Atmospheric and Ocean characteristics associated with NIO tropical cyclones: A comprehensive review vis-à-vis the intensity and movement

[1]Jagabandhu Panda*, [1]Debashis Paul, [2]Ashish Routray & [3]Ram Kumar Giri
[1]Department of Earth and Atmospheric Sciences, National Institute of Technology Rourkela, Odisha, India
[2] NCMRWF, Ministry of Earth Sciences, Sector-62, Noida, Uttar Pradesh, India
[3]India Meteorological Department, Lodi Road, New Delhi, India
Email: pandaj@nitrkl.ac.in; jagabandhu@gmail.com

ABSTRACT

This paper provides a comprehensive review of the characteristic features associated with the North Indian Ocean (NIO) tropical cyclones (or TCs), with a primary focus on their intensity and movement. It emphasizes upon various factors impacting the intensity and movement of TCs including moisture, eddies, low-level vertical wind shear, atmospheric conditions, sea surface temperature (SST), etc., i.e., both the atmospheric and ocean characteristics in a comprehensive manner. The review highlights the influence of intra- seasonal and inter-annual atmospheric phenomena, including monsoon systems, cold air intrusion, and the El Niño-Southern Oscillation (ENSO) on TC re-curvature. The narrative underscores the crucial role of ocean related factors, viz., SST, Tropical Cyclone Heat Potential (TCHP), ocean-currents, and eddies, in predicting and mitigating the impact of TCs in this region. It also discusses the challenges of accurately forecasting TC intensity and landfall, including inaccuracies in vortex initialization, incomplete physical process representation, and parameterization errors, and highlights the potential of ensemble techniques and data assimilation methods for improving the accuracy and reliability of predictions. Overall, this narrative provides valuable insights into the complex dynamics and thermodynamics of TCs over the NIO, which can aid in better understanding, predicting, and mitigating the impact of these natural disasters in this region.

Keywords: *Tropical cyclone; NIO; SST; ENSO; IOD; numerical modelling.*

1. Introduction

Tropical cyclones (or TCs) are one of the most destructive weather phenomena that derive energy from both ocean and atmosphere for their genesis and intensification (Tiwari et al., 2021; Palmen, 1948; Miller, 1958). TC activity is expected to be modulated under a changing climate scenario primarily due to ocean warming, alteration in thermodynamic equilibrium between ocean and atmosphere, and changes in flow fields (Webster et al., 2005; Nolan and Rappin, 2008; Rappin et al., 2010; Mohanty et al., 2012; Mohapatra et al., 2015; Singh et al. 2016, 2019). The North Indian Ocean (NIO) is a frequently TC active area, contributing 7% of TCs worldwide (Wahiduzzaman et al., 2017, 2021). The NIO comprises of the Arabian Sea (AS) and the Bay of Bengal (BOB) and experiences two TC seasons every year viz., the pre- monsoon season of April-May (may include June) and the other one in the post-monsoon season of October-December. Even though this region accounts for only 7% of the world's TCs, it witnesses more than 80% of global fatalities due to these storms, primarily due to coastal flooding. The BOB has been the site of some of the most catastrophic cyclones, resulting in significant casualties in the nearby rim countries (Madsen and Jakobsen, 2004; Kikuchi et al., 2009; McPhaden et al., 2009; Beal et al., 2020).

TCs generally intensify in regions with SST above 26°C, high moisture in the mid- tropospheric level, and minimal wind shear (Gray, 1968). The ocean becomes the primary energy source for TCs by exchanging heat flux with the atmosphere (Vinod et al., 2014). High SST increases TC intensification by promoting heat transfer from the ocean to the atmosphere (Emanuel, 1986), while TCs passing through the ocean lead to lower SST, which weakens cyclones by reducing heat transfer (DeMaria and Kaplan, 1999; Cione and Uhlhorn, 2003; Lloyd and Vecchi, 2011). SST cooling by TCs impacts their intensity, size, and structure

Table 1. IMD and JTWC categorization of TCs over the North Indian Ocean.

Classification	IMD (kts)	JTWC (kts)	T number
Low pressure area (LPA)	<17		1.0
Depression (D)	17–27		1.5
Deep depression (DD)	28–33	30-34	2.0
Cyclonic storm (CS)	34–47	35-45	2.5-3.0
Severe cyclonic storm (SCS)	48–63	46-55	3.5
Very severe cyclonic storm (VSCS)	64–89	65-77	4.0-4.5
Extreme severe cyclonic storm (ESCS)	90-119	90-115	5.0-6.0
Super cyclonic storm (SuCS)	≥120	≥115	6.5-8.0

through mechanisms such as frictional mixing, upwelling of cold water, internal waves, and air-sea heat flux (Price 1981, 1983, 1994; Jacob et al. 2000; Zedler et al. 2009; Sanford et al. 2011; Yang et al. 2015; Chen et al., 2020). Vertical mixing contributes 70–80% of TC-induced cooling, while horizontal advection and enthalpy flux account for only about 20% of the cooling process (Shay et al., 1992; Huang et al., 2009; Vincent et al., 2012). Although TC- induced cooling has significant effects, it generally does not change the TC trajectory (DeMaria and Kaplan, 1999; Cione and Uhlhorn, 2003; Lloyd and Vecchi, 2011).

Several studies (George and Gray, 1977; Chan and Gray, 1982; Dong and Neiman, 1986; Fiorino and Ellsbury, 1989; Peng and Williams, 1990; Shapiro and Oyama 1990; Franklin et al., 1996; Chan and Williams, 1987) examined the influence of environmental features on TC movement to understand the associated dynamics. Notably, the movement of the TC is mainly influenced by the rudder airflow, which reflects the synoptic winds around the cyclone. TC advection in the barotropic grid is governed by the wind around 500 hPa in a defined area around the TC center. The vertical depth of the drift current may also play a role in TC strength. Also, the concept of β effects and their nonlinear interactions (e.g., β circulation) alter TC motion. The β effect rises from the interface between the relative vorticity (RVOR) of the TC and the Earth's vorticity, resulting in a RVOR asymmetry in the TC called the β circulation. These asymmetries drive the TC motion westward and poleward. Several studies put efforts in examining the re-curvature scenarios of TC movement through numerical modeling approach (Thu and Krishnamurth, 1992; Holland and Wang, 1995; Leslie et al., 1998; O'shay and Krishnamurti, 2004). Since numerical models often fail to capture the intricacies of the underlying mechanics of TC overturning, significant inaccuracies still exist in predicting TC recurving paths (George and Gray, 1977; Holland and Wang, 1995; Li and Chan, 1999; Zhang et al., 2013). Although advanced data assimilation techniques (Kurihara et al., 1995; Bender et al., 2007) are capable of improving the accuracy of several characteristic features associated with re-curved TCs, there is no effective method to predict the re-curved tracks accurately in operational practice.

1.1 Classification in terms of intensity

The Dvorak approach is generally used to calculate the intensity of TCs (Sampson and Schrader, 2000) and represents it through 'T numbers' ranging from 1.0 to 8.0 with 0.5 intervals (Dvorak, 1975, 1984). The India Meteorological Department (IMD) also uses similar T numbers to differentiate the intensity of TCs over NIO. JTWC provides maximum sustained wind (MSW) that is averaged using 1-minute wind field data at 10 m height, whereas IMD uses 3 minutes' wind field data for computing MSW. Table 1 provides details about the intensity-based NIO TC categories by considering information related to IMD, and JTWC considerations as well as T numbers.

1.2 Classification in terms of movement or re-curvature

After the formation of TCs, they are influenced by the steering currents to move mostly to the west, north or northwest, disappear/ reappear over the sea, move to the northeast or southwest, or reach the coastal areas. However, some TC tracks have been defined as anomalous or unusual. These TCs with unusual tracks, are called re-curving types (Cheung, 2006). Re- curving TCs first move westward and turn eastward as they move poleward (Knaff, 2009). As defined by the South China Research Council (Cheung, 2006), a TC that recurves left within 24 hours and has a recurving angle of less than 30° (measured by comparing its mean path between the 12 hours before and after the occurrence of its re-curvature) is referred to as a recurving-left TC. Re-curving right TCs are defined as the TCs that turn right within 24 hours, with a recurving angle of at least 45° (measured by comparing the mean path of the storm 12 hours before and after the re-curvature). A meandering TC is defined as one that meanders or oscillates around a mean course with at least two recurving points with 1/2° latitude distance, each of which must be having a minimum of 30° angle, and 12 hours must pass between the recurving points. A looping TC is the one with a track that has or almost has an inter-section, where 1/2° latitude distance between two sides of the track is required within 24 hours.

2. Observational atmospheric and ocean characteristics

The understanding of the intricate environmental processes concerning genesis is essential for an in-depth and robust knowledge regarding NIO TCs. Generally, a low-pressure region over the ocean gradually consolidates into a depression and intensifies into a TC. The TC that makes landfall may weaken and reform into depressions (Chauhan et al., 2021). The land, atmosphere and ocean play a vital role in governing the TC activity (at least in the case of landfalling TCs). Therefore, it is essential to analyze all environmental factors, which possibly contribute to the NIO TC activity, especially to their distinct movement or intensification.

2.1 Atmospheric characteristics associated with TC intensification

Climate scientists have long been interested in TCs because they arise with a package of several elements including strong winds, heavy rainfall, and storm surges, which result in property and human losses at several instances. Coriolis forces, eddies, low-level vertical wind shear, moisture availability, and convection are essential factors impacting the synoptic processes that produce TCs. For instance, moist convection governs the movement of TCs, and associated momentum, energy and mass in the tropical atmosphere (Kumar et al., 2017). Albert et al. (2022) found a reasonable correlation between the Power Dispersion Index (PDI) and TCs of SCS category. They inferred that mid-tropospheric (at 600 hPa) relative humidity (RH), positive low level (at 850 hPa) RVOR, and a reduction in outgoing longwave radiation (OLR) all together lead to an increase in NIO TC frequency. Balaji et al. (2018) investigated TC activity in the NIO using accumulated cyclone energy (ACE) measurements and found an upward trend in recent years. The ACE is significantly correlated to the variation of SST, UOHC, atmospheric water vapor, and genesis potential index (GPI) and increases with them. According to Duan et al. (2021), RH and vertical wind shear in the middle and lower troposphere are the two most important factors influencing the formation of tropical cyclones. These two factors determine the bimodal seasonal cycles of the AS and BOB TCs. Tiwari et al. (2021) studied the TC characteristics in the BOB considering several variables including ACE and PDI. They also performed correlation and principal component analysis for VSCS, SCS, and CS-like TCs considering parameters such as SST, vertical wind shear, minimum sustained wind, minimum sea level pressure, RH etc. They observed that the close eddy current is the most crucial factor affecting the peak strength of BoB TCs. A study by Chan (2005) also highlighted the significance of the baroclinic process in TCs. However, the energy and heat transported by convection bring change in the temperature gradients and the vertical wind shear (Osuri et al., 2010). Also, an exhaustive analysis by Singh et al. (2019) indicated that an increasing SST, near-surface wind, mid-tropospheric RH, potential evaporation factor (PEF), etc., are helpful in the formation of intensified storms during the current warming scenario. It is supported by the large temperature anomaly difference between atmosphere and ocean, which modulates the intensification process resulting in enhanced TC intensity in a warming climate. Courtney et al. (2019) evaluated the strength of VSCS Hudhud using best track data sets from IMD and the JTWC to highlight the dependence on TC location and structure. Due to the different criteria of considering MSW from IMD and JTWC, they found distinct results for the two data sets (one underestimated and other overestimated). Mohanty et al. (2020) illustrated the effects of asymmetric wind-induced dry air entrainment on ESCS Fani. This dry air can significantly impact TC vorticity, structure, landfall, and strength. Some notable ocean parameters, which impact the TC characteristics, were discussed by few recent studies indicating the significance of eddy current, ocean temperature, etc., along with the atmospheric parameters (Nadimpalli, 2020a, 2020b; Singh and Bhaskaran, 2020). Therefore, the Ocean characteristics associated with TC intensification and movement are discussed later in sections 2.3-2.4.

2.2 Atmospheric characteristics associated with TC re-curvature

TC re-curvature refers to the scenario, when the direction of the steering flow changes or when a TC deviates from its usual west or northwest direction towards a different direction (Chan, 2005). Past research has primarily focused on the Western North Pacific (WNP) Ocean basin to investigate the causes of recurving TCs and their impact on the environmental wind. Multiple studies have suggested that the eastward-retreating subtropical ridge typically directs a TC to move along its boundary, while the approach of a mid-latitude westerly trough supports the re- curvature occurrence (Evans et al., 1991; Holland and Wang, 1995; Chen et al., 2009). The upper tropospheric westerlies have shown a strong correlation with the motion of recurving TCs (George and Gray, 1977; Hodanish and Gray, 1993). Also, intra-seasonal or inter-annual atmospheric phenomena have been found to influence re-curvature occurrence in cyclonic systems including those in monsoon time (Chen and Chang, 1980; Chen et al., 2009; Wu et al., 2013), which involve momentum exchange (Li and Chan, 1999), cold air intrusion (Peng et al., 2014), upper-tropospheric cold lows (Wei et al., 2016), variations in SST (Choi et al., 2013; Katsube and Inatsu, 2016), and El Niño–Southern Oscillation (ENSO) events (Cheung, 2006). Notably, Chan and Chan (2016) demonstrated that TCs at higher latitude have inherent recurving properties because of the combined effects of upper-tropospheric anticyclone flows on the equatorward side of the TCs and the diabatic heating associated with asymmetric convection.

