Cyclone warning services in India during recent years: A review

M. MOHAPATRA and M. SHARMA

India Meteorological Department, New Delhi – 110 003, India

e mail : mohapatraimd@gmail.com

सार - भारत को विभिन्न प्रकार की प्राकृतिक आपदाओं का सामना करना पड़ता है, जिनमें चक्रवात, बाढ़, सूखा, भूकंप, भूस्खलन, उष्ण लहर, शीत लहर, गरज वाले चंडवात और बवंडर शामिल हैं। अधिकांश आपदाएँ (लगभग 80%) जल मौसम विज्ञान से संबंधित हैं। जल मौसम विज्ञान से संबंधित आपदाओं में, उत्तरी हिंद महासागर (NIO) में बने चक्रवात, तटीय आबादी और इस क्षेत्र के समुद्र पर निर्भर व्यवसाय वाले समुदाय के लिए एक संभावित खतरा पैदा करते हैं। चक्रवातों का जोखिम प्रबंधन कई कारकों पर निर्भर करता है, जिसमें (*i*) आपदा और सुभेद्यता विश्लेषण, (*ii*) तैयारी और योजना, (*iii*) प्रारंभिक चेतावनी, (*iv*) रोकथाम और शमन शामिल हैं। प्रारंभिक चेतावनी के घटक में (*i*) निगरानी और पूर्वानुमान में कौशल (*ii*) प्रभावी चेतावनी उत्पाद का निर्माण और प्रसार (*iii*) आपदा पर कार्रवाई करने वाली इकाइयों के साथ समन्वय और (*iv*) भारत मौसम विज्ञान विभाग (IMD) द्वारा जारी चक्रवात की प्रारंभिक चेतावनी की विश्वसनीयता के बारे में सार्वजनिक धारणा और जागरूकता शामिल हैं। हालांकि हाल ही के वर्षों में भारत सरकार के पृथ्वी विज्ञान मंत्रालय (MoES)/IMD और नीति फ्रेम वर्क के आधुनिकीकरण कार्यक्रम के कारण चक्रवात की निगरानी और चेतावनी प्रणाली में उल्लेखनीय सुधार हुआ है, फिर भी राज्य और जिला स्तर पर अभी सुधार की गुंजाइश है जैसे (*i*) चक्रवात से संबंधित मेसोस्केल पर खतरे का पता लगाने और निगरानी में सुधार, (*ii*) तकनीकी उन्नयन के माध्यम से पूर्वानुमान के स्थानिक और कालिक पैमाने में सुधार, (*iii*) अत्याधुनिक प्रौद्योगिकी के माध्यम से राज्य के अंतिम छोर के व्यक्ति और आपदा प्रबंधकों के लिए चेतावनी का संचार, (*iv*) प्रारंभिक चेतावनी एजेंसियों और उपयोगकर्ता एजेंसियों के बीच समन्वित मानक संचालन प्रक्रिया विकसित करना और (*v*) वास्तविक समय पर सही पूर्वानुमान तथा जोखिम आधारित चेतावनी देना। यहाँ जलवायु विशेषताओं (स्थानिक और लौकिक वितरण और तीव्रता आदि) की इन सभी पहलुओं पर विशेष जोर देने, क्षति क्षमता, मॉडलिंग और पूर्वानुमान, पूर्वानुमान कौशल, सूचना प्रसार तंत्र, सामाजिक-आर्थिक प्रभावों, हाल के वर्षों में हुई उपलब्धियों, मौजूदा अंतराल क्षेत्रों और भविष्य की संभावनाओं पर चर्चा की गई है।

ABSTRACT. India experiences various types of natural hazards including cyclones, floods, droughts, earthquake, landslides, heat wave, cold wave, thunder squalls and tornadoes. Most of these hazards (about 80%) are hydro-meteorological in nature. Among the hydrometeorological hazards, the cyclones over the North Indian Ocean (NIO) pose a potential threat to coastal population as well as marine community of the region. The risk management of the cyclones depends on several factors including (*i*) hazard & vulnerability analysis, (*ii*) preparedness & planning, (*iii*) early warning, (*iv*) prevention and mitigation. The early warning component includes (*i*) skill in monitoring and prediction, (*ii*) effective warning products generation and dissemination, (*iii*) coordination with disaster response units and (*iv*) public awareness & perception about the credibility of early warning of cyclone issued by India Meteorological Department (IMD). Though there have been significant improvement in cyclone monitoring and warning system in recent years due to modernization programme of Ministry of Earth Sciences (MoES)/IMD and policy frame work of Govt of India, there is still scope for improvement at state and district level in terms of (*i*) improving the mesoscale hazard detection and monitoring in association with cyclone, (*ii*) improving the spatial and temporal scale of forecasts through technological upgradation, (*iii*) warning communication to last mile and disaster managers through state of art technology, (*iv*) developing synergized standard operation procedure among the early warning agencies and user agencies and (*v*) real time impact based forecast and risk based warning. All these aspects have been discussed with special emphasis on climatological characteristics (spatial and temporal distribution and intensity etc.), damage potential, modeling and prediction, Prediction skills, information dissemination mechanisms, socio-economic impacts, achievements in recent years, existing gap areas and future scope.

Key words – Tropical cyclones, Early warning, Disaster management.

1. Introduction

The tropical warm north Indian Ocean (NIO), like the tropical north Atlantic, the south Pacific and the northwest Pacific, is a breeding ground for the disastrous tropical cyclone (TC) phenomenon. Low lying coastal belts of West Bengal, Odisha and Andhra Pradesh have borne the brunt of the fury of these very severe TCs (IMD, 2003, 2008; Mohapatra *et al*., 2012a; Mohapatra, 2015a). Historically, in terms of loss to human life, the Bay of
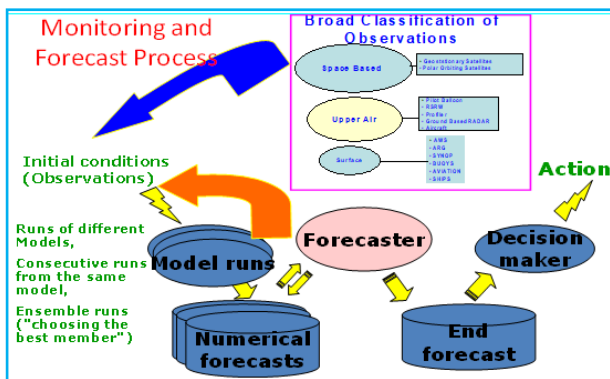
Fig. 1. Monitoring and Forecasting process of tropical cyclone (Mohapatra *et al.*, 2013b)

Bengal TCs accounted for deaths ranging from a thousand to three hundred thousand. The Bay of Bengal has experienced more than 75% of the total world-wide TCs causing human death of 5000 or more in last 300 years (Dube *et al*., 2013). Highest mortality associated with a TC has been recorded in Bangladesh (at time of incident, East Pakistan) Cyclone of 12-13 November 1970 with an estimated death toll of 300,000 people (Cerveny *et al*., 2017). The extremely severe cyclonic storm (ESCS) ''Phailin (2013)'' was the strongest cyclone (Mohapatra *et al.*, 2014a) that hit the eastern coast of the India (Odisha state) with a wind speed of 215 kmph gusting to 235 kmph since the super cyclone of 1999, which crossed the coast near Paradip with a wind speed of 260 kmph (Mohapatra *et al*., 2002). But the same story of casualties was not repeated as that of 1999 where approximately 10000 fatalities were reported. In the case of Phailin, a record 1 million people were evacuated across 18000 villages in both Odisha and Andhra Pradesh states to coastal shelters following the improved operational forecast guidance that benefited from highly skillful and accurate numerical model guidance for the movement, intensity, rainfall and storm surge (Mohanty *et al*., 2015). Thus, the property damage and death toll were minimized to 22 through the proactive involvement of three-tier disaster management agencies at central, state and district levels.

