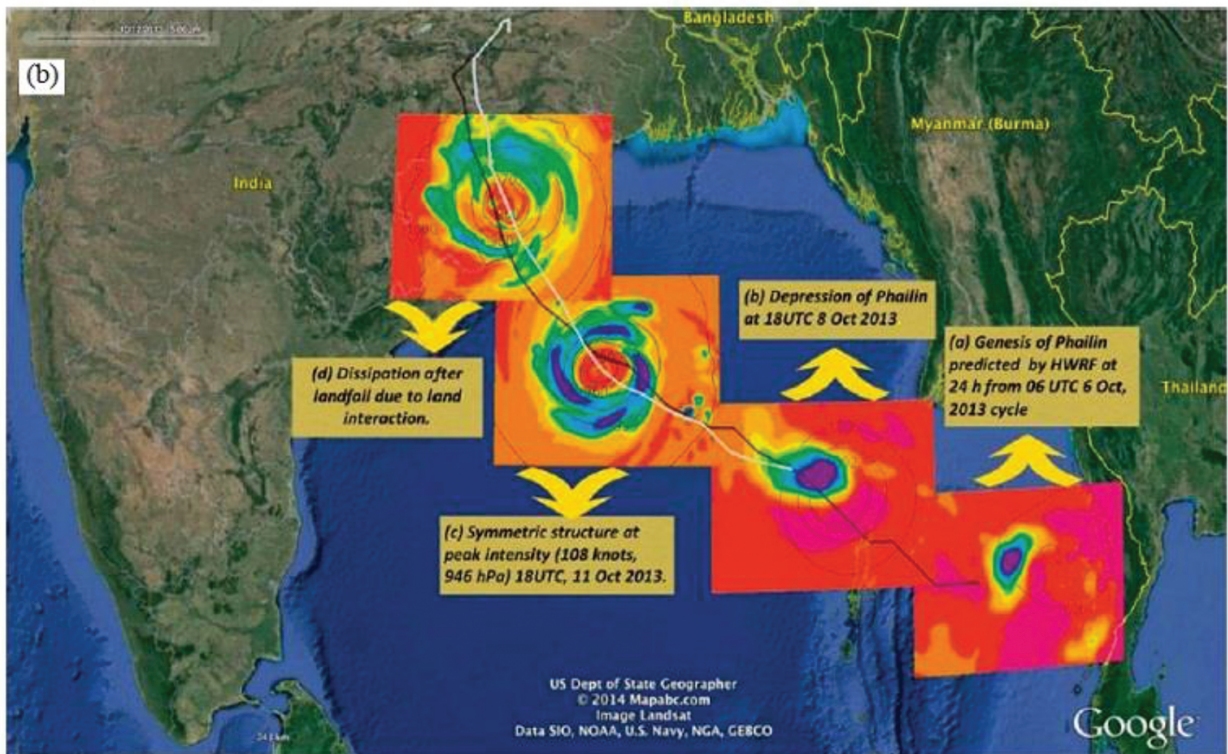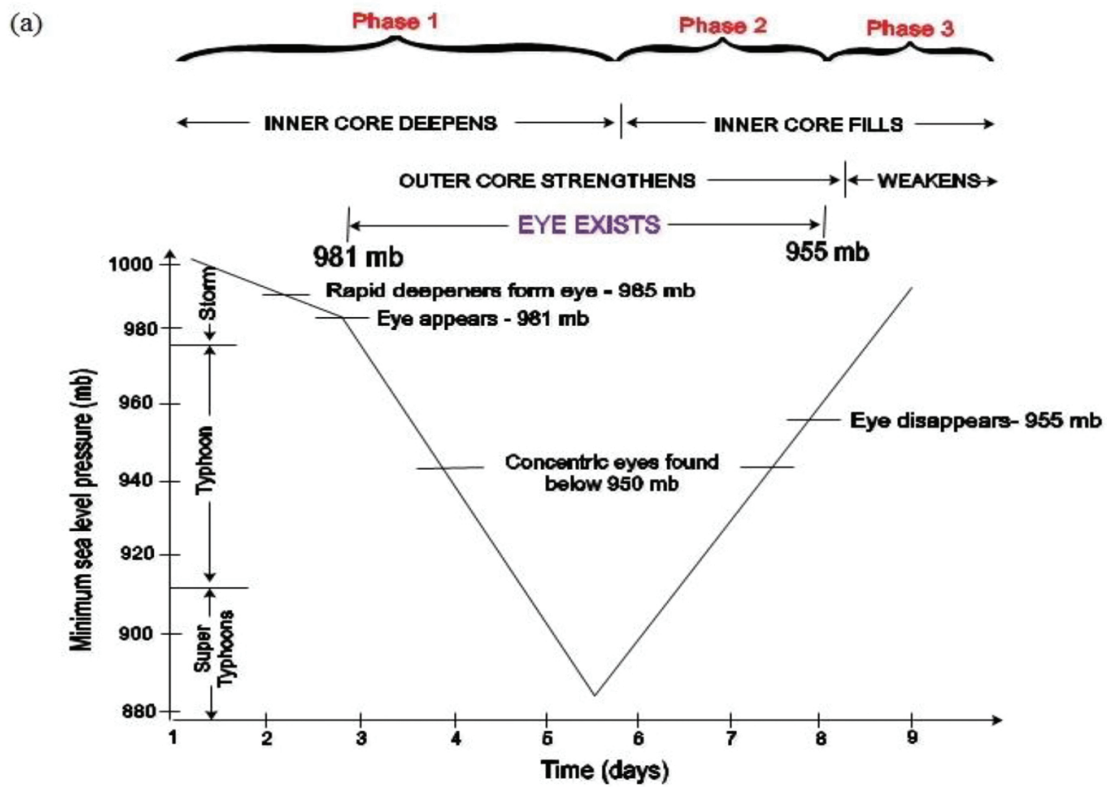
Figure 2. (a) Conceptual rendering from the main events in the life cycle of a tropical cyclone [18] and (b) different stages of tropical cyclone Phailin formed over Bay of Bengal [80].