Research on TC dynamics that includes re-curvature, has been primarily focused on the WNP basin owing to the high frequency of TC occurrences. However, the NIO basin experiences fewer TCs; but they significantly impact rim countries including India, Bangladesh, and Myanmar due to low-lying topography, high population density, socioeconomic conditions, and limited resources. Although 7% of global TCs occur in NIO basin (Neumann, 1993), they are usually strong enough to cause massive destruction. For instance, the TCs like Bhola (May 1970), and Nargis (April 2008) resulted in great loss of both life and property as they recurved to the right of their path (Chowdhury et al., 1993; Paul and Rahman, 2006; Webster, 2008). Although there is already considerable information about TC dynamics in general, more attention is required for the NIO TCs, particularly the recurving ones, since this region's demographic setting is distinct from others. Moreover, the environmental conditions govern the cyclogenesis process including intensity and movement (Riehl, 1972; Burroughs and Brand, 1973; Evans and McKinley, 1998; Knaff, 2009; Yamada et al., 2010; Bhattacharya et al., 2015; Singh et al., 2016, 2019, 2020); thus, it is essential to understand the variability of relevant parameters over the NIO basin pertaining to TC re- curvature.

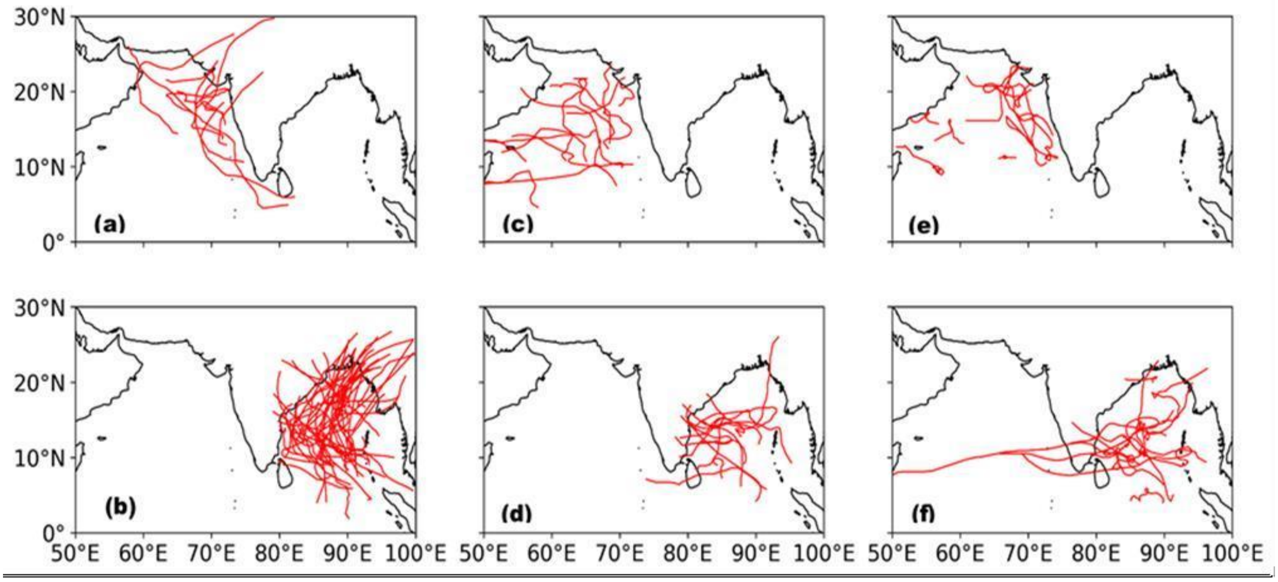

Figure 1: Total tracks of all recurving TCs that occurred over the NIO for the period 1981- 2022. The first column represents recurving right TCs, the second column represents recurving left TCs, and the third column represents looping TCs. The top row (a, c, e) is for Arabian Sea and the bottom row (b, d, f) is for Bay of Bengal.

During 1981-2022, the NIO region experienced 85 re-curving TCs, which included 28 in the pre-monsoon and 57 during the post-monsoon. Figure 1 demonstrates various categories of re-curving NIO TCs, which include re-curving right, re-curving left and looping types. Such TCs have shown the designated movement at least once in their life time. For determining the types of TCs based on their movement, the methodology adopted in this work is based on the studies of Akter and Tsuboki (2021). There have been very limited studies on recurving TCs over the NIO basin, including both observational (Yamada et al., 2010; Bhattacharya et al., 2015) and modeling (Akter and Tsuboki, 2021) studies. Also, the specific dynamics associated with TC re-curvatures is yet to be investigated thoroughly. Additionally, a better understanding of distinct seasonal variability of the recurving TC activity is necessary for precise predictions of their landfall and for taking appropriate measures to increase awareness and preparedness along the coastal areas.

2.3 Ocean characteristics associated with TC intensity

TCs are complicated natural phenomena that develop in warm oceans including NIO, with low atmospheric pressure. Several studies have documented the interaction of an Ocean basin with a TC formed over it, and tried to understand the associated dynamics and thermodynamics. For instance, Tiwari et al. (2021) confirmed an increase in SST over the NIO basin, while the study by Mishra et al. (2020) highlighted the significant contribution of AS warming to rising weather extremes. Several studies have highlighted regarding the link between SST and TC activity and associated characteristics (e.g., Patwardhan and Bhalme 2001; Singh et al. 2019a, 2019b; Mandal and Mohanty, 2010; Mohanty et al., 2019; Paul et al. 2022). For instance, Patwardhan and Bhalme (2001) found a substantial decline in the seasonal trend of TC frequency despite rise of SST in recent decades. Prakash and Pant (2017) explored the primary role of mixed layer heat budget in TC genesis. Figure 2 represents SST variation of four highly intensified systems that formed over NIO during pre-monsoon and post-monsoon months. The SST variation shows the values within 29.5℃-31.5℃ range along the track of all TCs except Kyarr. This indicates a significant role of SST in the intensification of TCs.

Ocean sub-surface factors including Tropical Cyclone Heat Potential (TCHP), currents, and eddies, significantly impact TC genesis and strength. Ocean heat content (OHC) has been demonstrated as a key element, controlling the

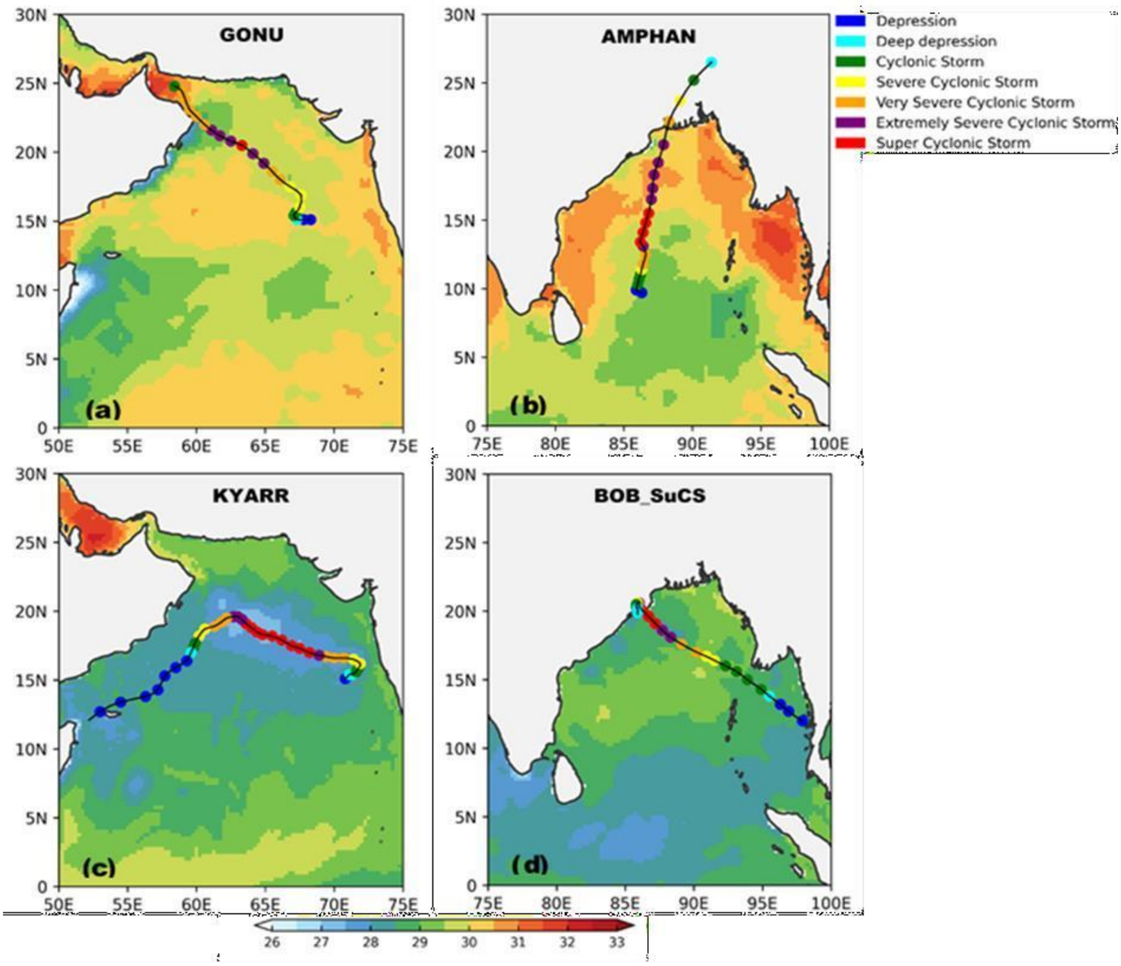

Figure 2: Variation of SST (°C) during the whole life period of NIO TCs, viz., Gonu (a), Amphan (b), Kyarr (c), and 1999 Odisha SuCS (d). The TCs in the top row are during pre- monsoon and in the bottom row are during post-monsoon months.

duration and strength of TCs in the NIO basin (Sharma and Ali 2014). Because of the constant flow of both sensible and latent heat fluxes from the ocean to the atmosphere, cyclones may persist or even get stronger when the ocean's heat content is high (Shay et al. 2000). Girishkumar et al. (2015) demonstrated a positive association between the accumulated heat potential of TCs in the BOB and their intensity. Usually, the average TCHP of a TC in the BOB is 89.3 kJ cm-2, whereas in the AS it is 89.34 kJ cm-2, indicating TCHP as precursor for TC intensification (Ghetiya & Nayak, 2020). For example, Figure 3 indicates that during pre-monsoon TCs, the TCHP values were ≥ 80kJcm-2, whereas in the case of post-monsoon TCs, the values were low to moderate. Nevertheless, within a 250-kilometer radius of a TC, the heat potential gets reduced by around 20 kJ cm-2 (Busireddy et al., 2019). This demonstrates the two-way feedback between TCs and the ocean.

The existence of mesoscale features such as eddies has a substantial impact on the TCs' strength. Warm core eddies (WCE) are linked with down welling and feature atypically high sea surface heights with a high OHC (Gopalan et al., 2000; Sadhuram et al., 2004; Kumar and Chakrabarti, 2011). As a TC passes over a WCE, it often strengthens owing to the water column's high OHC (Shay et al., 2000; Ali et al., 2007). In contrast, TC intensity decreases as it passes through a cold core eddy (Sreenivas and Gnaseelan, 2014). WCEs are often more prevalent in the BOB and the AS during the pre-monsoon season in comparison to post-monsoon season (Jangir et al., 2020). This is quite evident from Figure 4 as it can be observed that the two pre-monsoon TCs Gonu and Amphan encountered WCE along their paths resulting more intensification. The rapid intensification (RI) of TCs is aided by TCHP and eddy currents over warm waters (Lin et al., 2013), and the

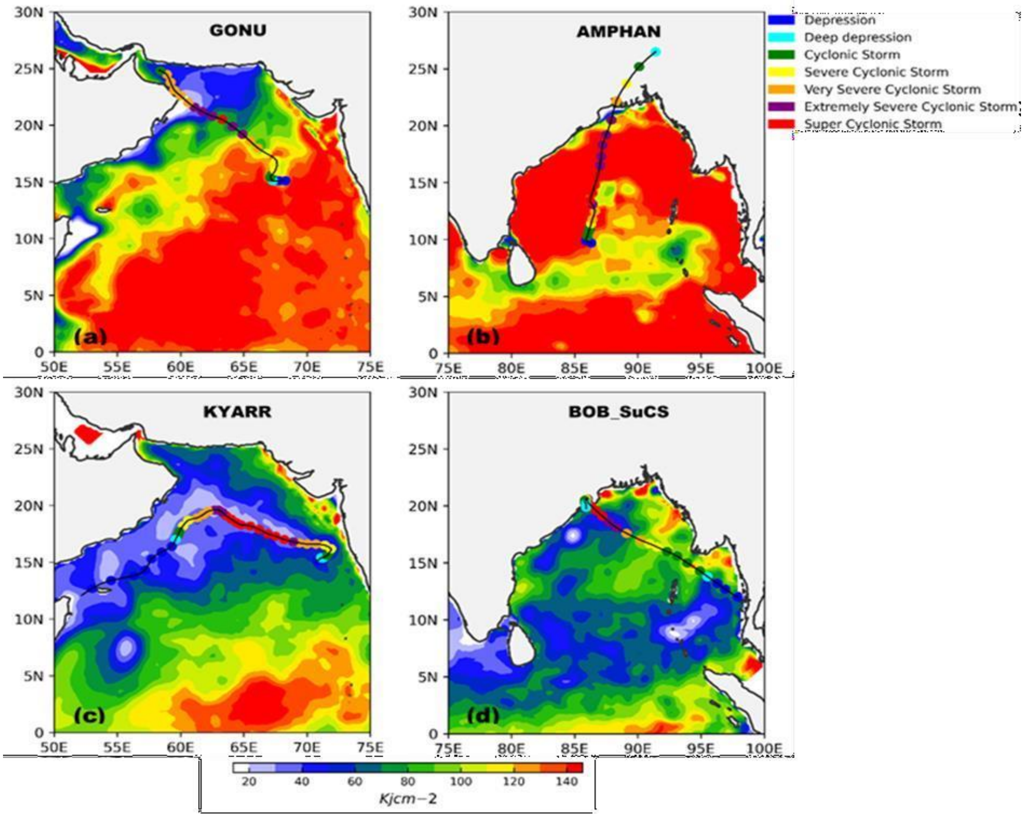

Figure 3: Variation of TCHP (kJcm-2) during the whole life period of NIO TCs, viz., Gonu (a), Amphan (b), Kyarr (c), and 1999 Odisha SuCS (d). The TCs in the top row are during pre- monsoon and in the bottom row are during post-monsoon months.