It is important to continuously upgrade all the components of early warning based on latest technology for effective management of TCs. The reduction of cyclone disasters depends on several factors including hazard analysis, vulnerability analysis and preparedness & planning, early warning, prevention and mitigation. The early warning is a major component for the south Asian region due to its socio-economic conditions. The early warning component includes skill in monitoring and prediction of cyclone, effective warning products generation and dissemination, coordination with

emergency response units and the public perception about the credibility of the official predictions and warnings. The entire process of cyclone early warning system is shown in a schematic diagram (Fig. 1). Details of the efforts made during the past is reviewed by Rathore *et al*. (2017); Mohapatra *et al*., 2014b; Mohapatra *et al*., 2013a&b; Mohapatra, 2017a; Mohapatra, 2015b.

The above success in reducing the loss of human lives has been possible due to modernised early warning system for TC which maximized the relevance and effectiveness of the cyclone warning during emergent situations. The above objective was accomplished (Mohapatra *et al*., 2013b) through:

(*i*)   Modernisation of observational system

(*ii*)   Modernisation of cyclone analysis and prediction system

(*iii*)   Updation of Standard Operation Procedure (SOP) for Cyclone monitoring and forecasting

(*iv*)   Institutional mechanism with various numerical weather prediction (NWP) modeling centres and disaster management agencies

(*v*)   Building Forecast Demonstration Projects on landfalling cyclones

(*vi*)   Value added warning products generation, presentation & dissemination

(*vii*)   Measures for enhancing confidence of disaster managers and public in forecast and warning through forecast verification and preparation of reports

(*viii*) Capacity building through training.

Here, a review has been made with respect to climatological aspects, hazard proneness of India and climate change aspects of TC over the NIO. Also the monitoring, prediction, physical understanding and warning services for cyclones over the Bay of Bengal and Arabian Sea region have been reviewed to find out the gap areas and future scope.

2.   Climatological characteristics of cyclones over the NIO

2.1. *Frequency of genesis and intensification*

Generally, under favourable environmental conditions, a pre-existing low pressure area develops into a cyclonic disturbance (CD) [maximum sustained wind speed (MSW)

TABLE 1

Classification cyclonic disturbances over the NIO (since 2015)

Low pressure system	Maximum sustained surface winds
Low pressure area (L)	< 17 knots
Depression (D)	17 - 27 kts
Deep Depression (DD)	28 - 33 kts
Cyclonic storm (CS)	34 - 47 kts
Severe Cyclonic storm (SCS)	48 - 63 kts
Very Severe Cyclonic storm(VSCS)	64 - 89 kts
Extremely Severe Cyclonic Storm (ESCS)	90 - 119 knots
Super Cyclonic storm (SuCS)	120 kts & above

of 17 knots or more] which intensifies into a TC (MSW: 34 knots or more) or a severe TC (MSW of 48 knots or more) or even a very severe TC (MSW of 64 knots or more). Detailed classification is shown in Table 1 (WMO, 2016). The 'cyclone' is a generic term associated with a low pressure system with MSW of 34 knots or more.

On an average, about 11 CDs develop over the NIO during a year including 9 and 2 over the BOB and AS (Mohapatra *et al.*, 2014b). Out of these, about five intensify into TC (4 over BOB and 1 over the AS), 3 into severe TC (2 over the BOB and 1 over the AS) and 1-2 into very severe TC. It accounts for about 7 percent of the global cyclones. The frequency of TC shows bimodal behavior with primary peak in November and secondary peak in May (Fig. 2). Similar is the case with severe TCs. However, the frequency of CDs (depression and TCs) does not show such behavior as maximum number of depressions form during monsoon season. The frequency of CDs shows maxima in October followed by November (Fig. 2).

About 50% of the depressions develop into TC intensity and only less than 25% of TC further intensify into severe TCs (Mohapatra *et al.*, 2015a). While it takes about 2 to 4 days to develop a low pressure area into a depression/deep depression, the intensification from a depression/deep depression to severe or very severe cyclones can occur in 24- to 48- hrs (IMD, 2003).

2.2. *Movement*

The track of the TCs during 1961-2018 are shown in Fig. 3. The TCs predominantly move west-northwestwards to northwestwards (Chinchole and Mohapatra, 2017). According to Chinchole and Mohapatra (2017), based on the data of 1990-2013, the 06-, 12- and 24- h average

translational speeds of CDs over the NIO are about 13.9, 13.6 and 13.0 kmph, respectively. The average speed is higher over the BOB than over the AS, as 6, 12 and 24- h average speed is about 14.3, 13.9 and 13.4 kmph over the BOB against 13.1, 12.8 and 12.5 kmph over the AS respectively. The translational speed is higher in the stage of VSCS and above in both the basins and in different seasons. Comparing the translational speeds in different seasons, it is minimum during winter seasons for all types of disturbances in both the Ocean basins. Comparing the translational speeds in different seasons over the AS, the speed is higher in monsoon followed by pre-monsoon season in case of D, higher in post-monsoon followed by monsoon season in case of CS or higher intensity of the disturbance. In case of DD, it is higher in post-monsoon followed by pre-monsoon season. Considering BOB, the translational speed is maximum in monsoon followed by pre-monsoon season in case of D, DD, CS and followed by post-monsoon in case of SCS. There is no significant difference in translational speeds in case of VSCS and SuCS during pre-monsoon and post-monsoon seasons. Nayak and Mohapatra (2017) analysing the rapid movement of TC, Viyaru (May, 2013) before landfall over Bangladesh, found that the translational speed increased significantly under the influence of middle to upper tropospheric westerly trough in middle to upper troposphere lying to the west of cyclone centre. The higher translation speed during monsoon season can be attributed to higher mean wind over the north BoB and central & northern India in middle and upper troposphere in association with Tibetan High. Similarly, the higher translational speed for the VSCS in post monsoon season may be attributed to the stronger mean wind due to mid latitude westerlies over the region. however, it needs to be established considering the past data sets.

The TCs crossing different coastal states during 1961-2018 are shown in Figs. 4(a&b). The BoB TCs more often strike Odisha-West Bengal coast in October, Andhra coast in November and the Tamil Nadu coast in December (Tyagi *et al.*, 2010). Over 48 percent of the TCs in the BoB strike different parts of the east coast of India, 26 percent strike coasts of Bangladesh &Myanmar, 6 percent cross Sri Lanka and about 20 percent dissipate over the sea itself. Percentage of cyclones dissipating over the AS is higher (63%) as the western Arabian Sea is cooler. Maximum landfall occurs over Gujarat coast (18% of total cyclones in AS) of India followed by Oman coast.