The phase 2 is usually marked by the strengthening of outer core wind (similar to the stage (c) of TC Phailin shown in **Figure 2(b)**), whereas the inner core wind diminishes. During this phase, the eye expands and the filling of the inner core continues through the inflowing air towards the cyclone centre. During the filling phase, the inertial stability of the outer core is twice as large as that of the deepening stage making the outer core rigid for the inflowing air. Gradually the expansion of the eye ceases and the central core fills. It is important to note that the longer a cyclone spends in phase 2, stronger the outer radius will be and the radius of the damaging winds expand as long as the eye exists.

During phase 3, the outer wind starts weakening (e.g. stage (d) of TC Phailin shown in **Figure 2(b)**) with the disappearance of eye. Once the eye is vanished, the inflow of angular momentum ceases that was responsible for the strengthening of the outer core and from where the decay of outer radius low level wind field begins. These characteristics are valid for the cyclones which do not suffer landfall because the landfall would erode the wind field irrespective of the appearance of eye.

Though the basic principles of structural evolution may hold good for the TCs occurring in NIO basin (refer to **Figure 2(b)** for different stages of the TC Phailin), the formation of a distinguished eye structure may always not be feasible. A distinguished eye may be seen in case of a very severe cyclonic storm in this basin during phase 2. However, an explicit analysis in this direction is not available in literature for the NIO basin even though few studies like [19] computed the radius of maximum wind seen in case of TC intensification.

2.3. Propagation

TCs generally originate in tropics and thereafter, travel westward [20, 21] or turn poleward and recurve towards eastward direction [21, 22] or suffers extratropical transition over land or water [23] before dissipation. If a time scale of 1–3 weeks is considered, then the evolution of Rossby wave train significantly influences the track of a TC. Across the subtropical regions, under the influence of synoptic scale ridging, the TCs tend to move more westerly, and under the influence of synoptic scale trough, TCs tend to recurve into the mid-latitude [24]. On a seasonal scale, it is seen that over the Indian Ocean, the advancement of monsoon has a considerable impact on TCs' growth and their track [25].

In principle, TCs move under the influence of its surrounding environment. When the easterlies are added with the wind at certain level from the storm, the resulting effect forces the system to move in a westward direction [26]. Since the winds are not constant with height, it complicates the movement. The 'β effect' or 'β drift' pushes the cyclone towards the northwest direction in the northern hemisphere. It superimposes a weak northwest ward (southwest ward) steering current upon the TC in the northern (southern) hemisphere.