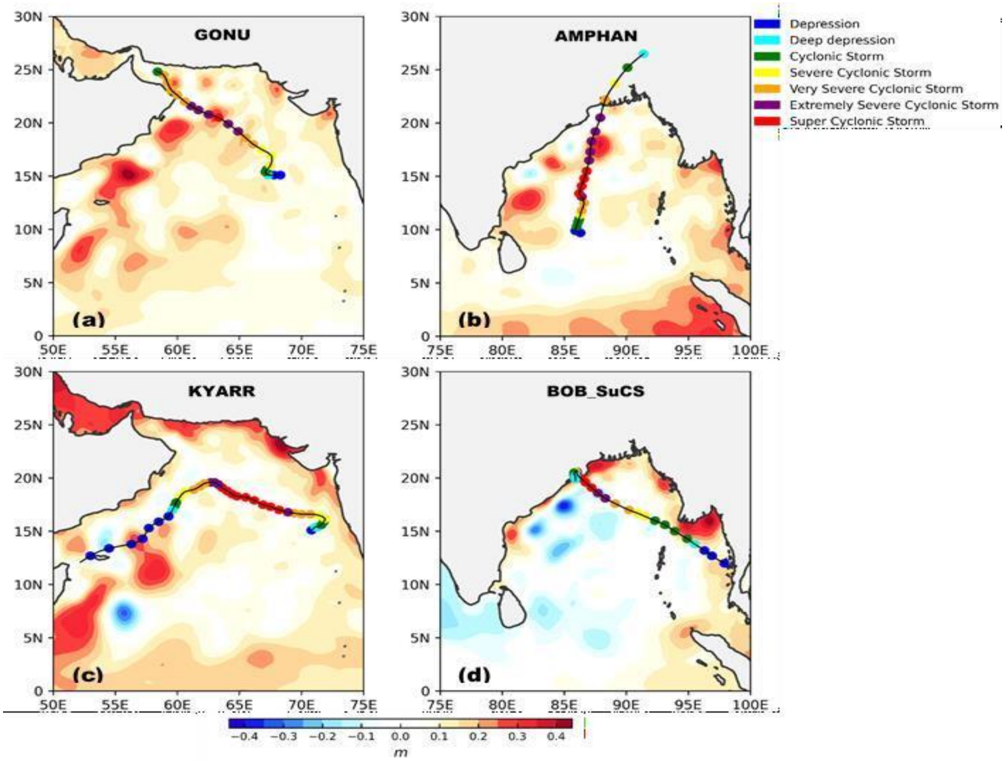

Figure 4: Variation of SLA (m) during the whole life period of NIO TCs, viz., Gonu (a), Amphan (b), Kyarr (c), and 1999 Odisha SuCS (d). The TCs in the top row are during pre-monsoon and in the bottom row are during post-monsoon months.

development of eddies along TC tracks quantifies the RI phase (Jangir et al., 2020; Paul et al., 2022). Eddies' role in TC intensification over the NIO was also addressed by Mawren and Reason (2017) and Patnaik et al. (2014).

2.4 Ocean characteristics associated with TC motion

Over the past few decades, there has been a significant effort to understand the motion of tropical cyclones (TCs). This motion is influenced by various internal, external, and interactive dynamical forces, making it a complex phenomenon. Beta drift (β) is one of the most fundamental processes involved in TC motion. This process is affected by the structure of the vortex and its latitude. It causes a northwestward motion of TCs in the Northern Hemisphere on a beta plane without any environmental steering flow. The beta-induced secondary steering flow over the center of the vortex, called the ventilation flow, is responsible for this motion. As noted in previous studies, the secondary steering flow is modulated by internal dynamic factors and the interaction between the TC and external forces (Wang et al. 1998; Chan 2005; Holland 1983; Chan and Williams 1987; Fiorino and Fiorino and Elsberry 1989). Similarly, the accuracy of TC track forecasts has improved due to the development of numerical models (Krishnamurti et al. 1999; McAdie and Lawrence 2000; Bender et al. 2007; Cangialosi and Franklin 2013; Ruf et al. 2016; Montgomery and Smith 2017). The thermodynamic effect of SST also governs partly the movement of TCs. Wu et al. (2005) studied the impact of TC- induced SST on TC movement by deriving symmetric and asymmetric anomalies around a TC center. The spatial distribution of large-scale asymmetric SST can also impact the TC motion differently. For instance, Chang and Madala (1980) demonstrated how various SST distributions with a mean flow can impact the behavior of a translating TC.

They found that TCs tend to move towards regions with warmer SST, and a favorable condition for TC deflection occurs when the SST gradient is perpendicular to the mean flow. SST distributions impact the TC motion by changing the total surface friction and heat flux exchange. Yun et al. (2012) investigated a north-eastward moving TC to show that the magnitude and gradient of SST significantly influences TC motion. They concluded that an eastward SST increase causes a greater eastward deflection of the TC compared to meridional SST gradient or SST magnitude variation. Choi et al. (2013) found that the asymmetry of SST can contribute to the occurrence or alteration of re-curvature in TCs. The sea surface cooling caused by a TC can also affect the path and intensity of a subsequent TC (Baranowski et al., 2014; Wu and Li, 2018). Previous studies (Price 1981; Zedler et al. 2002; Lin et al. 2003a; Black et al. 2007; D'Asaro et al. 2007) have reported that The amplitude of sea surface cooling is typically between 1 and 6 °C, with occasional extremes of up to ~11 °C. The cooling can cause a reversal in air-sea surface sensible and latent heat fluxes (Glenn et al., 2016). Notably, the upwelling component of near-inertial pumping tends to weaken or reverse warm subsurface anomalies to cold anomalies, while the down welling component strengthens warm subsurface anomalies. McPhaden et al. (2009) observed increased cooling on the right side of the track during the occurrence of Nargis in BOB. Similar observations were made in the AS during Phyan, where enhanced cooling was noted on the right side of the track (Byju and Prasanna Kumar, 2011).

The strong wind stress of a TC leads to a response in the upper ocean current, which tends to be biased towards the right (left) side of the TC tracks in the Northern (Southern) Hemisphere due to better wind-current resonance (Price 1981, 1983; Price et al. 1994; Sun et al. 2015; Zhang et al. 2020b). However, in the Northern Hemisphere, the current velocity to the right side of the TC track decays faster than that to the left side, as has been noted by Zhang et al. (2016a) and Wu et al. (2020a). Also, sea surface cooling caused by a TC tends to be biased toward the right (left) side of the TC tracks in the Northern (Southern) Hemisphere as described before. Therefore, the wind stress and ocean current are correlated well with the sea surface cooling caused by TC movement.

Similarly, sea surface salinity (SSS) tends to increase when a TC occurs. In contrast, sub- surface salinity decreases, with both effects biased towards the right (left) side of the TC tracks in the Northern (Southern) Hemisphere. Past studies (Bond et al. 2011; Girishkumar et al. 2014; Domingues et al. 2015; Zhang et al. 2016a; Abernathey and Haller 2018) have reported these changes typically ranging within one PSU, but may reach up to 1.5-3 PSU in some cases. However, TC precipitation can weaken the positive SSS anomaly and cause a negative SSS anomaly bias toward the left (right) side of the TC track in the Northern (Southern) Hemisphere (Girishkumar et al., 2014; Liu et al., 2020; Grodsky et al., 2012; Liu et al., 2014).

3. Effect of ocean-atmosphere oscillations on TCs over NIO

Tropical cyclone (TC) activity in the NIO is influenced by various climate modes such as El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Madden Julian Oscillation (MJO). The impacts of these phenomena extend further than the regions of their evolution, viz., the Pacific and the Indian Ocean (IO). ENSO is a major climate phenomenon resulting from the interaction between the ocean and atmosphere and is considered the leading mode of the coupled ocean-atmosphere system (McPhaden, 2002). ENSO events occur every 2-7 years with varying strengths and last for about 12-18 months (Chang et al., 2006). El Niño and La Niña, the extremes of ENSO, bring a range of climatic conditions, with the atmospheric response to SST anomalies in the Pacific (equatorial) influencing oceanic and atmospheric conditions worldwide (Trenberth, 1997; McPhaden, 2002).

An important issue in the scientific sphere is comprehending the impact of ENSO and IOD on TC genesis. The frequency of TCs in the NIO has been observed to exhibit decadal variability, with a 29-year cycle and a rise in activity during the 1990s (Singh et al., 2000). The ENSO mode also impacts TC activity, with a decrease in the BOB during May and November in the warm phase of ENSO (Singh et al., 2000; Girishkumar and Ravichandran, 2012; Girishkumar et al., 2015). During La Niña, there is an increase in TC activity in the post-monsoon season, especially for more intense (>64 kts) TCs (Girishkumar and Ravichandran, 2012). This is due to low-level cyclonic vorticity, higher convection, and greater TCHP in the BOB, which creates favorable conditions for the TC activity during La Niña. Moreover, genesis locations of TCs shift towards the east during La Niña, leading to a longer path over warm ocean waters, which may contribute to the development of more intense TCs. Singh et al. (2000) reported a decrease in TC activity over the BOB during warm phases of ENSO, while Mohanty et al. (2012) found that thermodynamically unstable atmospheres, warm SST (28- 30°C), and weak wind shears favor TC development. The impact of atmospheric and ocean conditions on TC activity has also been studied by several researchers (Liebmann et al., 1994; Goswami et al., 2003; Ali et al., 2007; Sengupta et al., 2007; Kikuchi et al., 2009; Lin et al., 2009). For instance, Camargo et al. (2007) reported a shift in the TC genesis potential index from the northern to the southern part of the BOB between the La Niña and El Niño years. Girishkumar and Ravichandran (2012) found that ENSO significantly influences the frequency, genesis location, and intensity of TCs in the BOB during October-December, with TC activity being higher (lower) during La Niña (El Niño) years. Like the modulation of TC activity by ENSO in the Pacific Ocean, temperature gradients across the IO impact the preferred regions of rising and descending moisture and air, thus influencing TC activity in the NIO.

IOD is a significant climate mode in the IO region on inter-annual time scales (Saji et al., 1999; Webster et al., 1999; Murtugudde et al., 2000). The IOD event typically develops during spring, peaks in fall, and ends in early winters (Saji et al., 1999). A positive (+ve) or negative (-ve) IOD phase is marked by cooler or warmer than normal water in the eastern tropical IO and warmer or cooler than normal water in the western tropical IO (Saji et al., 1999). This SST pattern substantially impacts atmospheric and ocean conditions in the IO region and worldwide (Saji et al., 1999; Ashok et al., 2001; Saji and Yamagata, 2003; Girishkumar et al., 2012). The inter-annual variability of SSTs in the IO also impacts TC activity in the NIO by modulating the large-scale atmospheric circulation pattern (Yuan and Ciao, 2013). During the positive (negative) phase of the IOD, TC genesis is generally decreased (increased), and the westerly steering flow over the BOB is strengthened (weakened), potentially leading to higher exposure on the eastern coastline of the BOB, but by fewer TCs (Yuan and Ciao, 2013). The inter-annual variability of TCs in the NIO is more closely related to variability in atmospheric circulation patterns than directly to the changing SST patterns, with higher vertical wind shear, lower horizontal wind shear, and lower mid-level tropospheric moisture being associated with periods of lower TC activity during positive IOD phases compared to negative IOD phases (Pattanaik, 2005; Li et al., 2016). The interaction between mid-tropospheric relative humidity and the long- term mean states of absolute vorticity and potential intensity controls the inter-annual variability of post-monsoon TCs over the BOB, with enhanced mid-tropospheric moisture favoring more frequent genesis in negative IOD phases (Yuan and Ciao, 2013). Singh (2008) found a negative and significant correlation between the Indian Ocean Dipole Mode (IODM) Index from September to October and November TC frequency in the BOB and suggested that IODM could be a potential predictor of intense cyclones in November over the BOB with a lead time of one month. Girishkumar and Ravichandran (2012) observed that a -ve IOD event could trigger extreme tropical cyclone cases in the BOB, similar to La Niña events. Drbohlav et al. (2007) proposed that the inconsistent easterlies and north easterlies bring ocean currents that influence the warm mean mixed layer of the central IO to the NIO, contributing to +ve IOD during El Niño years. It may alter the TC frequency in the NIO basin.