2.3. *Life period*

According to Kumar *et al.* (2017), based on the data of 1990-2013, the average life period of CDs over the NIO is about 2, 3, 3.5, 4, 5 and 5.75 days respectively for D, DD, CS, SCS, VSCS and SuCS. Although the VSCS stage
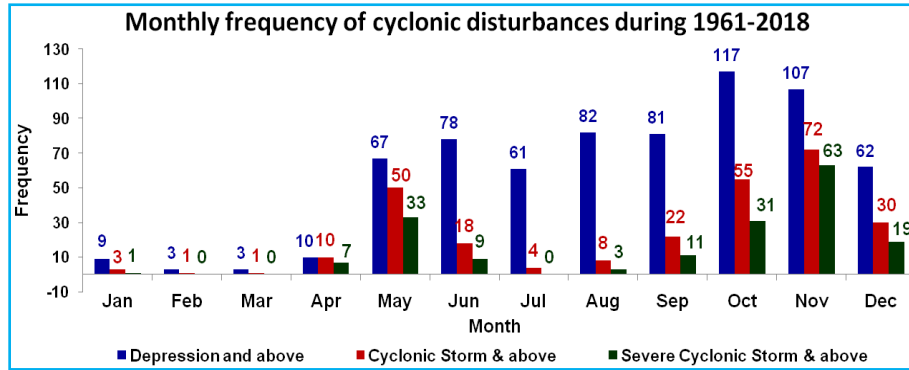
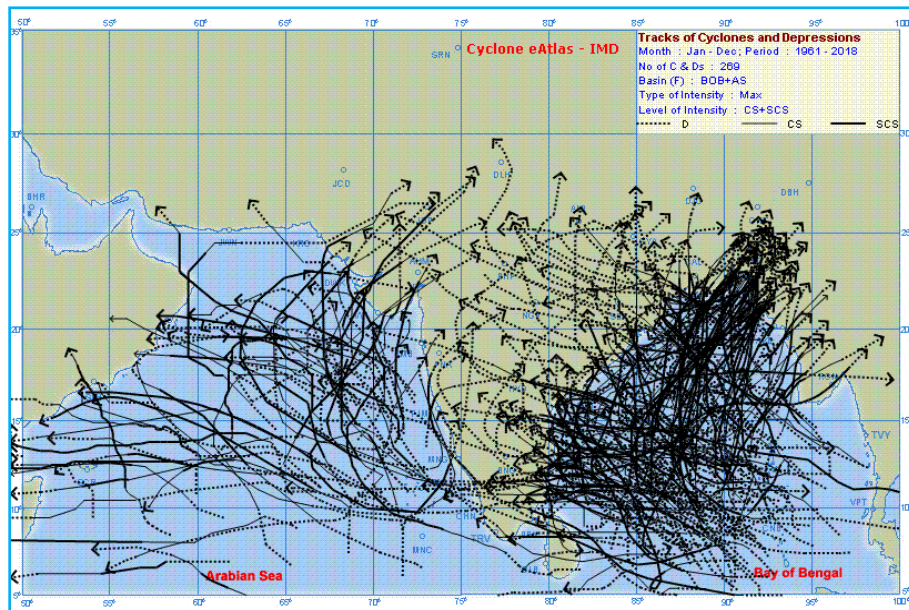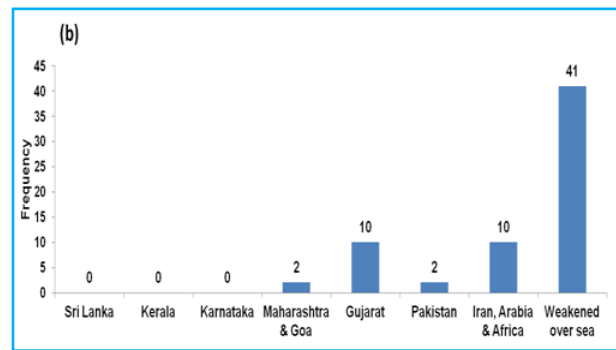**Fig. 2.** Monthly frequency of cyclonic disturbances during 1961-2018 over NIO (*Source*: IMD, 2008)
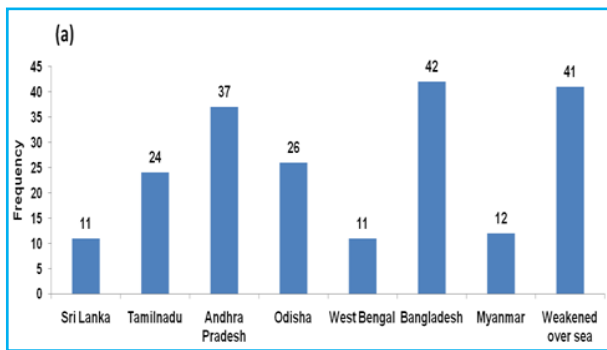

Fig. 3. Tracks of TCs (CS & SCS) over the NIO during 1961-2018 (*Source*: IMD, 2008)

Figs. 4(a&b). Frequency of TCs over the (a) BoB and (b) AS landfalling over different coastal states during 1961-2018 (*Source*: IMD, 2008)

has significantly higher duration over the AS than over the BOB in pre-monsoon and the year as a whole, it is significantly higher over the BOB than over the AS during post monsoon season. It is mainly attributed to the fact that the TCs forming over the AS during pre-monsoon season mainly move towards Arabia-Africa and also many of them recurve northeastwards later leading to longer life period in VSCS stage. In the post monsoon season, most of the TCs over the BoB form from the remnants of TCs from south China Sea and are more intense leading to

higher life period in VSCS stage. During the monsoon season, the duration D, DD and CS stages are significantly higher over BOB than they are over the AS as most of the D/DD/CS form as monsoonal system over the BoB and move west-northwestwards along the monsoon trough unlike those over the AS which usually form as onset vortex in June and have limited life period. In respect of cumulative duration of stages, D and above to SCS and above during pre-monsoon, D and above during monsoon season D and above to VSCS and above during post-monsoon as well as the year as a whole are higher over the BOB than over the AS while the cumulative duration of stages of CS and above, SCS and above, VSCS and above are higher over the AS than over the BOB during monsoon season due to the reasons mentioned above. However, it needs further study to establish above attribution.

2.4. *Accumulated cyclone energy (ACE) and power dissipation index (PDI)*

According to Mohapatra and Kumar (2017), the mean velocity flux (VF) of CDs (TCs) per year over the NIO based on data of 1990 - 2013 is about 39×10^2 kt (21 $\times 10^2$ kt) including about 10×10^2 kt (6×10^2 kt) over the AS and 29×10^2 kt (15×10^2 kt) over the BOB. The mean accumulated cyclone energy (ACE) per year for CDs (TCs) over the NIO is about 18×10^4 kt^2 (13.1×10^4 kt^2) including 13×10^4 kt^2 (9.5×10^4 kt^2) over the BOB and 5×10^4 kt^2 (3.6×10^4 kt^2) over the AS. The mean power dissipation index (PDI) per year for CDs (TCs) over the NIO is about 11×10^6 kt^3 (10×10^6 kt^3) including 3×10^6 kt^3 (3×10^6 kt^3) over the AS and 8×10^6 kt^3 (7×10^6 kt^3) over the BOB. Thus VF, ACE and PDI over BoB and AS are in the ratio of 2.8:1 (2.6:1), 2.7:1 (2.7:1) and 2.7:1 (2.3:1) respectively against the ratio of genesis frequency as 3.2:1 (2.2:1) for CDs (TCs). Hence the ratio of VF/ACE/PDI over BOB and AS is not in complete agreement with the genesis frequency, as these metrics also depend on duration and intensity of CDs and TCs like other Ocean basins. Comparing the energy metrics over the BOB and AS, the VF, ACE and PDI of both CDs and TCs are significantly higher over BOB than over AS during post-monsoon season and year as a whole. The VF and ACE of TC are higher over the AS than over the BOB during monsoon season. The VF of TC and VF & ACE of CD are higher over the BOB than over the AS during pre-monsoon season. Comparing the energy metrics in different seasons, the VF, ACE and PDI are significantly higher during the post-monsoon than in monsoon season in case of both CDs and TCs and higher in pre-monsoon than in monsoon season for TCs only over both the BOB and the NIO as a whole. It is significantly higher in post-monsoon than in pre-monsoon season in case of VF of TC and VF and ACE of CDs over the BOB and NIO. There is no significant difference in the values of VF, ACE and

PDI over the AS in different seasons. While the annual VF and PDI per year are more dependent on intensity, ACE is more but equally dependent on intensity and duration of TC over the NIO. All the above three annual metrics are relatively less dependent on genesis frequency of TC over the NIO. However, this relation changes when we consider BOB and AS as well as different seasons.

Considering the impact of ENSO, the VF, ACE and PDI are significantly less over BOB during post-monsoon season of El Nino years than in La Nina and normal years. There is no significant difference in VF/ACE/PDI over BOB during post-monsoon season of La Nina and normal years. There is significantly negative correlation of SST anomaly over Nino 3.4 region with VF/ACE/PDI over the BOB and hence NIO during post-monsoon season and no significant correlation during pre-monsoon season for all the Ocean basins under consideration.

Considering the impact of IOD, the VF for TCs over the BOB during post-monsoon season is significantly less (higher) during positive (negative) IOD years. There is no significant difference in energy metrics with respect to IOD index in pre-monsoon season over BOB and both the seasons over the AS for both CDs and TCs. The VF, ACE and PDI over the BOB are significantly higher in post-monsoon seasons with both La Nina and negative IOD conditions than with El Nino and positive IOD conditions. However, this combined influence has no impact during pre-monsoon season over the BOB and both pre- and post-monsoon seasons over the AS.