Apart from the factors mentioned earlier, the wind shear around anti-cyclonic flow at the top of the TCs also impacts their movement and can influence the track as much as the 'β drift'. There is a more complex phenomenon which influences the motion of a cyclone, known as 'Fujiwhara effect' [27]. Fujiwhara interaction describes the mutual rotation of two vortices about a common centre [28]. This centre typically refers to the mass weighted centroid of the

two vortices, if they are of equal strength. In the presence of the β effect, the two vortices rotate around each other relative to the centre of rotation. This centre of rotation is not fixed and, instead, moves northwest ward in response to the 'β effect'. 'Fujiwhara effect' is noticed over other basins of the world including Atlantic, but is not applicable for TCs formed over NIO.

2.4. Dissipation

The most common way of dissipation of a TC is its landfall. When the storm moves over land, it deprives itself from warm water and the available moisture over ocean. Consequently, it is deprived from the energy source and the warm core with thunderstorms near the centre turns into a remnant low-pressure area due to quick loss of energy. Weakening can also occur if it encounters a vertical wind shear that causes the heat engine and convection shift away from the centre. The rate of power dissipation of TCs can be computed [29] as

$$E_D = C_D \rho v^3$$

where E_D is the rate of energy dissipation per unit time per unit horizontal surface area, v defines the wind speed, ρ is for air mass density, and 'C_D' is the drag coefficient that depends upon the surface irregularities. Since the power dissipation in TCs is proportional to the cube of its wind velocity, the severity can be computed as the cumulative sum of the cube of the wind velocity over time according to the above equation.

3. Role of ocean in genesis and intensification

There are two sources which are capable of changing the TC intensity, one is internal variability and other one is environmental interaction. One important aspect of later source is the interaction between the ocean and the storm system. Usually TC is regarded as the most forceful case in air-sea interaction studies where energy from the warm ocean waters is delivered via surface heat flux [30]. The ocean response is quite sensitive to the surface drag coefficient. Emanuel [31] used a simple numerical model to establish the progress of hurricane intensity. Their findings advocate that in most cases, the intensity depends on three factors, viz. initial intensity of cyclone, thermodynamic state of atmosphere through which the cyclone propagates and finally the heat exchange with the upper layer of the ocean underlying the core of the cyclone. Rapid intensification of TC is noticed when it passes over the deep upper ocean mixed layer and that upper ocean thermal structure plays a significant role in the intensification process [32–34]. Sutyrin [35] performed simulations with a coupled model of the oceanic and atmospheric boundary layers and concluded that the interaction is strong enough to change the supply of heat and moisture fluxes from the ocean into the atmosphere significantly within few hours of the formation of the storm and consequently, influence the TC intensity.

The intensity of TC increases with increase in SST and upper ocean heat content [36]. The positive feedback occurs when genesis and intensification happens. During this phase, the

evaporation from the ocean surface stimulates surface wind that subsequently increases the moisture supply and consequently increasing the latent heat that is further utilized to drive the circulation. As a negative feedback, the decrease in SST results in the decrease in total heat flux (sum of latent heat and sensible heat), resulting in decrease in intensity of the storm. Besides these interactions, some of the mechanical energy supplied by the TC is dispersed laterally and vertically by the internal inertia-gravity waves with time [37].

On the other hand, the intensification of TC depends not only on SST but also on subsurface ocean thermal structure also considered as an important predictor for the TC intensification (e.g. see [38–40]). In the changing climate scenario, SST plays a bigger role during pre-monsoon season as compared to the post-monsoon period for governing TC activity over NIO region [41]. In contrast, the same may not be valid for other basins including North Atlantic Ocean, where an increasing trend in correlation between SST and TC power dissipative index is observed [42]. The influence of the changing climate on the TC genesis and intensification in the NIO region may therefore not be limited to the analysis relating SST only.

4. Numerical modelling of tropical cyclones

A significant number of studies regarding TC propagation, track prediction, time and place of landfall and intensity of the storm are carried out for several ocean basins including NIO. Considerable improvements in predicting the TCs are also achieved till date. In view of these, this section highlights the recent developments regarding TC predictability over NIO region and the current scenario.