MJO, a dominant mode of intra-seasonal variability, is an ocean-atmospheric coupled phenomenon that propagates eastward (Madden and Julian, 1994; Roxy et al., 2019). Previous studies have shown a strong connection between the MJO and TCs, since the MJO's propagation from the IO to the Pacific Ocean can impact the ENSO and TC activity in the IO (Mcphaden, 1999). The changes in equatorial wave dynamics resulting from the MJO have consequences for NIO's heat and mass balance (Deshpande et al., 2017). The MJO's impact on cyclogenesis is due to variations in low-level vorticity caused by Rossby wave gyres, meridional shears of equatorial zonal winds, and mid-tropospheric vertical motion (Wang and Moon, 2017). The impact of MJO on cyclogenesis varies with the region (Zhao and Li, 2019), indicating the importance of considering distinct environmental factors in different ocean basins. Although the modulation of cyclonic activity by MJO has been established, the basin dependency of MJO on cyclonic activity in NIO has not been well-documented. A comprehensive understanding of the MJO-TC relationship can aid in the short-term prediction of TC activity in BOB (Bhardwaj et al., 2019). Enhanced convection of MJO is dominant over NIO during phases 2 and 3, leading to high MJO activity and cyclogenesis. For instance, ESCS Fani formation was aided by high SST and MJO, indicating similar environmental conditions (Singh et al., 2021). The genesis of TCs could be determined through the genesis potential index (GPI) that considers mid-level relative humidity and low-level absolute vorticity as significant components during MJO active periods (Girishkumar and Ravichandran, 2012; Tsuboi and Takemi, 2014; Kuttippurath et al., 2021a, 2021b; Emanuel and Nolan, 2004; Murakami et al., 2011; Zhao et al., 2015).

Convectively coupled equatorial waves (CCEW) are significant large-scale phenomena in tropical regions and have been linked to tropical cyclogenesis in recent studies (Frank and Roundy, 2006; Shreck et al., 2012; Chen and Chou, 2014). These studies suggest that CCEWs are associated with enhanced convection, which creates favorable conditions for TC formation. The relationship between TC genesis and waves is established by analyzing rainfall, by applying a spectral filter to convection variables in a space-time domain (Knippertz et al., 2022). Besides CCEWs, which have strong precipitation and outgoing long-wave radiation (OLR) signals, several other equatorial waves, like those identified by the horizontal velocity structures, may be associated with TC occurrence too. In the current Numerical Weather Prediction (NWP) models, tropical rainfall variability is not predicted well on medium-range timescales due to the lack of explicitly resolved convection (Judt and Rios-Berrios, 2022; Dias, et al., 2018; Ying and Zhang, 2017). This causes a significant reduction in the model's ability to simulate the convectively coupled equatorial waves and associated TC genesis events. However, identifying equatorial waves dynamically, without relying on convection, could help use them as predictable precursors. A considerable obstacle is the large uncertainty in observations, for understanding the simultaneous TC genesis-wave relationship appropriately. Also, the time of emergence of waves before TC events and their impact on intensification process have not been studied well. Previous studies have examined the association between the MJO and TC genesis over the BOB (Liebmann et al. 1994; Krishnamohan et al. 2012; Tsuboi and Takemi 2014; Fosu and Wang 2015). However, the role of other equatorial waves and their interactions in the BOB has not been extensively studied. Although Schreck et al. (2012) and Frank and Roundy (2006) have mentioned the influence of equatorial waves on TC genesis in the NIO, their results are inconsistent. While Frank and Roundy (2006) suggested that cyclogenesis is more likely to occur in the presence of multiple waves, including the MJO, ER, MRG, and TD, other studies have suggested that the MJO plays a dominant role in TC genesis compared to other waves (Schreck et al. 2012; Li and Zhou 2018). Therefore, there is a need for a detailed investigation into the role of different equatorial waves and climate modes in governing the TC genesis, intensification and movement in the NIO region.

4. Numerical modeling of TC characteristics

Numerical models used for simulation of Earth's climate system and weather events involve representing the atmosphere, ocean, land, and cryosphere within the modeling framework. Numerical weather production (NWP) models have been used for research and operational purposes during the past 20 years and are constantly evolving with advancements in algorithms, parameterization schemes, and computing resources. NWP models incorporate both hydrostatic and non-hydrostatic assumptions and consider the conservation of momentum, mass, and energy in their governing equations. Tables 2 and 3 enlist some NWP models generally used in ocean and atmospheric studies including cyclones.

NWP models available worldwide for prediction and projection purposes include regional and global climate models. However, the challenges prevail in accurately predicting TC intensity, genesis, and landfall due to issues concerning vortex initialization, representation of physical processes, through parameterizations, and resolution of the models. Numerous studies have attempted to address these challenges through various means, such as assimilating satellite-derived wind data and incorporating Doppler Weather Radar (DWR) data into NWP systems to improve the predictability models (Osuri et al., 2012; Mohanty et al., 2014; Panda et al., 2015; Chen et al., 2020). Despite these efforts, TC predictions' biases persist and remain a challenge for forecasters.

On the other hand, space-borne sensors deliver continuous high-resolution data over sparse areas, mainly oceans (Guerbette et al., 2016). While conventional and satellite observations are routinely assimilated in the NWP model to produce a precise estimate of the initial model state, the use of satellite radiances is desired at several instances (Kelly and Thépaut, 2007; Montmerle et al., 2007; Sieglaff et al., 2009; Zupanski, 2013; Kumar and Shukla, 2019) including TC prediction. Previous research has shown that the assimilation of clear-sky radiance data from Microwave (MW) and Infrared (IR) sensors can improve temperature and moisture prediction (Madhulatha et al., 2018). And these parameters are crucial to govern the thermodynamics and dynamics associated with a TC. Zou et al. (2013) investigated the impact of radiances from the Advanced Technology Microwave Sounder (ATMS) assimilated into the HWRF (Hurricane Weather Research and Forecasting) model in TC track and intensity forecasts. Their findings suggested a consistently positive influence on model predictions. To improve the accuracy of severe weather event forecasting using numerical models, inclusion of precipitation and cloud-affected radiances from MW sensors is recommended (Madhulatha et al., 2018) in the data assimilation process.

Table 2. List of NWP models used in tropical cyclone studies.

Model	Advantage
WRF (Weather Research and Forecasting)	Can be used at various scales, includes advanced physics and data assimilation, widely used for research purpose.
HWRF (Hurricane Weather Research and Forecasting Model)	Specially designed for tropical cyclones, high resolution in the inner core, includes advanced physics and data assimilation, has been used operationally by the National Hurricane Center.
MPAS (Model for Prediction Across Scales)	Flexible and can adapt to a variety of scales, includes advanced physics and data assimilation
GFDL (Geophysical Fluid Dynamics Laboratory)	Specially designed for tropical cyclones, includes advanced physics, has been used operationally by the National Hurricane Center
ECMWF (European Centre for Medium – Range Weather Forecasts)	High resolution and accuracy, widely used and trusted globally, includes advanced physics and data assimilation.
CMC-GEM (Canadian Meteorological Centre Global Environmental Multiscale Model)	High resolution, includes advanced physics and data assimilation, widely used and trusted globally.
UKMO (United Kingdom Met Office)	High resolution and accuracy, includes advanced physics and data assimilation, widely used and trusted globally

Table 3. List of ocean models used in tropical cyclone studies.

Model	Advantage
COAMPS-TC (Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones)	Includes advanced physics and data assimilation, specifically designed for tropical cyclones, includes both atmosphere and ocean components.
CFSv2 (Climate Forecast System version 2)	Includes both atmosphere and ocean components, includes advanced physics and data assimilation, can be used for both seasonal and sub seasonal forecasting.
CMIP5 (Coupled Model Inter comparison Project phase 5)	Includes both atmosphere and ocean components, widely used for climate change studies and projections, includes advanced physics and data assimilation.
GFDL (Geophysical Fluid Dynamics Laboratory)	Specially designed for tropical cyclones, includes advanced physics, has been used operationally by the National Hurricane Center
IRI/Columbia Tropical Cyclone Model	Includes both atmosphere and ocean components, specifically designed for tropical cyclones, includes advanced physics and data assimilation.
Coastal Ocean WAves, Storm Surge, and Tide (COAWST)	Used in coastal and estuarine areas to simulate the interactions between the ocean, atmosphere, and waves, including the effects of storm surges and tides, which also includes TC studies.

The forecasting of TCs involves real-time predictions of various parameters such as genesis, track, landfall, intensity, RI, and decay after landfall. However, the outputs of NWP models can vary widely, leading to variations in predictions of track and landfall points. To overcome these limitations, several studies (Krishnamurti et al. 1999, 2000; Goerss 2000; Mackey and Krishnamurti 2001; Weber 2003; Williford et al. 2003) have suggested adopting ensemble techniques. These studies highlight that ensemble techniques can help address the uncertainties in the forecast, thus improving the accuracy and reliability of tropical cyclone predictions. Numerous studies have been conducted using NWP models to forecast TC geneis and movement in the NIO (Mohapatra 2014; Mohanty et al. 2014, 2019; Mohapatra and Sharma 2019). Mohapatra and Sharma (2019) highlighted the importance of NWP models, such as the NCMRWF Unified Model (NCUM) for global and regional predictions, and Global Forecast System (GFS), in forecasting track and intensity. Notably, NCUM modeling framework has been adopted from the U. K. Met Office unified modeling system. Mohapatra (2014) explained the methods used to verify track forecasts and noted that the track forecast errors are higher in the AS than the BOB and greater in the pre-monsoon season than the post- monsoon season.

Kotal et al. (2014) adopted the Cyclone Prediction System, developed by IMD for operational forecasting over the NIO, which has demonstrated reasonable skills in predicting the TC genesis, track, intensity etc., Although track prediction has developed in recent years, intensity prediction still poses a challenge. However, high-resolution NWP models have shown considerable improvement in the TC intensity forecasts. Several studies have also investigated the impact of data assimilation (DA) on TC forecasts (Rakesh and Goswami, 2011; Mohanty et al. 2014; Kutty et al. 2018, 2020). For instance, Rakesh and Goswami (2011) investigated the effect of background error statistics (BES) on TC forecasts over the NIO. They concluded that regional BES provides better TC track forecasts than global BES. Mohanty et al. (2014) demonstrated that quality observations from multiple sources could lead to reliable TC forecasts using the WRF (Weather Research and Forecasting) model. Kutty et al. (2020) showed that the hybrid ensemble transform Kalman filter (ETKF) outperforms the 3D-Var system in the WRF model.

Similarly, Prasad et al. (2013) assimilated India Ocean surface wind vector data from the Scatterometer onboard India's Oceansat-2 satellite into the Global Data Assimilation and Forecasting (GDAF) system at NCMRWF. The study found that assimilation of satellite data resulted in an improvement in the location of the cyclone centre and a reduction in the mean position error of the cyclone with respect to IMD's best track. Routray et al. (2019) evaluated the performance of the NCUM forecasts at 25 km resolution in predicting TC track and intensity over the NIO. The study found that the NCUM forecasts were slower than the system's actual translation speed for all forecast lengths. Additionally, the landfall prediction was delayed, and the intensity prediction skill was low for intense storms.