2.5. *TC structure*

According to Mohapatra and Sharma (2015), based on the data during 2007-2013, the average size of TC (radius of 34 kts wind) over the AS is about 43, 72, 120 nm respectively in case of CS, SCS, VSCS during pre-monsoon season and 70 nm in case of both CS & SCS during post monsoon season. Similarly, the average size of TC over BoB is about 73, 64 and 107 nm in case of CS, SCS & VSCS respectively during pre-monsoon season and 57, 64, 102 nm during post monsoon season. The size of the SuCS, which occurred during pre-monsoon season over the AS and post-monsoon season over the BOB is about 120 and 130 nm respectively. The size of outer core (34 knot wind radial extension) as well as inner core winds (50 and 64 knot wind radial extension) increases significantly with increase in intensification of TC over BOB during both pre-monsoon and post-monsoon seasons. Over the AS, the size of outer core of the TC increases with increase in intensity during pre-monsoon season and no significant change during post-monsoon season. The size of outer core (34 knot wind radial extension) as well

as inner core winds (50 and 64 knot wind radial extension) increases significantly with increase in intensification of TC over BOB during both pre-monsoon and post-monsoon seasons. Over the AS, the size of outer core of the TC increases with increase in intensity during pre-monsoon season and no significant change during post-monsoon season. The average sizes of outer core wind of the TCs over the BOB and AS as well as during pre-monsoon and post-monsoon seasons differ from each other in case of CS stage only. The average size of CS is higher in pre-monsoon than in post-monsoon season over the AS and opposite is the case over the BOB. The average size of the CS over BOB is higher than that over the AS during pre-monsoon season and there is no significant difference during post-monsoon season. Though overall size (radius of 34 knot wind) of the TC during pre-monsoon season is larger over BOB, as compared to that over the AS, the inner core is smaller. In case of 64 knot wind, the radius in case of TC over the BOB is almost half of that over the AS. The outer core of winds in TCs over the BOB is asymmetric in both pre-monsoon and post-monsoon seasons and for all categories of intensity of TCs. The region of higher radial extent shifts from southern sector in CS stage to northern sector in SCS/VSCS stage of TCs over the BOB during post-monsoon season. On the other hand, the asymmetry in inner core winds is significantly less during both the seasons and all categories of intensity. There is also no asymmetry in radial wind extension over the AS during both the seasons, except in case of outer core wind radial extension of VSCS during pre-monsoon season. It has been observed that the low level environment like enhanced cross equatorial flow, middle level relative humidity, thermal asymmetry, vertical wind shear and proximity of TC to the land surface are the determining factors for the size and asymmetry of TCs over the NIO. The asymmetry is higher in the sector associated with higher relative humidity, higher vertical wind shear, higher cross equatorial flow/embedded monsoon circulation.

3. Climate change and TC over the NIO

3.1. *Trend in frequency and location of genesis*

There is no significant trend in frequency of CDs excluding the short lived systems (life period of less than a day) over the BOB and AS during 1891-2010 (Mohapatra *et al.*, 2012b). Considering the trend in frequency of CDs during satellite era (1961-2010), there is significant (at 95% level of confidence) decreasing trend in frequency of CDs over the BOB and NIO and no trend over the AS (Mohapatra *et al.*, 2014b). The frequency of CD has decreased at the rate of 1.6 per decade and 1.5 per decade over the NIO and BOB respectively. This trend is

mainly due to the decreasing trend in frequency of CDs during monsoon season. Considering the frequency of (*i*) TCs, (*ii*) severe TCs and (*iii*) very severe TCs during satellite era (1961-2010), there are significant (at 95% level of confidence) decreasing trends in all these frequencies over the BOB and NIO as a whole (Mohapatra *et al.*, 2013c and 2014b). The frequency of TCs has decreased at the rate of about 0.7 per decade and 0.6 per decade respectively over the NIO and BOB. The frequency of SCS or higher intensity storms has decreased at the rate of about 0.5 per decade each over the NIO and BOB. The frequency of very severe TC has decreased at the rate of about 0.56 per decade over the NIO. There is no significant trend in the above frequencies over the AS. Mandal and Prem Krishna (2009) have also shown decreasing trend of frequency of very severe TC over the NIO during 1965-2008 and no trend in the MSW associated with VSCS during the same period. Thus past studies indicate that there has been decreasing trend of CDs, TCs, severe TCs and very severe TCs over the BOB and NIO and no trend over the AS.

According to Mohapatra *et al*. (2015a) and Mohapatra *et al*. (2017a), significant decreasing trends in the frequencies of CDs as well as TCs are observed for the monsoon season and year as a whole over BOB and hence over the NIO for the period 1901-2010. There is a decrease of about 3 CDs including 2 TCs during a year from the beginning of 20th century to the beginning of 21st century over the BOB and hence the NIO. However, there is a significant increasing trend in severe TCs (0.7 per 100 years) during the post-monsoon season over both BOB and hence NIO during the same period. For the AS, there is a significant increase in the frequency of CDs during the monsoon and the post-monsoon seasons (0.5 and 0.6 per 100 years) and hence in the year as a whole (1.1 per 100 years). Considering the trends in decadal scales, significant decreasing trend in the frequency of TC is also observed for the BOB during the monsoon season (-1.6 per decade) and year as a whole (-1.8 per decade).

According to Mohapatra *et al*. (2015a), based on data of satellite period (1961-2010), when monitoring has been most accurate without missing storms and minimum under/over estimation of intensity, the CD, TC and severe TC frequencies during the last five decades over the BOB and NIO show a significant decreasing trend for the monsoon and post-monsoon seasons and the year as a whole with maximum decrease in the monsoon season in contrast to the data for the period of 1901-1960 which does not show any significant trend.

The past studies show that there has been significant increasing trend in SST over the BOB, AS and NIO during the satellite era (Pattanaik, 2005; Roxy *et al*., 2015;

Elsner & Kocher, 2000). Pattanaik (2005) based on the NOAA SST data during 1891-2004 has shown that the SST over BOB (Lat. 10-25° N and Long. 80-100° E) shows significant increasing trend during pre-monsoon, monsoon and post monsoon seasons. Similar increasing trend is also observed over equatorial Indian Ocean (0° N-10° N, 55° E-95° E). Wang (1995) has also shown a rapid transition to warm state of Indian Ocean since 1978. Thus there is decrease in frequency of CDs, TCs and severe TCs since 1970s, though there is increase in SST over the BOB and NIO.

Examination of role of ENSO on the CD/TC trends indicates that the impact of ENSO has decreased in recent years (Mohapatra *et al.*, 2015a; Mohapatra *et al.*, 2017a). However, in the case of post-monsoon TCs and severe TCs, significantly negative relation has emerged since mid-seventies with concurrent Nino 3.4 and Nino 4 SST and antecedent Nino 3.4 and Nino 4 SST of JJAS, which could be in association with the climate shift over the Pacific in association with Pacific Decadal Oscillation (PDO). It needs further investigation.

Singh *et al.* (2018), based on sea surface temperature (SST) anomaly variation, analysed by dividing the period 1880-2015 into pre-warming period (PWP) during 1880-1946 and current warming period (CWP) during 1947-2015 with negative and positive anomalies respectively. According to them, a clear decreasing trend is seen in annual TC frequency during CWP for NIO region and particularly BOB. However, the TC frequencies were increasing during the PWP. TC activity over southern and northern BOB is decreasing sharply during CWP. Southern sector of BOB hosts mostly severe systems and middle sector most TCs. TC activity over the eastern sector of AS shows considerable enhancement during CWP. An increasing SST, surface wind, mid-tropospheric relative humidity and potential evaporation factor (PEF) are helpful in the formation of intensified storms during CWP. The activities during PWP were reverse compared to that of CWP. A large temperature anomaly difference between atmosphere and Ocean also perceived to play a key role in modulating the enhanced intensity of TCs during CWP. The SST range of 27.5 °C to 29.5 °C and supportive flow field is helping to enhance the middle and upper tropospheric moisture content; eventually, resulting in increased SST, PEF and relative humidity through a possible feedback mechanism. According to Knutson *et al.* (2019), there is significant increase in intense TCs over the AS during pre-monsoon season with a low confidence as the frequency of intense TCs are less and the studies are based on recent years only.