4.1. Model predictability

Various regional models such as GFDL (USA), ALADIN (France), Quasi-Lagrangian Limited Area Model or QLM (India), MM5 (USA), etc. are used for TC research and operational forecasting purpose. Apart from these, the Eulerian-mass-based dynamical core of Weather Research and Forecasting (WRF) model, designed as the successor to MM5 is also used to predict TCs. The variants of WRF regional model are Advanced Research WRF or ARW and non-hydrostatic mesoscale model or WRF-NMM. Though these numerical models are quite capable for real-time predictions in regional scale, they need appropriate initial and boundary conditions from global models. For example, a recent study carried out by Kumar [43] discusses about the impact of European Centre for Medium-Range Weather Forecasts (ECMWF), National Centers for Environmental Prediction (NCEP) and National Centre for Medium Range Weather Forecasting (NCMRWF) global model analysis on the WRF model forecast for TC prediction over Indian region. This study indicates some of the inherent limitations of such global analyses data sets including the consideration of few fundamental aspects like that of the middle tropospheric humidity profiles those are important for TC genesis. Another limitation of such data sets is their horizontal resolution though recent advancements have made availability of some of the usable global analyses for the desired purpose with higher spatial resolutions up to 0.25°.

Since NWP models are equipped with real-time prediction capability, they are being used increasingly for the TC prediction over NIO region as well. Some of the numerical models and their skills are discussed here. For instance, QLM regional model was adopted by Prasad [44] for cyclone track prediction over NIO region and found the performance to be reasonable. The recurvature of the cyclones were also well predicted. However, the model performance for TC intensity prediction was not satisfactory. Another notable study by Mohanty et al. [45] used MM5 to simulate Orissa (Odisha) super cyclone (1999) for predicting track, intensity, mean sea level pressure and associated precipitation. Though such types of studies were able to improve the prediction of several relevant parameters including TC tracks, they were not so successful in predicting the intensity accurately like the studies performed using QLM. Similarly, some recent studies used three variants of the next-generation mesoscale WRF model (i.e. ARW, WRF-NMM, and Hurricane Weather Research and Forecasting Model or HWRF) for TC research and operational purpose as well [51, 53, 56, 57, 66]. It may be noted that ARW uses Arakawa C-grid staggering while WRF-NMM and HWRF use Arakawa E-grid. All of the WRF model variants use terrain following co-ordinate system and specific physical parameterizations. Since several modelling features in WRF are quite advanced (e.g. moving nest feature in HWRF) as compared to MM5, it is expected that at least one or more variants of it would show better performance for TC prediction over NIO region. Extensive research in this direction using ARW suggests some significant improvements in predicting the tropical cyclogenesis and cyclone tracks [10, 46–54]. However, it is noticed that improvement in prediction of TC intensity is found to be slower than that of track [51, 55].

A comparison study among MM5, WRF-ARW and WRF-NMM for very severe cyclone Mala (2006) developed over BOB found that ARW could simulate the TC intensity in terms of minimum central pressure and maximum sustainable wind with better accuracy [56]. However, MM5 simulated a more rapidly intensified storm and delayed landfall and WRF-NMM failed to simulate the intensity of the storm properly. On the other hand, WRF-NMM predicted TC track more accurately as compared to ARW and MM5. The TC Mala when simulated using HWRF with different initial conditions, the track error was found to be ~200 km and the intensity prediction was reasonably good for some considered initial conditions though the amount and spatial distribution of rainfall was well simulated by the model [57]. In order to improve the predictability, appropriate nesting technique, horizontal and vertical resolutions as well as physical parameterizations are considered [59, 68] besides data assimilation [60]. In view of these aspects, the HWRF system is now implemented at IMD along with the already operational ARW model for forecasting of TCs over NIO basin. As part of the Forecast Demonstration Project (FDP) conducted by IMD, it is analysed that the performance of ARW without data assimilation is reasonable over BOB [61]. Its performance improves when available observations are assimilated. Similar is the case with WRF-NMM. On the other hand, HWRF is capable of simulating rapid intensification of TCs over NIO region due to its improved vortex relocation and initialization procedures [49].