Malakar et al. (2020) evaluated six re-analyses data sets and found that GFS had the least error in the position of the TC center, mean sea level pressure (MSLP), and maximum wind speed. However, the GFS analyses tends to over-predict the category of TCs, particularly during the most intensified stages beyond cyclonic storms. Deshpande et al. (2021) assessed the skill of the Global Ensemble Forecast System (GEFS) in predicting TC track and intensity over the NIO. The study considered 13 cyclonic storms and found that the ensemble mean (ENS mean) track error was comparable with the control run up to 48 hours, after which the track error was less for ENS mean. The study also found that the cyclone intensity was under- estimated in terms of Maximum Sustained Wind (MSW) speed, and the error in the control run was less than the ENS mean. Figure 5 shows the observed and model-simulated MSLP along with 10 m wind magnitude at 12UTC on 18th May 2020 during SuCS Amphan. It can be observed that both MSLP and 10 m wind are well captured by the numerical models WRF and MPAS (model for prediction across scales). It can be inferred that both models are capable enough for such TC studies over the NIO region. The interplay between atmosphere, ocean, and land plays a

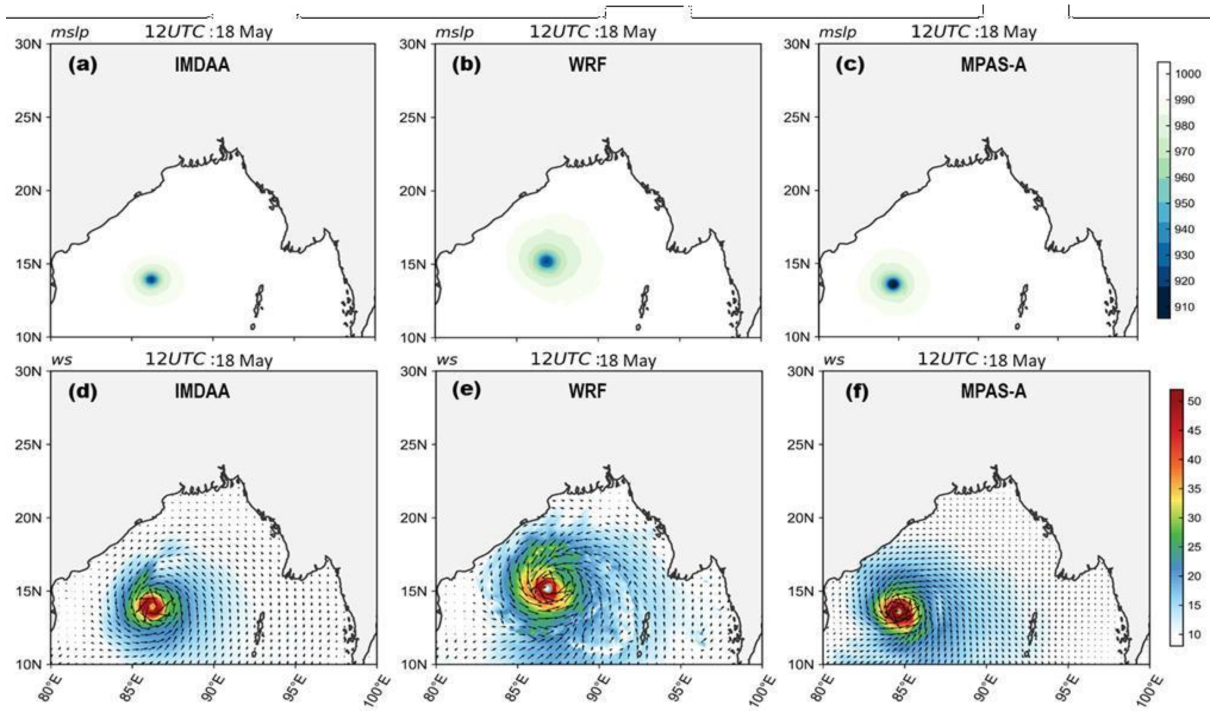

Figure 5: Observation and Model analyzed MSLP (hPa) and 10 m wind vectors with magnitude (m/s) at 12UTC 18th May for SuCS Amphan. First column is for IMDAA (12 km resolution), second column for high resolution WRF simulations with SST input (6km) and third column for high resolution MPAS-A simulation with SST input (10 km).

crucial role in tropical TC genesis, impacting its intensification and track through flux exchanges. Mohanty et al. (2001) have confirmed that land-air-sea interactions significantly impact the regional circulation pattern, creating strong teleconnections between regional and global scale features. Recent research emphasizes the importance of air-sea interface in predicting TC intensity. Moisture difference and surface entropy flux between air and sea are well-known factors that enhance TC intensity and destructiveness. Standalone models used for TC forecasts are often biased and inaccurate due to unrealistic feedback. Current NWP models provide static SST, with a high probability of bias in results (Bender and Ginis, 2000; Bender et al., 2007). Coupled ocean-atmosphere models have emerged as a useful tool in improving predictability skills. Several studies have tested the predictability of coupled models over the NIO and other oceans. For example, Mohanty et al. (2019) conducted a sensitivity experiment of the HWRF- POM/HYCOM coupled ocean-atmosphere model, while Prakash and Pant (2017) used WRF-ROMS to demonstrate the benefits of a coupled atmosphere-ocean model in simulating atmospheric and ocean parameters during extreme weather conditions associated with intense cyclones. While coupling between ocean-atmosphere has been extensively studied, three-way coupled models have received less attention. However, including realistic land surface features has shown potential in improving prediction skills of models.

5. Concluding remarks

This study presents a review literature on the atmospheric and ocean characteristics associated with the TCs over NIO primarily focusing on TC intensity and movement. In this paper, numerical modelling approach for prediction of TC intensity and movement is also included. Although efforts have been put forward to include all relevant topics owing to the advancement of TC research, especially in India, some relevant papers might have been missed out.

TCs are complex phenomena that require a comprehensive understanding of the environmental factors influencing their development, intensity, and track. Moist convection, Coriolis forces, eddies, low-level vertical wind shear, moisture, and other atmospheric conditions are important factors that affect the TC formation and life cycle. Several studies have suggested a positive correlation between mid-tropospheric relative humidity, low level relative vorticity, and a decrease in outgoing longwave radiation with an increase in TC frequency. Also, the correlation between accumulated cyclone energy increase and variations in SST, upper ocean heat content, atmospheric water vapor, and genesis potential index is significant. Other factors that influence the formation and intensity of TCs include eddy currents, baroclinic processes, asymmetric wind-induced dry air entrainment, and ocean and atmospheric temperature gradient. Re-curvature occurs when a TC deviates from its usual west or northwest direction. The steering flow and upper tropospheric westerlies have a strong correlation with the recurving TC motion. The eastward-retreating subtropical ridge typically directs a TC to move along its boundary, while the approach of a mid-latitude westerly trough can enhance the effect of re-curvature. Furthermore, intra seasonal or inter annual atmospheric phenomena such as monsoon systems, momentum exchange, cold air intrusion, upper- tropospheric cold lows, variations in SST, and the ENSO also influence re-curvature TCs over NIO are very much influenced by oceanic factors such as SST, TCHP, ocean- currents, and eddies. SST and TCHP are significant precursors for TC intensification, with warm core eddies also playing a crucial role. The rapid intensification of TCs is aided by TCHP and eddy currents over warm waters. SST distribution, sea surface cooling caused by previous TCs, and SSS impact TC motion too. SST distribution affects TC motion by changing the total surface friction and heat flux exchange. Sea surface cooling can cause a reversal in air-sea surface sensible and latent heat flux. The right (left) side of TC tracks tend to experience more cooling and increased SSS, with changes typically ranging within one PSU. Besides, understanding the dynamics and thermodynamics associated with TC development and life cycle while involving the ocean, is crucial for predicting and mitigating the impact of TCs in the NIO region.

The frequency and intensity of TCs in the NIO are also influenced by climate modes such including ENSO, IOD, and MJO. ENSO results from the interaction between the ocean and atmosphere and thus, has a dominant role in the tropical-coupled ocean-atmosphere system including TCs. El Niño brings a decrease in TC activity in the BOB during May and November, while La Niña results in an increase in the post-monsoon season, particularly for more intense TCs. IOD is a significant climate variability mode in the Indian Ocean that impacts TC activity in the NIO by modulating the large-scale atmospheric circulation pattern. During the positive (negative) phase of the IOD, TC genesis is generally decreased (increased). The inter-annual variability of TCs in the NIO is more closely related to variability in atmospheric circulation patterns than directly to the changing SST patterns, with higher vertical wind shear, lower horizontal wind shear, and lower mid-level tropospheric moisture being associated with periods of lower TC activity during positive IOD phases compared to negative phases.

NWP models are used to forecast TC intensity and track by representing the Earth's climate system. However, accurately predicting TC intensity, genesis, and landfall is challenging due to limitations in models such as inaccuracies in vortex initialization, incomplete physical process representation, parameterization errors, coarse resolution, etc. Incorporating satellite and weather radar observations into NWP models has shown signature to improve TC prediction. Also, Space-borne sensors, particularly satellite radiances from Microwave (MW) and Infrared (IR) sensors, have been seen to enhance temperature and moisture analysis, thereby improving model predictions. Ensemble techniques can also be useful in addressing uncertainties in forecasts, improving the accuracy and reliability of TC predictions. High-resolution NWP models have shown significant improvement in TC intensity forecasts. However, data assimilation techniques using good-quality observations from multiple sources has shown to produce reliable and better TC forecasts.

References

Abernathey, R., & Haller, G. (2018). Transport by Lagrangian vortices in the eastern Pacific. Journal of Physical Oceanography, 48(3), 667-685.

Akter, N., & Tsuboki, K. (2021). Recurvature and movement processes of tropical cyclones over the Bay of Bengal. Quarterly Journal of the Royal Meteorological Society, 147(740), 3681-3702.

Albert, J., Krishnan, A., Bhaskaran, P. K., & Singh, K. S. (2021). Role and influence of key atmospheric parameters in large-scale environmental flow associated with tropical cyclogenesis and ENSO in the North Indian Ocean basin. Climate Dynamics, 1-18.

Ali, M. M., Jagadeesh, P. V., & Jain, S. (2007). Effects of eddies on Bay of Bengal cyclone intensity. Eos, Transactions American Geophysical Union, 88(8), 93-95.

Ashok, K., Guan, Z., & Yamagata, T. (2001). Impact of the Indian Ocean dipole on the relationship between the Indian monsoon rainfall and ENSO. Geophysical research letters, 28(23), 4499-4502.

Balaji, M., Chakraborty, A., & Mandal, M. (2018). Changes in tropical cyclone activity in north Indian Ocean during satellite era (1981–2014). International Journal of Climatology, 38(6), 2819-2837.

Baranowski, D. B., Flatau, P. J., Chen, S., & Black, P. G. (2014). Upper ocean response to the passage of two sequential typhoons. Ocean Science, 10(3), 559-570.

Beal, L. M., Vialard, J., Roxy, M. K., Li, J., Andres, M., Annamalai, H., ... & Parvathi, V. (2020). A road map to IndOOS-2: Better observations of the rapidly warming Indian Ocean. Bulletin of the American Meteorological Society, 101(11), E1891-E1913.

Bender, M. A., & Ginis, I. (2000). Real-case simulations of hurricane–ocean interaction using a high-resolution coupled model: Effects on hurricane intensity. Monthly Weather Review, 128(4), 917-946.

Bender, M. A. (1997). The effect of relative flow on the asymmetric structure in the interior of hurricanes. Journal of the Atmospheric Sciences, 54(6), 703-724.

Bender, M. A., Ginis, I., Tuleya, R., Thomas, B., & Marchok, T. (2007). The operational GFDL coupled hurricane–ocean prediction system and a summary of its performance. Monthly Weather Review, 135(12), 3965-3989.

Bhardwaj, P., Singh, O., Pattanaik, D. R., & Klotzbach, P. J. (2019). Modulation of Bay of Bengal tropical cyclone activity by the Madden-Julian oscillation. Atmospheric research, 229, 23-38.

Bhattacharya, S. K., Kotal, S. D., & Kundu, P. K. (2015). An analysis of recurvature and decay of the tropical cyclone 'madi'(2013) over the Bay of Bengal. Tropical Cyclone Research and Review, 4(1), 27-37.

Black, P. G., D'Asaro, E. A., Drennan, W. M., French, J. R., Niiler, P. P., Sanford, T. B., ... & Zhang, J. A. (2007). Air–sea exchange in hurricanes: Synthesis of observations from the coupled boundary layer air–sea transfer experiment. Bulletin of the American Meteorological Society, 88(3), 357-374.

Bond, N. A., Cronin, M. F., Sabine, C., Kawai, Y., Ichikawa, H., Freitag, P., & Ronnholm, K. (2011). Upper ocean response to Typhoon Choi-Wan as measured by the Kuroshio Extension Observatory mooring. Journal of Geophysical Research: Oceans, 116(C2).

Burroughs, L. D., & Brand, S. (1973). Speed of tropical storms and typhoons after recurvature in the western North Pacific Ocean. Journal of Applied Meteorology (1962-1982), 452- 458.

Busireddy, N. K. R., Ankur, K., Osuri, K. K., Sivareddy, S., & Niyogi, D. (2019). The response of ocean parameters to tropical cyclones in the Bay of Bengal. Quarterly Journal of the Royal Meteorological Society, 145(724), 3320-3332.

Byju, P., & Kumar, S. P. (2011). Physical and biological response of the Arabian Sea to tropical cyclone Phyan and its implications. Marine environmental research, 71(5), 325-330.

Camargo, S. J., Emanuel, K. A., & Sobel, A. H. (2007). Use of a genesis potential index to diagnose ENSO effects on tropical cyclone genesis. Journal of Climate, 20(19), 4819- 4834.

Cangialosi, J. P., & Franklin, J. L. (2012). National Hurricane Center forecast verification report. NOAA National Hurricane Center Tech. Rep, 79.

Chan, J. C. (2005). The physics of tropical cyclone motion. Annu. Rev. Fluid Mech., 37, 99- 128.

Chan, J. C., & Williams, R. T. (1987). Analytical and numerical studies of the beta-effect in tropical cyclone motion. Part I: Zero mean flow. Journal of atmospheric sciences, 44(9), 1257-1265.

Chan, J. C., & Gray, W. M. (1982). Tropical cyclone movement and surrounding flow relationships. Monthly Weather Review, 110(10), 1354-1374.

Chan, K. T., & Chan, J. C. (2016). Tropical cyclone recurvature: An intrinsic property? Geophysical Research Letters, 43(16), 8769-8774.

Chang, P., Yamagata, T., Schopf, P., Behera, S. K., Carton, J., Kessler, W. S., ... & Xie, S. P. (2006). Climate fluctuations of tropical coupled systems—the role of ocean dynamics. Journal of Climate, 19(20), 5122-5174.

Chang, S. W., & Madala, R. V. (1980). Numerical simulation of the influence of sea surface temperature on translating tropical cyclones. Journal of Atmospheric Sciences, 37(12), 2617-2630.

Chen, G., & Chou, C. (2014). Joint contribution of multiple equatorial waves to tropical cyclogenesis over the western North Pacific. Monthly Weather Review, 142(1), 79-93.