Variability in formation/intensification with respect to the sub-basins is brought out by Mohapatra *et al.*

(2015a) by depicting significant trends in ratio of BOB to AS frequencies of CDs, TCs and severe TCs. The ratio shows significant decreasing trends for CD, TC and severe TC frequencies over BOB compared to that over AS during all the three seasons and hence year as a whole except for pre-monsoon severe TCs which shows a significant increasing trend. Considering the recent 50 years (1961-2010), there is a decreasing trend in the ratio of severe TCs for all the seasons and year as a whole, TCs during monsoon, post-monsoon and year as a whole and CDs during monsoon season and the year as a whole.

The trends in seasonal variability in formation of CDs/TCs/severe TCs are analysed by Mohapatra *et al.* (2015a) and Mohapatra *et al.* (2017a) from the ratio of frequency of CDs/TCs/ severe TCs during post-monsoon to pre-monsoon season. There is an increasing trend in the ratio of CDs, TCs and severe TCs over NIO, BOB and AS over the period of 1901-2010. However, considering the recent five decades, the ratio shows a significant decreasing trend for CDs and severe TCs over the BOB and NIO and increasing trend for TCs over the AS. There is no significant trend in other cases.

On the location of cyclogenesis (Mohapatra *et al.*, 2015a), a northward shift in the mean latitude of formation by about 1° is observed over BOB during the post-monsoon season between the periods 1951-1980 and 1981-2010 (though not significant) and a significant northward shift in the mean latitude of formation over AS during the pre-monsoon season.

3.2. *Trend in rate of intensification*

Regarding trends in intensification, considering the long period of 1901-2010, there are significant decreasing trends in rate of intensification of CDs into TCs during the monsoon and the post-monsoon seasons over the NIO, during the monsoon season over the BOB and during the monsoon and post-monsoon seasons and the year as a whole over the AS (Mohapatra *et al.*, 2015a). However, once formed, intensification of TCs into severe TCs has increased during the recent years as significant increasing trends are observed in the ratio of severe TC to TC frequency during all the seasons and the year as a whole over all the three basins except during the pre-monsoon season over the AS where significant decreasing trend is observed.

According to Mohapatra *et al.* (2015a), there are significant decreasing trends in rate of intensification of CDs to TCs during all the three seasons (pre monsoon, monsoon and postmonsoon) over NIO and BOB in the recent five decades (1961-2010). Over the AS, in contrast to the long term decreasing trends (1901-2010) in rate of

intensification from CD to TC, there is significant increasing trend during all the three seasons and the year as a whole in the recent five decades. Considering the rate of intensification from TC to severe TC, significant decreasing trends are noted in the monsoon and post-monsoon seasons as well as year as a whole over the BOB which is in contrast to the long term increasing trends. Similarly, over the AS, the long term significant decreasing (increasing) trend in rate of intensification of TCs to severe TCs during the pre-monsoon (post-monsoon) season, changes to significantly increasing (decreasing) trend during the satellite era (1961-2010). The rate of intensification of TCs to severe TCs for the monsoon season over the AS, which was significantly positive in the long term, has become insignificant during 1961-2010. Over the NIO as a whole, while the significantly positive annual trend for the long period data has changed to insignificant trend, significantly increasing trend in post-monsoon season has changed into significantly decreasing trend during 1961-2010.

On the environmental influences (Mohapatra *et al.*, 2017a), significant decreasing trend in mid-tropospheric humidity is associated with the decreasing trends in frequency of CDs and their intensification to severe TCs over BOB during post-monsoon season. Interestingly, low level cyclonic vorticity has also decreased over the southern parts of BOB south of 15° N which is the climatological region of cyclogenesis during October to December, but, it has increased over the northern BOB during the recent years. During the pre-monsoon season, the decreasing trend in intensification of CD to TC over BOB is associated with unfavourable decrease in mid-tropospheric humidity. However, enhanced intensification from TC to severe TC could be associated with increased low level cyclonic vorticity over BOB as well as other synoptic scale forcings. During the monsoon season the decreasing trends over the BoB are associated with significant decrease in mid-tropospheric humidity despite increased SST and decreased vertical wind shear.

Over AS, there are increasing trends in intensification of CDs to TCs and TCs to severe TCs which could be in association with decreased vertical wind shear aside from other synoptic scale forcing.

3.3. *Trend in frequency of landfalling TCs*

Tyagi *et al*. (2010) have shown no significant trend in frequency of landfalling CDs over east and west coasts of India during 1891-2007 excluding the short lived systems. Singh *et al*. (2018) analysing the landfalling TCs during CWP and PWP based on sea surface temperature

(SST) anomaly variation found that Bangladesh, Andhra Pradesh (AP) and Tamil Nadu (TN) are more vulnerable to severe TCs formed over BOB during the CWP. Gujarat is prone to severe cyclones and Arabian Peninsula countries are vulnerable to CS formed over the AS during the CWP. During CWP, Bangladesh and Arakan coast are more vulnerable to CD landfall in pre-monsoon season, whereas in post-monsoon months, AP, TN and Bangladesh are more prone coastal areas of BOB. Gujarat and Iran, Arabia & Africa (IAA) are more vulnerable coastal areas of AS irrespective of seasons considered. The enhanced genesis over southern and middle sector of BOB is mainly responsible for more landfall over AP, TN and Bangladesh. In addition, change in wind direction from NW to N-NW in middle and upper tropospheric levels and increased meridional SST over BOB are found to be encouraging the landfall activity near AP and TN coasts.

3.4. *Impact of trends in CD on monsoon rainfall*

Considering the impacts of trends in CDs on southwest monsoon rainfall significant positive relation existed between monsoon rainfall of sub-divisions over Central India and CD frequency during the period 1940 to 1990 (Mohapatra *et al*., 2015a). It decreased drastically subsequently and became insignificant. Significantly negative relation that existed earlier between southwest monsoon rainfall over Bihar, Marathwada, Rayalaseema and Tamil Nadu & Puducherry and CD frequency has also decreased and become insignificant subsequently. The significant positive relation that existed between northeast monsoon rainfall over Rayalaseema and Tamil Nadu & Puducherry and frequency of CDs upto 1980, has decreased and become insignificant subsequently. The above mentioned decrease in relationship is mainly due to decrease in frequency of CDs over BOB. However, the relationship of monsoon rainfall with the frequency of low pressure system (LPS) and number of LPS days has increased. Thus the adverse impact of decrease in CDs has been compensated by increase in frequency of lows (Mohapatra and Mohanty, 2004).

3.5. *Trends in energy metrics of TCs*

There is a significant decreasing trend in VF, ACE and PDI of TCs over AS during post-monsoon season and PDI of TCs over the BOB and NIO during pre-monsoon season, mainly due to similar trend in average intensity of TCs (Mohapatra and Vijay Kumar, 2017). The observed trends in energy metrics are not supported by the similar trends in SST over Nino 3.4 region as well as the IOD index. It indicates that there are other large scale features which influence the trends in various energy metrics of CDs/TCs.