The high-resolution mesoscale modelling systems provide better guidance for TC forecast up to 72 h over NIO region [61]. They require high-resolution global analyses data sets for appropriate initial and boundary conditions in order to bring in large-scale boundary forcing

[62]. In order to reduce model errors, the initial and boundary conditions can be improved by adopting appropriate data assimilation techniques by incorporating the conventional, radar and satellite observations before running the model [61]. Thus, these aspects need special attention as far as predictability of TCs over NIO region is concerned.

4.2. Role of physical parameterizations

The physical parameterizations which include cumulus convection, surface fluxes of heat, moisture, momentum and vertical mixing in the planetary boundary layer play an important role in determining structural development, intensification and movement of TCs [10, 46, 48, 50, 53, 58, 63–65]. A number of studies emphasized upon these aspects during the past three decades. For the simulation purpose, they use the previously mentioned models (see Section 5.1). Most of these studies conduct simulations over a particular ocean basin. For instance, Osuri et al. [50] conducted a systematic study on customization of ARW model considering several physical parameterization schemes for the simulation of five TCs over NIO region. The study found that the combination of Yonsei University (YSU) planetary boundary layer (PBL) parameterization with KF convection scheme provided a better prediction for structural characteristics, intensity, track and rainfall. Similar results were also achieved by several studies including that of [10, 46, 48]. Thus, most of the studies (including [65]) found the performance of KF scheme to be better for the prediction of TCs over NIO region. However, recent studies by Kanase and Salvekar [53] obtained that the Betts-Miller-Janjic (BMJ) convection scheme performs better as compared to other parameterizations in the group although the study also favoured using YSU PBL physics. On the other hand, it found that WRF single-moment (WSM)-6 microphysics better represents mid-tropospheric heating as compared to WSM-3 favouring better intensity simulation.

Though HWRF has not been extensively used for sensitivity studies with respect to physical parameterizations for simulation of TCs over NIO region, its primitive variant WRF-NMM was used in recent past by some of the researchers. For example, studies by Pattanayak et al. [66] found that the combination of Simplified Arakawa-Schubert (SAS) convection, YSU PBL, Ferrier microphysics and NMM land-surface parameterization schemes in WRF-NMM performs better in predicting track and intensity of TC Nargis (2008) over BOB. Therefore, an extensive evaluation of HWRF is needed in order to determine the combination of physical parameterizations that performs better for TC prediction over NIO region before it is adopted for the operational forecasting purpose.

4.3. Significance of grid resolution

The grid resolution of a model also impacts the TC prediction [51, 58, 59, 67]. However, there are very few studies available relating to the impact of grid resolution on TC prediction over NIO region. One of the notable studies by Rao [68] evaluated the impact of horizontal resolution and the advantages of the nested domain approach in the prediction of Orissa (Odisha) super cyclone intensification and movement by using MM5 model. Results from this study indicate that the enhancement of resolution produces higher intensity but does not influence the track of the storm. The nested experiments produced cyclone track closely agreeing with

the observations, while the single domain based simulations show the deviation of the track towards north. A more recent study by Osuri et al. [51] found that the use of high resolutions in operational ARW model improves the prediction of recurving TC tracks and their intensity. In a climatological framework, Community Atmospheric Model or CAM showed sensitiveness to the prediction of more number of intensified tropical cyclones over most of the global basins including NIO. Further, it also found that the duration of tropical storms would be much larger in high resolutions simulations. Thus, it is realized that the model horizontal grid resolution impacts significantly the TC track, intensity and duration besides other relevant meteorological parameters.

4.4. Significance of data assimilation

Most of the times, the use of data assimilation techniques in TC simulations helps in improving the model predictability. For this purpose, satellite-based observations, aircraft measurements and radar data are used besides the conventional data sets. The widely used data assimilation techniques are primarily based on either ensemble Kalman filter (EnKF) or variational techniques (3DVAR or 4DVAR). Most of the studies related to TC simulation were done using variational data assimilation techniques for improving the TC prediction over NIO region. For example, the studies such as [52, 69–71] used 3DVAR techniques for assimilating satellite, radar and conventional measurements for improving the initial and boundary conditions of MM5 and ARW mesoscale models in order to better predict TC structure, track, intensity and associated relevant meteorological variables including rainfall. In some situations, the improvement was not significantly noticed. For instance, the studies by Singh et al. [70] found that assimilation of SSM/I wind speed data resulted in simulating weak intensity and failed to make an impact on track prediction.