Chen, H., Li, S., He, H., Song, J., Ling, Z., Cao, A., ... & Qiao, W. (2021). Observational study of super typhoon Meranti (2016) using satellite, surface drifter, Argo float and reanalysis data. Acta Oceanologica Sinica, 40, 70-84.

Chen, R., Zhang, W., & Wang, X. (2020). Machine learning in tropical cyclone forecast modeling: A review. Atmosphere, 11(7), 676.

Chen, T. C., Wang, S. Y., Yen, M. C., & Clark, A. J. (2009). Impact of the intraseasonal variability of the western North Pacific large-scale circulation on tropical cyclone tracks. Weather and forecasting, 24(3), 646-666.

Chen, T. J. G., & Chang, C. P. (1980). The structure and vorticity budget of an early summer monsoon trough (Mei-Yu) over southeastern China and Japan. Monthly Weather Review, 108(7), 942-953.

Cheung, N. K. W. (2006). The roles of ENSO on the occurrence of abruptly recurving tropical cyclones over the Western North Pacific Ocean Basin. Advances in Geosciences, 6, 139- 148.

Choi, Y., Yun, K. S., Ha, K. J., Kim, K. Y., Yoon, S. J., & Chan, J. C. (2013). Effects of asymmetric SST distribution on straight-moving Typhoon Ewiniar (2006) and recurving Typhoon Maemi (2003). Monthly weather review, 141(11), 3950-3967.

Chowdhury, A. M. R., Bhuyia, A. U., Choudhury, A. Y., & Sen, R. (1993). The Bangladesh cyclone of 1991: why so many people died. Disasters, 17(4), 291-304.

Cione, J. J., & Uhlhorn, E. W. (2003). Sea surface temperature variability in hurricanes: Implications with respect to intensity change. Monthly Weather Review, 131(8), 1783- 1796.

Courtney, J. B., Langlade, S., Sampson, C. R., Knaff, J. A., Birchard, T., Barlow, S., ... & Shimada, U. (2019). Operational perspectives on tropical cyclone intensity change part 1: Recent advances in intensity guidance. Tropical Cyclone Research and Review, 8(3), 123-133.

D'Asaro, E. A., Sanford, T. B., Niiler, P. P., & Terrill, E. J. (2007). Cold wake of hurricane Frances. Geophysical Research Letters, 34(15).

DeMaria, M., & Kaplan, J. (1999). An updated statistical hurricane intensity prediction scheme (SHIPS) for the Atlantic and eastern North Pacific basins. Weather and Forecasting, 14(3), 326-337.

Deshpande, A., Gnanaseelan, C., Chowdary, J. S., & Rahul, S. (2017). Interannual spring Wyrtki jet variability and its regional impacts. Dynamics of Atmospheres and Oceans, 78, 26-37.

Deshpande, M., Kanase, R., Krishna, R. P. M., Tirkey, S., Mukhopadhyay, P., Prasad, V. S & Mohapatra, M. (2021). Global Ensemble Forecast System (GEFS T1534) evaluation for tropical cyclone prediction over the North Indian Ocean. Mausam, 72(1), 119-128.

Dias, J., Gehne, M., Kiladis, G. N., Sakaeda, N., Bechtold, P., & Haiden, T. (2018). Equatorial waves and the skill of NCEP and ECMWF numerical weather prediction systems. Monthly Weather Review, 146(6), 1763-1784.

Domingues, R., Goni, G., Bringas, F., Lee, S. K., Kim, H. S., Halliwell, G., ... & Pomales, L. (2015). Upper ocean response to Hurricane Gonzalo (2014): Salinity effects revealed by targeted and sustained underwater glider observations. Geophysical Research Letters, 42(17), 7131-7138.

Dong, K., & Neumann, C. J. (1986). The relationship between tropical cyclone motion and environmental geostrophic flows. Monthly weather review, 114(1), 115-122.

Drbohlav, H. K. L., Gualdi, S., & Navarra, A. (2007). A diagnostic study of the Indian Ocean dipole mode in El Niño and non–El Niño years. Journal of Climate, 20(13), 2961-2977.

Duan, W., Yuan, J., Duan, X., & Feng, D. (2021). Seasonal variation of tropical cyclone genesis and the related large-scale environments: Comparison between the Bay of Bengal and Arabian Sea sub-basins. Atmosphere, 12(12), 1593.

Dvorak, V. F. (1975). Tropical cyclone intensity analysis and forecasting from satellite imagery. Monthly Weather Review, 103(5), 420-430.

Dvorak, V. F. (1984). Tropical cyclone intensity analysis using satellite data (Vol. 11). US Department of Commerce, National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service.

Emanuel, K. A. (1986). An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. Journal of Atmospheric Sciences, 43(6), 585-605.

Emanuel, K. A., & Nolan, D. S. (2004, May). Tropical cyclone activity and the global climate system. In Preprints, 26th Conf. on Hurricanes and Tropical Meteorology, Miami, FL, Amer. Meteor. Soc. A (Vol. 10).

Evans, J. L., & McKinley, K. (1998). Relative timing of tropical storm lifetime maximum intensity and track recurvature. Meteorology and Atmospheric Physics, 65, 241-245.

Evans, J. L., Holland, G. J., & Elsberry, R. L. (1991). Interactions between a barotropic vortex and an idealized subtropical ridge. Part I: Vortex motion. Journal of Atmospheric Sciences, 48(2), 301-314.

Fan, K., Wang, X., & He, Z. (2020). Control of salinity stratification on recent increase in tropical cyclone intensification rates over the postmonsoon Bay of Bengal. Environmental Research Letters, 15(9), 094028.

Fiorino, M., & Elsberry, R. L. (1989). Some aspects of vortex structure related to tropical cyclone motion. Journal of Atmospheric Sciences, 46(7), 975-990.

Fosu, B. O., & Wang, S. Y. S. (2015). Bay of Bengal: coupling of pre-monsoon tropical cyclones with the monsoon onset in Myanmar. Climate Dynamics, 45, 697-709.

Frank, W. M., & Roundy, P. E. (2006). The role of tropical waves in tropical cyclogenesis. Monthly weather review, 134(9), 2397-2417.

Franklin, J. L., Feuer, S. E., Kaplan, J., & Aberson, S. D. (1996). Tropical cyclone motion and surrounding flow relationships: Searching for beta gyres in omega dropwindsonde datasets. Monthly weather review, 124(1), 64-84.

George, J. E., & Gray, W. M. (1977). Tropical cyclone recurvature and nonrecurvature as related to surrounding wind-height fields. Journal of Applied Meteorology (1962-1982), 34-42.

Ghetiya, S., & Nayak, R. K. (2020). Genesis potential parameter using satellite derived daily tropical cyclone heat potential for North Indian ocean. International Journal of Remote Sensing, 41(23), 8934-8947.

Girish kumar, M. S., Suprit, K., Chiranjivi, J., Udaya Bhaskar, T. V. S., Ravichandran, M., Shesu, R. V., & Pattabhi Rama Rao, E. (2014). Observed oceanic response to tropical cyclone Jal from a moored buoy in the south-western Bay of Bengal. Ocean Dynamics, 64, 325-335.

Girishkumar, M. S., Suprit, K., Vishnu, S., Prakash, V. T., & Ravichandran, M. (2015). The role of ENSO and MJO on rapid intensification of tropical cyclones in the Bay of Bengal during October–December. Theoretical and Applied Climatology, 120, 797-810.

Girishkumar, M. S., & Ravichandran, M. (2012). The influences of ENSO on tropical cyclone activity in the Bay of Bengal during October–December. Journal of Geophysical Research: Oceans, 117(C2).

Girishkumar, M. S., Thanga Prakash, V. P., & Ravichandran, M. (2015). Influence of Pacific Decadal Oscillation on the relationship between ENSO and tropical cyclone activity in the Bay of Bengal during October–December. Climate Dynamics, 44, 3469-3479.

Goerss, J. S. (2000). Tropical cyclone track forecasts using an ensemble of dynamical models. Monthly Weather Review, 128(4), 1187-1193.

Gopalan, A. K. S., Krishna, V. V., Ali, M. M., & Sharma, R. (2000). Detection of Bay of Bengal eddies from TOPEX and in situ observations. Journal of Marine Research, 58(5), 721-734.

Goswami, B. N., Ajayamohan, R. S., Xavier, P. K., & Sengupta, D. (2003). Clustering of synoptic activity by Indian summer monsoon intraseasonal oscillations. Geophysical Research Letters, 30(8).

Grodsky, S. A., Reul, N., Lagerloef, G., Reverdin, G., Carton, J. A., Chapron, B., ... & Kao, H.

Y. (2012). Haline hurricane wake in the Amazon/Orinoco plume: AQUARIUS/SACD and SMOS observations. Geophysical Research Letters, 39(20).

Hodanish, S., & Gray, W. M. (1993). An observational analysis of tropical cyclone recurvature. Monthly Weather Review, 121(10), 2665-2689.

Holland, G. J. (1982). Tropical cyclone motion: Environmental interaction plus a beta effect. COLORADO STATE UNIV FORT COLLINS DEPT OF ATMOSPHERIC SCIENCE.

Holland, G. J., & Wang, Y. (1995). Baroclinic dynamics of simulated tropical cyclone recurvature. Journal of Atmospheric Sciences, 52(4), 410-426.

Huang, P., Sanford, T. B., & Imberger, J. (2009). Heat and turbulent kinetic energy budgets for surface layer cooling induced by the passage of Hurricane Frances (2004). Journal of Geophysical Research: Oceans, 114(C12).

Jacob, S. D., Shay, L. K., Mariano, A. J., & Black, P. G. (2000). The 3D oceanic mixed layer response to Hurricane Gilbert. Journal of Physical Oceanography, 30(6), 1407-1429.

Jangir, B., Swain, D., & Ghose, S. K. (2021). Influence of eddies and tropical cyclone heat potential on intensity changes of tropical cyclones in the North Indian Ocean. Advances in Space Research, 68(2), 773-786.

Judt, F., & Rios-Berrios, R. (2021). Resolved convection improves the representation of equatorial waves and tropical rainfall variability in a global nonhydrostatic model. Geophysical Research Letters, 48(14), e2021GL093265.

Katsube, K., & Inatsu, M. (2016). Response of tropical cyclone tracks to sea surface temperature in the western North Pacific. Journal of Climate, 29(5), 1955-1975.

Kelly, G., & Thépaut, J. N. (2007). Evaluation of the impact of the space component of the Global Observing System through Observing System Experiments. ECMWF Newsletter, 113, 16-28.

Kikuchi, K., Wang, B., & Fudeyasu, H. (2009). Genesis of tropical cyclone Nargis revealed by multiple satellite observations. Geophysical Research Letters, 36(6).

Knaff, J. A. (2009). Revisiting the maximum intensity of recurving tropical cyclones. International Journal of Climatology: A Journal of the Royal Meteorological Society, 29(6), 827-837.

Knapp, K. R., & Kruk, M. C. (2010). Quantifying interagency differences in tropical cyclone best-track wind speed estimates. Monthly Weather Review, 138(4), 1459-1473.

Knippertz, P., Gehne, M., Kiladis, G. N., Kikuchi, K., Rasheeda Satheesh, A., Roundy, P. E.,

... & Wheeler, M. C. (2022). The intricacies of identifying equatorial waves. Quarterly Journal of the Royal Meteorological Society, 148(747), 2814-2852.

Kourzeneva, E., Asensio, H., Martin, E., & Faroux, S. (2012). Global gridded dataset of lake coverage and lake depth for use in numerical weather prediction and climate modelling. Tellus A: Dynamic Meteorology and Oceanography, 64(1), 15640.

Kotal, S. D., Bhattacharya, S. K., & Bhowmik, S. R. (2014). Development of NWP based objective cyclone prediction system (CPS) for North Indian Ocean tropical cyclones— evaluation of performance. Tropical Cyclone Research and Review, 3(3), 162-177.

Krishnamohan, K. S., Mohanakumar, K., & Joseph, P. V. (2012). The influence of Madden– Julian oscillation in the genesis of north Indian Ocean tropical cyclones. Theoretical and applied climatology, 109, 271-282.

Krishnamurti, T. N., Kishtawal, C. M., LaRow, T. E., Bachiochi, D. R., Zhang, Z., Williford, C. E., ... & Surendran, S. (1999). Improved weather and seasonal climate forecasts from multimodel superensemble. Science, 285(5433), 1548-1550.

Krishnamurti, T. N., Kishtawal, C. M., Zhang, Z., LaRow, T., Bachiochi, D., Williford, E., ... & Surendran, S. (2000). Multimodel ensemble forecasts for weather and seasonal climate. Journal of Climate, 13(23), 4196-4216.

Kumar, P., & Shukla, M. V. (2019). Assimilating INSAT-3D thermal infrared window imager observation with the particle filter: A case study for Vardah Cyclone. Journal of Geophysical Research: Atmospheres, 124(4), 1897-1911.

Kumar, S., Routray, A., Tiwari, G., Chauhan, R., & Jain, I. (2017). Simulation of Tropical Cyclone 'Phailin'Using WRF Modeling System. Tropical Cyclone Activity over the North Indian Ocean, 307-316.

Kurihara, Y., Bender, M. A., Tuleya, R. E., & Ross, R. J. (1995). Improvements in the GFDL hurricane prediction system. Monthly Weather Review, 123(9), 2791-2801.