3.6. *Climate change impact on TC in relation to quality of best tracks*

According to Mohapatra *et al.* (2012b) and Mohapatra *et al.* (2013c), the historical TC data are available from 1648 onwards over the AS and 1737 onwards over the BoB. There has been improvement in best track information in different phases due to improvement in observational network, terminology and classification, area of responsibility and standard operation procedure. Based on quality and availability, the whole period of best track information may be broadly classified into four phases, *viz.*, (*i*) pre-1877, (*ii*) 1877-1890, (*iii*) 1891-1960 and (*iv*) 1961-2010. The period of 1961-2010 may be further classified into (a) 1961-1973, (b) 1974-1990 and (c) 1991-2010. The frequency of TCs till 1877 was highly underestimated as the average frequency was slightly less than one for TC over the Bay of Bengal (0.8 per year) and one in three years over the Arabian Sea (0.3 per year). Intensity and other parameters are not well defined. The information during 1877-1890 has a number of limitations including very meagre observational data, leading to average CDs, TCs and severe TCs of 6.3, 2.6 and 0.9 per year, respectively. While the surface observations got an optimum level by 1960 due to augmentation in 1940s and 1950s, radar observations got so by 1973, pilot balloon and radio wind observations by 1980. The polar satellite input was used since 1961, Dvorak's technique since 1974, Indian geostationary satellite since 1983, AWS and buoys observation since 1997 and enhanced AWS network along with microwave imageries since 2008 (Mohapatra *et al.*, 2011, 2012d, 2014c, 2015c). As a result, average CDs, TCs and severe TCs were 11.8, 5.4 and 2.0 per year during 1891-1960 and 10.8, 4.7 and 2.9 per year during 1961-2010, respectively. The average location estimation errors of TCs and depressions are about 55 km over the sea areas during 1961-2010. The average landfall point estimation error has been 140 km or more prior to 1891 for west coast and more than 105 km for east coast. It reduced to about 100 km by the end of 1940 for both the coasts and to 55 km by the end of 1960. It further reduced to about 25 km mainly due to installation of coastal AWS by 2010. The average error in intensity estimation has reduced over the years. During the pre-satellite era (till 1960), the average error in intensity estimation may be up to 8-17 knots (5-9 mps) in depression/deep depression stage, 26-28 knots (13-14 mps) in cyclonic storm stage and 37 knots (19 mps) in severe cyclonic storm or higher stage. It could have reduced gradually during polar satellite era. It could have been at least T0.5 (about 5-20 knots or 3-10 mps) with the introduction of Dvorak's classification of intensity since 1974. The underestimation of genesis and intensification and error in centre location of the CDs during pre-satellite era have been more significant over the AS due to larger open sea area compared to that over the BoB. Considering genesis and intensification along the coast, both genesis of depression and its intensification into TC have been underestimated till 1940s along north Tamil Nadu to Orissa coast and till 1950 along Gujarat coast. The intensification of TC into severe TC has been underestimated along entire east coast and Gujarat coast till 1960. The area to the west of 65° N (west AS) had virtually reported no depressions during pre-satellite era unlike during satellite era. Also, the tracks and lifetime have been shorter by at least one day in 50% of the cases and longer in 15% in pre-satellite era compared to satellite era. It has also been smoother during pre-satellite era compared to satellite era. The perception of long-term changes in frequency and intensity of CDs changes depending upon the period of data due to above-mentioned uncertainties in the best tracks data. While there is significant decreasing trend (0.75 per decade) in frequency of CDs including short-lived CDs, the trend is insignificant (0.11 per decade) when such CDs are excluded. Similarly, the trend characteristics change when we consider TCs and severe TCs. The optimum observational network leading to better estimation of location and intensity of CDs was available since 1961. Hence, the climatology of genesis, location, intensity, movement (track) and landfall can be best represented based on the data set of 1961 onwards.

Several efforts have been made in the IMD to update climatological records on TCs of the NIO as it provides useful guidance on early warning and planning of coastal regions. Recently an electronic atlas has been published for tracks of TCs over the Bay of Bengal and Arabian Sea (IMD, 2008). It is available in cyclone page of IMD's website with free access (www.imd.gov.in). The 3/6 hourly data are also available in RSMC website since INSAT era (1982 onwards) alongwith many derived parameters like energy metrics, life period, frequency of VSCS, ESCS, SuCS, landfall characteristics, damage and impacts (www.rsmcnewdelhi.imd.gov.in). The SOP, terminology, data & products and tools have also improved in recent years and new best track parameters have been introduced by RSMC, New Delhi. Details are available in Sharma and Mohapatra (2017).

4.   TC hazard proneness of India

The hazards associated with TCs are long-duration rotatory high velocity winds, very heavy rain and storm tide. India has a coastline of about 7516 km of which 5400 km is along the mainland. The entire coast is affected by cyclones with varying frequency and intensity. An attempt has been made by Mohapatra *et al.* (2012a) and Mohapatra (2015a), to classify TC hazard proneness of districts by adopting a hazard criteria based on

frequency and intensity of cyclone, wind strength, probable maximum precipitation and probable maximum storm surge. Ninety-six districts including 72 districts touching the coast and 24 districts not touching the coast, but lying within 100 km from the coast have been classified based on their proneness. Out of 96 districts, 12 are very highly prone, 41 are highly prone, 30 are moderately prone and the remaining 13 are less prone. Twelve very highly prone districts include South and North 24 Praganas, Medinipur and Kolkata of West Bengal, Balasore, Bhadrak, Kendrapara and Jagatsinghpur districts of Odisha, Nellore, Krishna and east Godavari districts of Andhra Pradeshand Yanam of Puducherry. The remaining districts of Odisha and Andhra Pradesh, which touch the coast are highly prone districts. The north Tamil Nadu coastal districts are more prone than the south Tamil Nadu districts (south of about 10° N latitude). Most of the coastal districts of Gujarat and north Konkan are also highly prone districts. The remaining districts in the west coast and south Tamil Nadu are either moderately prone or less prone districts. This classification is only based on hazard criteria. Vulnerability of the place has not been taken into consideration. Therefore, composite cyclone risk of a district, which is the product of hazard and vulnerability, needs to be assessed separately through detailed study. Such an initiative is being taken by NDMA through the World Bank assisted National Cyclone Risk Mitigation Project (NCRMP). The MSW indicated against a district in this study is the 3-min average wind speed normally recorded by IMD. Keeping in mind that it is the 3-second peak-gust wind speed that is usually adopted for design of buildings and structures (Lakshmanan *et al.*, 2009), the MSW indicated against the districts (Mohapatra *et al.*, 2012a) need to be multiplied by an appropriate factor for design of all buildings and structures in general and for the design of the post-disaster service structures (such as cyclone shelters, hospitals, transmission lines and communication towers, schools, etc.). The analysis is based on the estimation of daily point PMP by IMD. The criteria adopted for categorization of PMP is arbitrary and subjective. However, IMD and Central Water Commission are developing a new PMP atlas based on longer and latest data. The PMP atlas needs to be prepared considering the actual extreme rainfall over the districts due to TCs only. There is scope for reanalysis of TC hazard proneness based on PMP of districts in association with TCs. The wind data in association with TC is based on the period of 1971-2010. It is mainly based on the wind estimated by Dvorak's technique (Dvorak, 1984) and post-cyclone survey report along with the coastal observations available from IMD's observational network. There is further scope for improvement in estimation of TC wind hazard with upgradation of observational network with high wind speed recorder (HWSR), Doppler Weather Radar and validation of Dvorak's technique

based on instrumented aircraft observation from the core and periphery of the TC. The study is based on the residual storm surge height in association with the TC crossing coast. It does not take into consideration the total water envelope due to astronomical tide, in-shore current, river discharge, heavy rainfall distribution etc. All these factors can influence the storm surge and hence resultant tidal wave. Therefore, there is further scope to estimate the storm surge hazard based on total water envelope and coastal inundation and hence to modify the hazard proneness of the coastal districts (Srinivas *et al.*, 2015; Murty *et al.*, 2017). If speed and the size of the storm varies, then it is going to have an impact on all the aforementioned factors based on maximum duration of the wind strength/rainfall/storm surge and maximum area (size) to be impacted by the landfalling TC. Hence, the degree of proneness may vary in such conditions, thus necessitating the dynamical risk mapping as envisaged in NCRMP.

5.   Observational systems for cyclones over the NIO

It is important to correctly determine the location and intensity of the TC, as initial error in location and intensity can lead to increase in error in forecast location and intensity (Mohanty *et al.*, 2010). Hence, there is a need of dense observational network over the sea and along the coast. The observational network for TC monitoring consists of land-based surface and upper-air stations, Doppler Weather Radars (DWRs), satellites, ships and buoy. The synoptic charts are prepared and analysed every three hour to monitor the TCs over the NIO based on standard operation procedure (SOP) (IMD, 2013). The availability of various types of observation and their confidence level are discussed by Sharma and Mohapatra (2017).

IMD has a good network of surface observatories satisfying the requirement of WMO. There are 70 departmental manned surface observatories of IMD at present all along the coast. There are 21 pilot balloon observatories and 15 radiosonde/radio wind (RS/RW) observatories (Mohapatra *et al.*, 2012b). The meteorological data thus collected all over these stations are used on real time basis for TC monitoring. The high wind speed recorder for TC monitoring has been installed at 21 places. Further it is planned to install HWSR at each coastal district.