Although there are no significant studies related to the use of 4DVAR and EnKF techniques for simulating NIO TCs, there are literatures, which demonstrate the usage of four dimensional data assimilation (FDDA) nudging technique in order to improve the ARW model predictability. For example, [71–73] used FDDA nudging technique in order to improve ARW initial and boundary conditions for the simulation of several TCs over NIO region those occurred during 2007–2010. These studies primarily emphasized upon TC track and intensity forecasts. While some of them reported remarkable improvements in track prediction and landfall position with either 12- or 18-h of nudging yielding maximum impact [72, 74], some others noticed relatively less impact of FDDA observational nudging on intensity prediction [73].

5. Tropical cyclone climatology over NIO region

Since hundreds of years, the Indian Ocean is a breeding basin for disastrous TCs associated with heavy rainfall, torrential wind and storm surges. The cyclones in 1970 and 1991 caused a loss of more than 400,000 lives. During the Odisha super cyclone (1999), more than 10,000 lives were lost and a destruction of 1.9 million houses occurred in 14 districts. Recently, Nargis (2008) caused ~1 40,000 deaths in Myanmar. In 2015, cyclonic storm Komen caused a heavy loss

throughout Bangladesh, Myanmar, northeast India and eastern parts of India although the loss of lives was very few as compared to previous cases because of the improvement in TC predictability. This was also realized in case of Phailin (2013) and Hudhud (2014).

TCs usually form over NIO basin in two seasons, that is, pre-monsoon (March-April-May) and post-monsoon (October–November–December) period. In total, about 1108 numbers of cyclonic systems are formed over NIO region (includes both BOB and Arabian Sea, AS) during 1891–2015. It includes depressions (or D), cyclonic storms (or CS) and severe cyclonic storms (or SCS). However, the cyclonic systems do not form each month of every year. If the average monthly distribution of these three types of cyclonic systems (**Figure 3**) is analysed, it is evident that maximum number of cyclones occur between the months of May to December. Maximum numbers of depressions are formed in August. Maximum numbers of CS are formed in the month of October, while November is the most favourable month for the formation of SCS. Though the number of total cyclonic systems in May is relatively less, ~48.7% of cyclonic disturbances are transformed to very severe cyclonic storms. However, this transformation is found to be 43.9 and 41.7%, respectively, in the months of April and November. Annually the probability of intensification of depression to CS is ~44.8%, depression to SCS is ~21.3% and the probability of intensification of CS to SCS is ~47.5%.
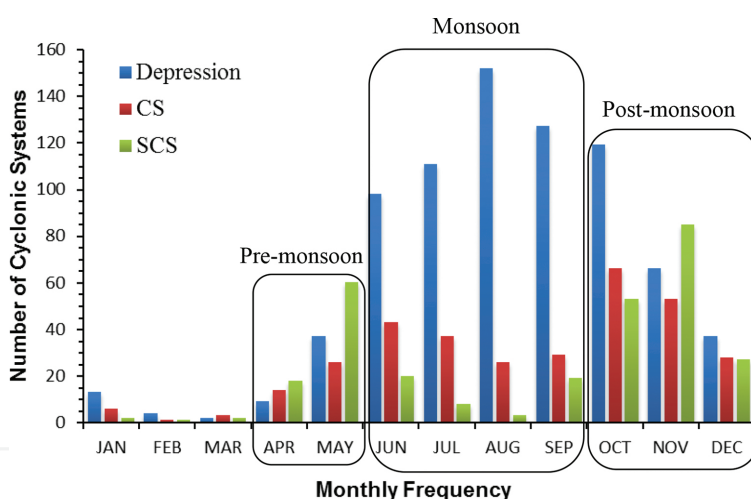

Figure 3. Monthly frequency of cyclonic disturbances in North Indian Ocean region during 1891–2015. Here depression signifies the low-pressure systems which do not transform to cyclonic storms; CS is for the cyclonic storms and SCS represents the severe cyclonic storms.