Kuttippurath, J., Murasingh, S., Stott, P. A., Sarojini, B. B., Jha, M. K., Kumar, P., ... & Pandey, P. C. (2021). Observed rainfall changes in the past century (1901–2019) over the wettest place on Earth. Environmental Research Letters, 16(2), 024018.

Kuttippurath, J., Sunanda, N., Martin, M. V., & Chakraborty, K. (2021). Tropical storms trigger phytoplankton blooms in the deserts of north Indian Ocean. NPJ Climate and Atmospheric Science, 4(1), 11.

Kutty, G., Gogoi, R., Rakesh, V., & Pateria, M. (2020). Comparison of the performance of HYBRID ETKF-3DVAR and 3DVAR data assimilation scheme on the forecast of tropical cyclones formed over the Bay of Bengal. Journal of Earth System Science, 129, 1-14.

Kutty, G., Muraleedharan, R., & Kesarkar, A. P. (2018). Impact of representing model error in a hybrid ensemble-variational data assimilation system for track forecast of tropical cyclones over the Bay of Bengal. Pure and Applied Geophysics, 175, 1155-1167.

Leslie, L. M., LeMarshall, J. F., Morison, R. P., Spinoso, C., Purser, R. J., Pescod, N., & Seecamp, R. (1998). Improved hurricane track forecasting from the continuous assimilation of high quality satellite wind data. Monthly weather review, 126(5), 1248- 1258.

Li, R. C., & ZHOU, W. (2018). Revisiting the intraseasonal, interannual and interdecadal variability of tropical cyclones in the western North Pacific. Atmospheric and Oceanic Science Letters, 11(2), 198-208.

Li, Y. S., & Chan, J. C. (1999). Momentum transports associated with tropical cyclone recurvature. Monthly weather review, 127(6), 1021-1037.

Li, Z., Li, T., Yu, W., Li, K., & Liu, Y. (2016). What controls the interannual variation of tropical cyclone genesis frequency over Bay of Bengal in the post-monsoon peak season? Atmospheric Science Letters, 17(2), 148-154.

Liebmann, B., Hendon, H. H., & Glick, J. D. (1994). The relationship between tropical cyclones of the western Pacific and Indian Oceans and the Madden-Julian oscillation. Journal of the Meteorological Society of Japan. Ser. II, 72(3), 401-412.

Lin, I. I., Chen, C. H., Pun, I. F., Liu, W. T., & Wu, C. C. (2009). Warm ocean anomaly, air sea fluxes, and the rapid intensification of tropical cyclone Nargis (2008). Geophysical Research Letters, 36(3).

Lin, I. I., Goni, G. J., Knaff, J. A., Forbes, C., & Ali, M. M. (2013). Ocean heat content for tropical cyclone intensity forecasting and its impact on storm surge. Natural Hazards, 66, 1481-1500.

Lin, I. I., Liu, W. T., Wu, C. C., Chiang, J. C. H., & Sui, C. H. (2003). Satellite observations of modulation of surface winds by typhoon-induced upper ocean cooling. Geophysical research letters, 30(3).

Liu, F., Zhang, H., Ming, J., Zheng, J., Tian, D., & Chen, D. (2020). Importance of precipitation on the upper ocean salinity response to typhoon kalmaegi (2014). Water, 12(2), 614.

Liu, Z., Xu, J., Sun, C., & Wu, X. (2014). An upper ocean response to Typhoon Bolaven analyzed with Argo profiling floats. Acta Oceanologica Sinica, 33, 90-101.

Lin, I. I., Black, P., Price, J. F., Yang, C. Y., Chen, S. S., Lien, C. C., ... & D'Asaro, E. A. (2013). An ocean coupling potential intensity index for tropical cyclones. Geophysical Research Letters, 40(9), 1878-1882.

Mackey, B. P., & Krishnamurti, T. N. (2001). Ensemble forecast of a typhoon flood event. Weather and forecasting, 16(4), 399-415.

Lin, S. J. (2004). A “vertically Lagrangian” finite-volume dynamical core for global models. Monthly Weather Review, 132(10), 2293-2307.

Madhulatha, A., Rajeevan, M., Bhowmik, S. R., & Das, A. K. (2018). Impact of assimilation of conventional and satellite radiance GTS observations on simulation of mesoscale convective system over Southeast India using WRF-3DVar. Pure and Applied Geophysics, 175, 479-500.

Madsen, H., & Jakobsen, F. (2004). Cyclone induced storm surge and flood forecasting in the northern Bay of Bengal. Coastal Engineering, 51(4), 277-296.

Malakar, P., Kesarkar, A. P., Bhate, J. N., Singh, V., & Deshamukhya, A. (2020). Comparison of reanalysis data sets to comprehend the evolution of tropical cyclones over North Indian Ocean. Earth and Space Science, 7(2), e2019EA000978.

Mandal, M., & Mohanty, U. C. (2010). Simulation of severe land-falling bay of bengal cyclones during 1995–1999 using mesoscale model MM5. Marine Geodesy, 33(4), 315- 337.

Mawren, D., & Reason, C. J. C. (2017). Variability of upper-ocean characteristics and tropical cyclones in the S outh W est I ndian O cean. Journal of Geophysical Research: Oceans, 122(3), 2012-2028.

McAdie, C. J., & Lawrence, M. B. (2000). Improvements in tropical cyclone track forecasting in the Atlantic basin, 1970–98. Bulletin of the American Meteorological Society, 81(5), 989-998.

McPhaden, M. J. (2002). El Niño and La Niña: causes and global consequences. Encyclopedia of global environmental change, 1, 353-370.

McPhaden, M. J., Foltz, G. R., Lee, T., Murty, V. S. N., Ravichandran, M., Vecchi, G. A., ... & Yu, L. (2009). Ocean-atmosphere interactions during cyclone nargis. EOS, Transactions American Geophysical Union, 90(7), 53-54.

Miller, B. I. (1958). Rainfall rates in Florida hurricanes. Monthly Weather Review, 86(7), 258-264.

Mohanty, U. C., Osuri, K. K., & Pattanayak, S. (2014). Mesoscale modelling for tropical cyclone forecasting over the North Indian Ocean. Monitoring and prediction of tropical cyclones in the Indian Ocean and climate change, 274-286.

Mohanty, S., Nadimpalli, R., Mohanty, U. C., Mohapatra, M., Sharma, A., Das, A. K., & Sil, S. (2021). Quasi-operational forecast guidance of extremely severe cyclonic storm Fani over the Bay of Bengal using high-resolution mesoscale models. Meteorology and Atmospheric Physics, 133, 331-348.

Mohanty, U. C., Nadimpalli, R., Mohanty, S., & Osuri, K. K. (2019). Recent advancements in prediction of tropical cyclone track over north Indian Ocean basin. Mausam, 70(1), 57- 70.

Mohanty, U. C., Niyogi, D. S., Raman, S., & Sarkar, A. (2001). Numerical study of the role of land–air–sea interactions for the northeasterly monsoon circulations over Indian Ocean during INDOEX. Current Science, 60-68.

Mohanty, U. C., Osuri, K. K., Pattanayak, S., & Sinha, P. (2012). An observational perspective on tropical cyclone activity over Indian seas in a warming environment. Natural hazards, 63, 1319-1335.

Mohapatra, M. (2014). Tropical cyclone forecast verification by India Meteorological Department for north Indian Ocean: A review. Tropical Cyclone Research and Review, 3(4), 229-242.

Mohapatra, M., & Sharma, M. (2019). Cyclone warning services in India during recent years: A review. Mausam, 70(4), 635-666.

Mohapatra, M., Nayak, D. P., Sharma, M., Sharma, R. P., & Bandyopadhyay, B. K. (2015). Evaluation of official tropical cyclone landfall forecast issued by India Meteorological Department. Journal of Earth System Science, 124, 861-874.

Montgomery, M. T., & Smith, R. K. (2017). Recent developments in the fluid dynamics of tropical cyclones. Annual Review of Fluid Mechanics, 49, 541-574.

Montmerle, T., Rabier, F., & Fischer, C. (2007). Relative impact of polar-orbiting and geostationary satellite radiances in the Aladin/France numerical weather prediction system. Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography, 133(624), 655- 671.

Murakami, H., Wang, B., & Kitoh, A. (2011). Future change of western North Pacific typhoons: Projections by a 20-km-mesh global atmospheric model. Journal of Climate, 24(4), 1154-1169.

Murtugudde, R., McCreary Jr, J. P., & Busalacchi, A. J. (2000). Oceanic processes associated with anomalous events in the Indian Ocean with relevance to 1997–1998. Journal of Geophysical Research: Oceans, 105(C2), 3295-3306.

Nadimpalli, R., Osuri, K. K., Mohanty, U. C., Das, A. K., Kumar, A., Sil, S., & Niyogi, D. (2020). Forecasting tropical cyclones in the Bay of Bengal using quasi-operational WRF and HWRF modeling systems: an assessment study. Meteorology and Atmospheric Physics, 132, 1-17.

Nadimpalli, R., Srivastava, A., Prasad, V. S., Osuri, K. K., Das, A. K., Mohanty, U. C., & Niyogi, D. (2020). Impact of INSAT-3D/3DR radiance data assimilation in predicting tropical cyclone Titli over the Bay of Bengal. IEEE Transactions on Geoscience and Remote Sensing, 58(10), 6945-6957.

Neumann, C.J. (1993). Global overview. Chapter 1. In: Global Guide to Tropical Cyclone Forecasting, Vol. 1. Geneva: World Meteorological Organization, pp. 1–1.5.

Nolan, D. S., & Rappin, E. D. (2008). Increased sensitivity of tropical cyclogenesis to wind shear in higher SST environments. Geophysical research letters, 35(14).

O'Shay, A. J., & Krishnamurti, T. N. (2004). An examination of a model's components during tropical cyclone recurvature. Monthly weather review, 132(5), 1143-1166.

Osuri, K. K., Mohanty, U. C., Routray, A., Kulkarni, M. A., & Mohapatra, M. (2012). Customization of WRF-ARW model with physical parameterization schemes for the simulation of tropical cyclones over North Indian Ocean. Natural Hazards, 63, 1337- 1359.

Osuri, K. K., Routray, A., Mohanty, U. C., & Kulkarni, M. A. (2010). Simulation of tropical cyclones over Indian Seas: data impact study using WRF-Var assimilation system. Indian Ocean tropical cyclones and climate change, 115-124.

Palmén, E. (1948). On the distribution of temperature and wind in the upper westerlies. Journal of Atmospheric Sciences, 5(1), 20-27.

Panda, J., Singh, H., Wang, P. K., Giri, R. K., & Routray, A. (2015). A qualitative study of some meteorological features during tropical cyclone PHET using satellite observations and WRF modeling system. Journal of the Indian Society of Remote Sensing, 43, 45-56.

Patnaik, K. V. K. R. K., Maneesha, K., Sadhuram, Y., Prasad, K. V. S. R., Ramana Murty, T. V., & Brahmananda Rao, V. (2014). East India Coastal Current induced eddies and their interaction with tropical storms over Bay of Bengal. Journal of operational oceanography, 7(1), 58-68.

Pattanaik, D. R. (2005). Variability of oceanic and atmospheric conditions during active and inactive periods of storms over the Indian region. International Journal of Climatology: A Journal of the Royal Meteorological Society, 25(11), 1523-1530.

Patwardhan, S. K., & Bhalme, H. N. (2001). A study of cyclonic disturbances over India and the adjacent ocean. International Journal of Climatology: A Journal of the Royal Meteorological Society, 21(4), 527-534.

Paul, A., & Rahman, M. (2006). Cyclone mitigation perspectives in the Islands of Bangladesh: a case of Sandwip and Hatia Islands. Coastal Management, 34(2), 199-215.

Paul, D., Panda, J., & Routray, A. (2022). Ocean and atmospheric characteristics associated with the cyclogenesis and rapid intensification of NIO super cyclonic storms during 1981–2020. Natural Hazards, 114(1), 261-289.

Peng, M. S., & Williams, R. T. (1990). Dynamics of vortex asymmetries and their influence on vortex motion on a β-plane. Journal of the atmospheric sciences, 47(16), 1987-2003.

Peng, S., Qian, Y. K., Lai, Z., Hao, S., Chen, S., Xu, H., ... & Liu, D. (2014). On the mechanisms of the recurvature of super typhoon Megi. Scientific Reports, 4(1), 4451.

Prakash, K. R., & Pant, V. (2017). Upper oceanic response to tropical cyclone Phailin in the Bay of Bengal using a coupled atmosphere-ocean model. Ocean Dynamics, 67, 51-64.

Prasad, V. S., Dutta, S., Pattanayak, S., Johny, C. J., George, J. P., Kumar, S., & Rani, S. I. (2021). Assimilation of satellite and other data for the forecasting of tropical cyclones over NIO. MAUSAM, 72(1), 107-118.

Price, J. F. (1981). Upper ocean response to a hurricane. Journal of Physical Oceanography, 11(2), 153-175.

Price, J. F. (1983). Internal wave wake of a moving storm. Part I. Scales, energy budget and observations. Journal of Physical Oceanography, 13(6), 949-965.

Price, J. F., Sanford, T. B., & Forristall, G. Z. (1994). Forced stage response to a moving hurricane. Journal of Physical Oceanography, 24(2), 233-260.

Rakesh, V., & Goswami, P. (2011). Impact of background error statistics on forecasting of tropical cyclones over the north Indian Ocean. Journal of Geophysical Research: Atmospheres, 116(D20).