At present IMD is receiving and processing meteorological data from two Indian satellites namely INSAT-3D and INSAT-3DR. It provides 1 km resolution imagery in visible band, 4 km resolution in IR band and 8 km in WV channel. Half hourly satellite imageries are obtained from all the six imager channels and hourly

images from the sounder channels of INSAT-3D satellite. At present 48 nos. of satellite images are taken daily from INSAT-3D and 3DR. These images are cascaded in such a way that the cloud imagery is available every 15 minutes alternatively from INSAT 3D and 3DR. During TC situation, data from different satellites are processed at hourly/half hourly intervals to assess the location and intensity. In addition to above, the products like outgoing long wave radiation, quantitative precipitation estimates, sea surface temperatures (SST), cloud motion vectors, water vapour derived wind vector, isotherm analysis on Enhanced infrared images and satellite derived dynamical parameters are also analysed on operational mode for TC monitoring.

At present Dvorak technique is used but manually applied. Recently efforts have been made for automation of this technique (Goyal *et al*., 2017). The microwave imageries were introduced for monitoring and guidance in a subjective manner during later part of 2000s. It was used more objectively to locate the system centre since 2010. Microwave imageries are more helpful in predicting the structural characteristics and intensification in short range, as the characteristics of intensification is first observed in microwave imageries unlike VIS and IR imageries (Jha *et al*., 2013).

On 23rd September, 2009, polar orbiting satellite OCEANSAT - II was launched by Indian Space Research Organisation (ISRO) which carried a ku band pencil beam scatterometer to provide ocean surface winds at 10 m height for early detection. Winds from this satellite were used regularly for locating the centre and intensity of the tropical systems in the formative stage. The OSCAT suffered an anomaly early in February 2014, which could not be recovered and ceased operations on April 2, 2014. In the absence of this product, the sea surface wind as estimated by scatterometer based satellites (ASCAT) and Windsat is used in locating the centre of the TC. Since 2017, SCATSAT 1 is providing the sea surface winds, However, it has the limitations as it provides only two observations. It also suffers from rain contamination and inability to measure the wind speed more than 50 knots (28 mps) (Uhlhorn and Black, 2003).

Gray's Parameters (Gray, 1968) including SST and Ocean heat content, convective instability, wind shear, low level relative vorticity, Coriolis parameter and upper level divergence are monitored for genesis and intensification and these parameters are mostly estimated by satellite technique. Past studies (Bhatia & Sharma, 2013; Goyal *et al.*, 2013, 2016a&b, 2017) have built up a store-house of knowledge on satellite applications in cyclone monitoring in the NIO.

Government of India has established a National Data Buoy Programme (NDBP) at National Institute of Ocean Technology (NIOT), Chennai. Under this programme, twelve moored data buoys are deployed currently in the NIO. The data buoys are fitted with sensors to measure air pressure, air temperature, wind speed and direction and sea surface temperature among other parameters. These buoys have resulted in better monitoring, validation of scatterometer winds and hence reduction of location and intensity error in association with ship and satellite observations. As per the guidelines issued to Indian voluntary observing fleet (IVOF), synoptic observations are made at the main standard times: 0000, 0600, 1200 and 1800 UTC by the ships. When additional observations are required, they are made at one or more of the intermediate standard times: 0300, 0900, 1500 and 2100 UTC. Over the NIO, 186 ships are registered under IVOF. The ship observations were quite high during pre-satellite period (before 1960s). It gradually decreased with the advent of polar orbiting satellite in 1960s and reduced further with the introduction of Indian geostationary satellites during 1980s.

There are twenty three radars presently spreading across the country [Fig. 5(a)]. Various products derived from DWR data using software algorithms are extremely useful to the forecasters for estimating the storm's center, intensity, location and for very short range forecasting and its future path. The existing digital DWRs have also been networked to super computers for NWP models. Composite images are being generated centrally. Data is also converted to scientific formats such as NetCDF, HDF5 and Opera BUFR for assimilation in NWP models. A Radar image of a matured TC indicating eye, eye wall, spiral bands, pre-cyclone squall lines and streamers as shown in Fig. 5(b).

6. Standard operation procedure for monitoring of cyclone

Various kinds of analytical procedure are described in Standard Operation Procedure (SOP) Manual (IMD, 2003, 2013). A systematic check list is prepared for identification of location and intensity of cyclone. The procedure necessarily deals with determination of location and intensity along with other characteristics like associated MSW, estimated central pressure and pressure drop at the centre, shape and size, radius of outermost closed isobar, point and time of landfall, if any or area of dissipation etc. with the available observations in the storm region (Sharma and Mohapatra, 2017). The TC analysis, prediction and decision-making process are made by blending scientifically based conceptual models, dynamical and statistical models, meteorological datasets, technology and expertise. For this
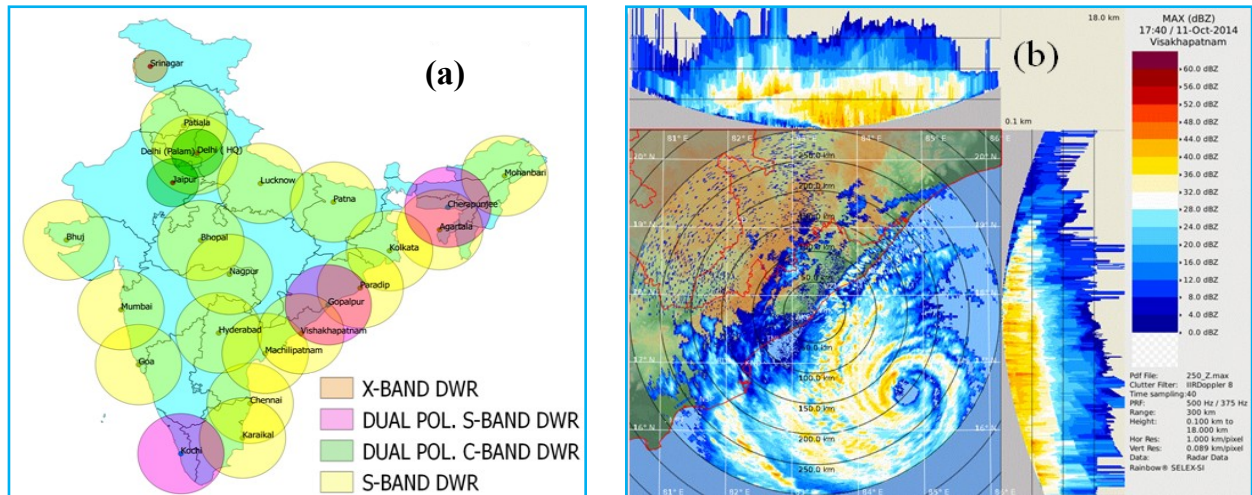
Figs. 5(a&b). (a) Radar Network of IMD (*Source*: RSMC New Delhi, 2019) and (b) DWR imagery of VSCS, Hudhud (8-14 October, 2014)
(*Source*: RSMC New Delhi, 2015)

purpose, a decision support system (DSS) in a digital environment is used to plot and analyse different weather parameters, satellite, radar and NWP model products. In this hybrid system, synoptic method could be overlaid on NWP models supported by modern graphical and Geographical Interface System (GIS) applications to produce high quality analyses and forecast products, prepare past and forecast tracks upto 120 h, depict uncertainty in track forecast and to forecast wind in different sectors of TC. Also, additional help is taken from websites to collect and analyse radar data and products from IMD's radar network and neighbouring countries, satellite imageries and products from IMD and international centres and data, analysis and forecast products from various national and international centres. The automation of the process has increased the efficiency of system, visibility of IMD and utility of warning products leading to minimum loss of life (Mohapatra *et al*., 2013b).

There is a growing need for improvement in TC vital parameters (Knaff *et al*., 2011) in view of the requirements of NWP models and storm surge models (Chourasia *et al*., 2013), as most of the NWP models fail to simulate accurately the location and intensity of the TC. The creation of synthetic vortex helps in improving the track and intensity forecast of the model. In the parametric storm surge prediction models, the surface wind structure in the quadrant base form alongwith the radius of maximum wind (RMW) and pressure drop (ΔP) at the centre are utilised to create the wind stress and hence predict the storm surge (Dube *et al*., 2013). Sharma and Mohapatra (2017) have discussed the SOP for determination of various TC vital parameters by IMD.