BOB contributes about 75% of TCs during cyclone seasons (pre- and post-monsoon periods) and the AS contributes ~25% [75]. The possible reason could be that BOB is generally more stratified than AS because its upper-ocean part is relatively warmer resulting in higher SST. In addition, low flat coastal terrain and funnel shape, shallow water of BOB [76], monsoonal wind (trough), more middle tropospheric moisture availability and lower tropospheric westward travelling disturbances such as easterly waves (often serve as the 'seedling' circulations) play roles in generating more number of cyclonic systems over BOB. Most of the monsoon troughs generated because of re-intensification of westerly propagating disturbances or from in situ

depressions help in the formation of cyclonic systems over this region as well. Boreal summer intraseasonal oscillation (BSISO) also modulates the topical cyclogenesis over BOB [77], and it may be noted that the genesis potential index is high during the active phase of the BSISO.

The studies like that of [4] indicate that under the global warming scenario, the number and proportion of cyclones reaching SCS are increasing in almost all basins of the world especially indicating the impact of climate change. **Figure 4** shows the decadal variation of cyclonic disturbances and CSs over NIO, that is, over BOB and AS. It is clear from the curve that there is a significant decreasing trend in the number of cyclonic disturbances and CS. When the number of SCS are analysed, it shows a slight increase or may be considered as a constant trend in decadal scale (**Figure 4**). During 1961–1970 and 1971–1980, there was most number of SCS. Besides El-Nino Southern Oscillation (ENSO), MJO (Madden-Julian Oscillation) and IOD (Indian Ocean Dipole) may also play appreciable role in modulating the TC activity over NIO region [13, 16, 17, 77].
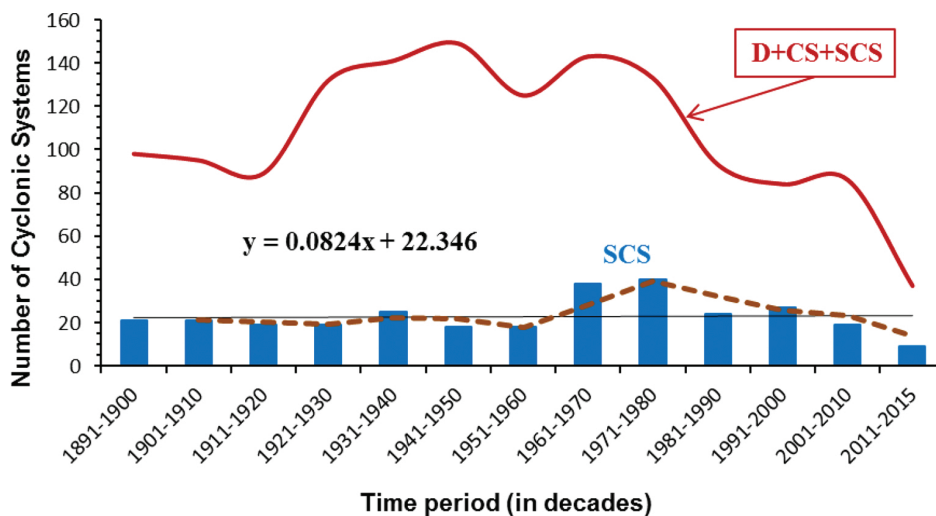

Figure 4. Variation of decadal frequency of cyclonic disturbances or depressions (D), cyclonic storms (CS) and severe cyclonic storms (SCS) over NIO region (smooth curved line). The bar diagrams represent SCS during 1891–2015. The dotted line indicates the moving trend and line shows the linear trend.

For the past three decades, the number of SCS has somehow decreased to a considerable value (**Figure 4**). However, Mohanty et al. [75] demonstrated that there is a considerable increase of SCS by about 65% during the warming period 1951–2007 by analysing the genesis and intensity of TCs over NIO basin in yearly scale. In the southern sector of BOB, a considerable increase of ∼71% in SCS is found in post-monsoon season. Rate of dissipation of SCS over BOB is also significantly reduced besides increase in mean SST in the warming scenario and these features contribute to increase in the number of SCS over NIO. In the western sector of AS, a significant increase in SCS is also observed in the warming conditions. Therefore, the intensity of the SCS is increasingly becoming significant in the changing climate scenario. When the 'T Numbers' of the cyclones are analysed in satellite era, it is found that the Odisha super cyclone (1999) was the strongest recorded CS in the NIO basin during 1990–2015.