Rappin, E. D., Nolan, D. S., & Emanuel, K. A. (2010). Thermodynamic control of tropical cyclogenesis in environments of radiative-convective equilibrium with shear. Quarterly Journal of the Royal Meteorological Society, 136(653), 1954-1971.

Riehl, H. (1972). Intensity of recurved typhoons. Journal of Applied Meteorology (1962-1982), 613-615.

Routray, A., Dutta, D., & George, J. P. (2019). Evaluation of track and intensity prediction of tropical cyclones over North Indian Ocean using NCUM global model. Pure and Applied Geophysics, 176, 421-440.

Roxy, M. K., Dasgupta, P., McPhaden, M. J., Suematsu, T., Zhang, C., & Kim, D. (2019). Twofold expansion of the Indo-Pacific warm pool warps the MJO life cycle. Nature, 575(7784), 647-651.

Ruf, C. S., Atlas, R., Chang, P. S., Clarizia, M. P., Garrison, J. L., Gleason, S., ... & Zavorotny,

V. U. (2016). New ocean winds satellite mission to probe hurricanes and tropical convection. Bulletin of the American Meteorological Society, 97(3), 385-395.

Sadhuram, Y. (2004). Record decrease of sea surface temperature following the passage of a super cyclone over the Bay of Bengal. Indian Academy of Sciences.

Saji, N. H., & Yamagata, T. (2003). Structure of SST and surface wind variability during Indian Ocean dipole mode events: COADS observations. Journal of Climate, 16(16), 2735- 2751.

Saji, N. H., Goswami, B. N., Vinayachandran, P. N., & Yamagata, T. (1999). A dipole mode in the tropical Indian Ocean. Nature, 401(6751), 360-363.

Saji, N. H., Xie, S. P., & Yamagata, T. (2006). Tropical Indian Ocean variability in the IPCC twentieth-century climate simulations. Journal of Climate, 19(17), 4397-4417.

Sampson, C. R., & Schrader, A. J. (2000). The automated tropical cyclone forecasting system (version 3.2). Bulletin of the American Meteorological Society, 81(6), 1231-1240.

Sanford, T. B., Price, J. F., & Girton, J. B. (2011). Upper-ocean response to Hurricane Frances (2004) observed by profiling EM-APEX floats. Journal of Physical Oceanography, 41(6), 1041-1056.

Schreck, C. J., Molinari, J., & Aiyyer, A. (2012). A global view of equatorial waves and tropical cyclogenesis. Monthly Weather Review, 140(3), 774-788.

Sengupta, D., Goddalehundi, B. R., & Anitha, D. S. (2008). Cyclone-induced mixing does not cool SST in the post-monsoon north Bay of Bengal. Atmospheric Science Letters, 9(1), 1-6.

Shapiro, L. J., & Ooyama, K. V. (1990). Barotropic vortex evolution on a beta plane. Journal of Atmospheric Sciences, 47(2), 170-187.

Sharma, N., & Ali, M. M. (2014). Importance of ocean heat content for cyclone studies. Oceanography: Open Access, 1-4.

Shay, L. K., Black, P. G., Mariano, A. J., Hawkins, J. D., & Elsberry, R. L. (1992). Upper ocean response to Hurricane Gilbert. Journal of Geophysical Research: Oceans, 97(C12), 20227-20248.

Shay, L. K., Goni, G. J., & Black, P. G. (2000). Effects of a warm oceanic feature on Hurricane Opal. Monthly Weather Review, 128(5), 1366-1383.

Sieglaff, J. M., Schmit, T. J., Menzel, W. P., & Ackerman, S. A. (2009). Inferring convective weather characteristics with geostationary high spectral resolution IR window measurements: A look into the future. Journal of Atmospheric and Oceanic Technology, 26(8), 1527-1541.

Singh, K. S., & Bhaskaran, P. K. (2020). Prediction of landfalling Bay of Bengal cyclones during 2013 using the high resolution Weather Research and Forecasting model. Meteorological Applications, 27(1), e1850.

Singh, K., Panda, J., & Kant, S. (2020). A study on variability in rainfall over India contributed by cyclonic disturbances in warming climate scenario. International Journal of Climatology, 40(6), 3208-3221.

Singh, K., Panda, J., Osuri, K. K., & Vissa, N. K. (2016). Progress in tropical cyclone predictability and present status in the North Indian Ocean region. Recent developments in tropical cyclone dynamics, prediction, and detection, 1, 193.

Singh, K., Panda, J., Sahoo, M., & Mohapatra, M. (2019). Variability in tropical cyclone climatology over North Indian Ocean during the period 1891 to 2015. Asia-Pacific Journal of Atmospheric Sciences, 55, 269-287.

Singh, O. P., Ali Khan, T. M., & Rahman, M. S. (2000). Changes in the frequency of tropical cyclones over the North Indian Ocean. Meteorology and Atmospheric physics, 75(1-2), 11-20.

Singh, V. K., Roxy, M. K., & Deshpande, M. (2021). Role of warm ocean conditions and the MJO in the genesis and intensification of extremely severe cyclone Fani. Scientific reports, 11(1), 1-10.

Sreenivas, P., & Gnanaseelan, C. (2013). Impact of oceanic processes on the life cycle of severe cyclonic storm “Jal”. IEEE Geoscience and Remote Sensing Letters, 11(2), 519-523.

Sun, J., Oey, L. Y., Chang, R., Xu, F., & Huang, S. M. (2015). Ocean response to typhoon Nuri (2008) in western Pacific and South China Sea. Ocean Dynamics, 65, 735-749.

Thu, T. V., & Krishnamurti, T. N. (1992). Vortex initialization for typhoon track prediction. Meteorology and Atmospheric Physics, 47, 117-126.

Tiwari, G., Rameshan, A., Kumar, P., Javed, A., & Mishra, A. K. (2022). Understanding the post-monsoon tropical cyclone variability and trend over the Bay of Bengal during the satellite era. Quarterly Journal of the Royal Meteorological Society, 148(742), 1-14.

Torn, R. D., & Snyder, C. (2012). Uncertainty of tropical cyclone best-track information. Weather and Forecasting, 27(3), 715-729.

Trenberth, K. E., & Stepaniak, D. P. (2001). Indices of el Niño evolution. Journal of climate, 14(8), 1697-1701.

Tsuboi, A., & Takemi, T. (2014). The interannual relationship between MJO activity and tropical cyclone genesis in the Indian Ocean. Geoscience Letters, 1, 1-6.

Velden, C., Harper, B., Wells, F., Beven, J. L., Zehr, R., Olander, T., ... & McCrone, P. (2006). The Dvorak tropical cyclone intensity estimation technique: A satellite-based method that has endured for over 30 years. Bulletin of the American Meteorological Society, 87(9), 1195-1210.

Vincent, E. M., Lengaigne, M., Madec, G., Vialard, J., Samson, G., Jourdain, N. C., ... & Jullien, S. (2012). Processes setting the characteristics of sea surface cooling induced by tropical cyclones. Journal of Geophysical Research: Oceans, 117(C2).

Vinod, K. K., Soumya, M., Tkalich, P., & Vethamony, P. (2014). Ocean-atmosphere interaction during Thane cyclone: a numerical study using WRF.

Wahiduzzaman, M., Oliver, E. C., Wotherspoon, S. J., & Holbrook, N. J. (2017). A climatological model of North Indian Ocean tropical cyclone genesis, tracks and landfall. Climate Dynamics, 49, 2585-2603.

Wahiduzzaman, M., Yeasmin, A., Luo, J. J., Quadir, D. A., Van Amstel, A., Cheung, K., & Yuan, C. (2021). Markov Chain Monte Carlo simulation and regression approach guidedby El Niño–Southern Oscillation to model the tropical cyclone occurrence over the Bay of Bengal. Climate Dynamics, 56, 2693-2713.

Wang Bin, R. L., Yuqing, W., & Liguang, W. (1999). Dynamics in tropical cyclone motion: A review. Chinese Journal of Atmospheric Sciences, 22(4), 416-434.

Wang, B., & Moon, J. Y. (2017). An anomalous genesis potential index for MJO modulation of tropical cyclones. Journal of Climate, 30(11), 4021-4035.

Weber, H. C. (2003). Hurricane track prediction using a statistical ensemble of numerical models. Monthly Weather Review, 131(5), 749-770.

Webster, P. J., Holland, G. J., Curry, J. A., & Chang, H. R. (2005). Changes in tropical cyclone number, duration, and intensity in a warming environment. Science, 309(5742), 1844- 1846.

Webster, P. J., Moore, A. M., Loschnigg, J. P., & Leben, R. R. (1999). Coupled ocean– atmosphere dynamics in the Indian Ocean during 1997–98. Nature, 401(6751), 356-360.

Webster, P. J. (2008). Myanmar's deadly daffodil. Nature Geoscience, 1(8), 488-490.

Wei, N., Li, Y., Zhang, D. L., Mai, Z., & Yang, S. Q. (2016). A statistical analysis of the relationship between upper-tropospheric cold low and tropical cyclone track and intensity change over the western North Pacific. Monthly Weather Review, 144(5), 1805- 1822.

Williford, C. E., Krishnamurti, T. N., Torres, R. C., Cocke, S., Christidis, Z., & Kumar, T. V. (2003). Real-time multimodel superensemble forecasts of Atlantic tropical systems of 1999. Monthly weather review, 131(8), 1878-1894.

Wu, G., Ren, S., Xu, J., Wang, D., Bao, Q., Liu, B., & Liu, Y. (2013). Impact of tropical cyclone development on the instability of South Asian High and the summer monsoon onset over Bay of Bengal. Climate dynamics, 41, 2603-2616.

Wu, L., Wang, B., & Braun, S. A. (2005). Impacts of air–sea interaction on tropical cyclone track and intensity. Monthly weather review, 133(11), 3299-3314.

Wu, R., & Li, C. (2018). Upper ocean response to the passage of two sequential typhoons. Deep Sea Research Part I: Oceanographic Research Papers, 132, 68-79.

Wu, R., Zhang, H., & Chen, D. (2020). Effect of Typhoon Kalmaegi (2014) on northern South China Sea explored using Muti-platform satellite and buoy observations data. Progress in Oceanography, 180, 102218.

Yamada, H., Moteki, Q. and Yoshizaki, M. (2010) The unusual track and rapid intensification of cyclone Nargis in 2008 under a characteristic environmental flow over the Bay of Bengal. Journal of the Meteorological Society of Japan, 88, 437–453.

Yang, B., Hou, Y., Hu, P., Liu, Z., & Liu, Y. (2015). Shallow ocean response to tropical cyclones observed on the continental shelf of the northwestern S outh C hina S ea. Journal of Geophysical Research: Oceans, 120(5), 3817-3836.

Ying, Y., & Zhang, F. (2017). Practical and intrinsic predictability of multiscale weather and convectively coupled equatorial waves during the active phase of an MJO. Journal of the Atmospheric Sciences, 74(11), 3771-3785.

Yuan, J., & Cao, J. (2013). North Indian Ocean tropical cyclone activities influenced by the Indian Ocean Dipole mode. Science China Earth Sciences, 56, 855-865.

Fan, Y., & Van den Dool, H. (2008). A global monthly land surface air temperature analysis for 1948–present. Journal of Geophysical Research: Atmospheres, 113(D1).

Zedler, S. E., Dickey, T. D., Doney, S. C., Price, J. F., Yu, X., & Mellor, G. L. (2002). Analyses and simulations of the upper ocean's response to Hurricane Felix at the Bermuda Testbed Mooring site: 13–23 August 1995. Journal of Geophysical Research: Oceans, 107(C12), 25-1.

Zedler, S. E., Niiler, P. P., Stammer, D., Terrill, E., & Morzel, J. (2009). Ocean's response to Hurricane Frances and its implications for drag coefficient parameterization at high wind speeds. Journal of Geophysical Research: Oceans, 114(C4).

Zhang, H., Chen, D., Zhou, L., Liu, X., Ding, T., & Zhou, B. (2016). Upper ocean response to typhoon Kalmaegi (2014). Journal of Geophysical Research: Oceans, 121(8), 6520- 6535.

Zhang, H., Liu, X., Wu, R., Chen, D., Zhang, D., Shang, X., ... & Zhang, W. (2020). Sea surface current response patterns to tropical cyclones. Journal of Marine Systems, 208, 103345.

Zhang, W., Leung, Y., & Chan, J. C. (2013). The analysis of tropical cyclone tracks in the western North Pacific through data mining. Part I: Tropical cyclone recurvature. Journal of applied meteorology and climatology, 52(6), 1394-1416.

Zhao, C., & Li, T. (2019). Basin dependence of the MJO modulating tropical cyclone genesis. Climate Dynamics, 52(9-10), 6081-6096.

Zhao, H., Yoshida, R., & Raga, G. B. (2015). Impact of the Madden–Julian oscillation on western North Pacific tropical cyclogenesis associated with large-scale patterns. Journal of Applied Meteorology and Climatology, 54(7), 1413-1429.

Zou, X., Weng, F., Zhang, B., Lin, L., Qin, Z., & Tallapragada, V. (2013). Impacts of assimilation of ATMS data in HWRF on track and intensity forecasts of 2012 four landfall hurricanes. Journal of Geophysical Research: Atmospheres, 118(20), 11-558.

Zupanski, M. (2013). All-sky satellite radiance data assimilation: Methodology and challenges. Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications (Vol. II), 465-488.