Analysing the track of cyclones over BOB and AS from e-atlas available at IMD, New Delhi, it is observed that most of the cyclonic systems developing over the NIO basin move in a northwesterly direction. However, there are cases of recurvature towards the northeast or east to southwest. The frequency of recurvature is higher towards the northeast compared to southwest or east. The probability of recurvature is higher over the AS when the system moves to the north of 15°N increasing the possibility of landfall over Gujarat coast. Over BOB, there is no such preferred latitude/longitude for the recurvature prospects. On the other hand, the probability of recurvature towards northeast region is higher during the pre-monsoon season.

Out of 1108 cyclones formed during last 124 years, 751 (68%) have crossed east coast of India, 214 (19.31%) Bangladesh, 57 (5.18%) Myanmar, 63 (5.68%) west coast of India and 26 (2.3%) numbers of cyclones crossed the coastal regions between India and Pakistan affecting the economy of both the countries. According to studies by Tyagi et al. [78], over 60% of TCs formed over BOB suffer landfall in different parts of east coast of India, 30% strike coasts of Bangladesh and Myanmar and about 10% dissipate over the sea itself. The differences in observed percentages are because of the obvious reason, that is, consideration of different time periods. However, it is evident that NIO basin is quite significant in view of the TC occurrence and highly populated and economically growing south Asian region.

6. Ongoing activities and possible recommendations for future

In order to improve the prediction of TC predictability over BOB region, the modernization of the observational system is being carried out by IMD, which includes setting up of two clusters of surface meso-meteorological networks: one along the coasts of Odisha-West Bengal and the other around Andhra Pradesh coasts [2]. About 443 numbers of existing automatic weather station (AWS) are there set up in different states of India. For NIO basin, it is considered very important to acquire weather reconnaissance aircraft facility to provide information on environmental winds and thermodynamical structures in the inner core region of TCs. The FDP (2008) is an attempt in this direction to determine the possible improvements in track and landfall predictions by using aircraft data.

The programmes named as STORM and PRWONAM are carried out with the support of Ministry of Earth Sciences (MOES) and Department of Science and Technology. MOES is also involved in strengthening of the deep ocean and met-ocean buoys network. In addition, IMD has established high wind speed recorder systems, S-band Doppler radars and Global Positioning System (GPS) equipment along the coastal areas of India [79]. Under the Indo-French collaboration, Oceansat-II (was functional till 2014) and MEGHA-TROPIQUES satellite with capability of repeated scanning over BOB region are/were functional to provide data related to sea surface winds, clouds, humidity, temperature, rainfall and radiation. The earth receiving stations for METOP and MODIS satellite data have been installed at IMD. Products like cloud motion vector (CMV), water vapour wind (WVW), out-going longwave radiation (OLR), quantitative precipitation estimate (QPE), Sea Surface Temperature (SST), upper tropospheric humidity (UTH) and cloud top temperature (CTT) are derived from other satellites including KALPANA-1 and INSAT-3D.

Several research institutes such as National Centre for Medium Range Weather Forecasting, Noida; Indian National Centre for Ocean Information Services, Hyderabad; Indian Space Research Organization (ISRO), Air Force and academic institutes including IITs (Indian Institute of Technology), NITs (National Institute of Technology), universities contribute towards providing their valuable input through academic research regarding various aspects of TC activity over NIO region. With these inputs and in-house research and development, IMD has been able to strengthen its capability in recent past, both from numerical modelling as well as observational point of view by taking into account both in situ and satellite measurements.

Despite increased capability for TC prediction over NIO region, few aspects still need to be addressed. Those key areas include accuracy in track prediction, time and place of landfall, accurate storm surge prediction and improving the intensity predictability. In addition, the changes in tropical cyclogenesis need to be understood in the changing climate scenario. It is because the severity of TCs is found to be increasing in the warming environment [75]. The improvement in numerical model predictions can be done by improving physical parameterization schemes, incorporating observations from different sources including those from satellites and radars in the model initial and boundary conditions through appropriate data assimilation techniques and considering improved SSTs. In addition, better disaster management need to be done alongside in order to reduce the loss of lives and properties.

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