7. Monitoring and prediction of TC over NIO

7.1. *Extended range*

IMD started extended range prediction for cyclogenesis from April, 2018. Cyclogenesis is predicted based on evaluation of:

(*i*) Madden Jullian Oscillation (MJO) phase and amplitude following Mohapatra and Adhikary (2011).

(*ii*) The mean sea level pressure (MSLP) and 10 m wind fields from various global models including IMD-GFS, NCEP-GFS, NCUM, ECMWF, IMD-GEFS, NEPS following the criteria for genesis (IMD, 2013).

(*iii*) IITM/IMD CFSv-2 cyclogenesis probability, MSLP & 850 hpa winds forecast for 4 weeks (Pattanaik and Mohapatra, 2016).

(*iv*) IMD's Genesis Potential Parameter (Kotal and Bhattacharya, 2013).

(*v*) 30 days **cyclogenesis forecast from (**http://www.atmos.albany.edu/facstaff/roundy/tcforecast/tcforecast.html).

(*vi*) **Tropical cyclone formation product probability by RAMMB, CIRA for next 48 hours (**http://rammb.cira.colostate.edu/projects/gparm/).

(*vii*) **Global Tropics Hazards and Benefits Outlook by NOAA for next two weeks (**http://www.cpc.ncep.noaa.gov/products/precip/CWlink/ghazards/).
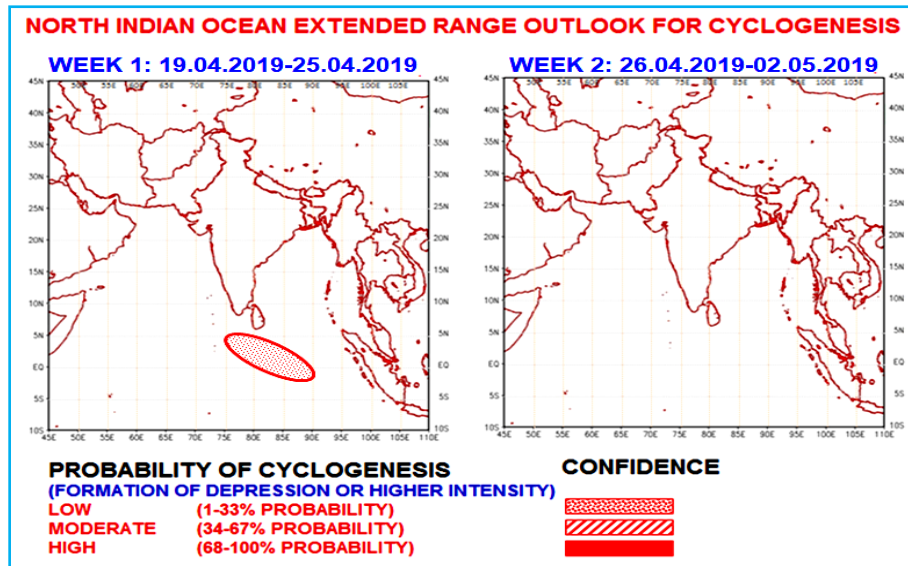
Fig. 6. Typical example of graphical extended range prediction of cyclogenesis for TC FANI

(*viii*) NINO 3.4 values for El-Nino or La-Nina conditions and dipole index for Indian Ocean Dipole (IOD) from Bureau of Meteorology (www.bom.gov.au).

Accordingly, the cyclogenesis probability for week 1 and 2 is issued based on consensus approach once in a week (every Thursday). It contains information about large scale features over the region, model guidance on probable cyclogenesis from various global/regional models, probability of cyclogenesis as LOW (0-33%), MODERATE (34-67%) and HIGH (68-100%) alongwith verification of forecast issued during last two weeks. The product is available on RSMC website at http://www.rsmcnewdelhi.imd.gov.in/images/bulletin/eroc.pdf. It is found very suitable for the forecasters to improve monitoring and forecasting in medium range based on extended range prediction and also it helps in planning and preparedness with longer lead period. A typical example of extended range prediction of cyclogenesis for TC Fani is shown in Fig. 6.

7.2. *Medium range prediction of cyclogenesis*

Genesis parameters are evaluated in following steps to monitor the cyclogenesis:

Step 1: SST, depth of 26 °C isotherm and Ocean thermal energy

Step II: Conditional instability through a deep and moist atmospheric layer

Step III: Pre-existing disturbance

Step IV: Environmental conditions (vertical wind shear, low level vorticity, upper level divergence etc.)

Step V: NWP and dynamical-statistical model forecasts for genesis

Based on synoptic, statistical, dynamical-statistical and NWP models guidance, a consensus decision is taken on genesis of depression and its likely intensification into TC on daily basis.

Prior to 2014, it was being issued qualitatively for next 24 hours. Since 2014, it was being issued with probabilistic guidance as Nil (0%), Low (1-25%), Fair (26-50%), Moderate (51-75%) and High (76-100%) for next 72 hours. The lead period of forecast has been further extended to 120 hours from 2018.

7.3. *Determination of location of centre and intensity of cyclone*

The location of the centre of the TC is determined based on (a) Synoptic, (b) Satellite (INSAT/METSAT/microwave/ASCAT/SCAT SAT) and (c) Radar observations. When the TC is far away from the coast and not within the radar range, satellite estimate gets more weight, though it is modified sometimes with availability of ship and buoy observations. When the TC comes closer to the coast, radar estimate gets maximum preference followed by satellite. When TC is very close to coast or over the land surface, coastal observations get the highest preference followed by radar and satellite observations. Various steps for determination of centre and intensity of TC are discussed by Sharma and Mohapatra, 2017.

In synoptic technique, the centre of the system is determined by considering the centroid of the wind distribution at the surface level. In the pressure field, the location of lowest mean sea level pressure is considered as the centre of the system (IMD, 2003). For intensity estimation, the available surface observations are taken into consideration to find out MSW and number of closed isobars at the interval of 2 hPa within a specified region around the system centre (IMD, 2003).

Based on satellite observations, in the initial stage (depression/deep depression), the centre is determined, from the centre of the low cloud lines (IMD, 2003). There are four types of cloud pattern (Dvorak, 1984) in TC. In case of shear pattern, when the convection lies away from the centre, centre is same as the centre of low cloud lines. As the system intensifies and acquires the banding pattern, the centre is determined from the banding feature using logarithmic spiral. In the central dense overcast (CDO) pattern, the centre of CDO is the centre of the system. In the eye pattern, the centre determination is easier and accurate as it is same as the centre of the eye of the cyclone.

The intensity classification by satellite technique is based on Dvorak's technique (Dvorak, 1984; Velden *et al*., 2006). The pressure wind relationship by Mishra and Gupta (1976) is used to find estimated central pressure (Sharma and Mohapatra, 2017). As there is no aircraft reconnaissance in the NIO, Dvorak's technique has not been verified and also the pressure wind relationship not verified. Comparison of satellite based intensity and the best track estimates of IMD indicate a difference of about 0.5 T (Goyal *et al*., 2013). Recently the microwave imageries and brightness temperatures are also used to determine central pressure and MSW (Jha *et al*., 2013). However, this technique has not been validated over the NIO due to non-availability of aircraft reconnaissance.

Based on radar observations, the *eye* or the centre of the TC can be derived from a continuous and logical sequence of observations. The geometric centre of the echo-free area is reported as the *eye location*. If the wall cloud is not completely closed, it is still usually possible to derive an eye location with a high degree of confidence by sketching the smallest circle or oval that can be superimposed on the inner edge of the existing portion of the wall cloud. When the wall cloud is not developed fully but a centre of circulation is identifiable, then this feature is observed and reported similar to the eye. When the eye or centre is indistinct or outside the range or the radar beam overshoots the inner eyewall when it does not extend very high, spiral band overlays are used to estimate the location of the centre (IMD, 1976). Based on observed

winds from DWR, the intensity can be determined (Raghavan, 2013). As radar based winds are not available at surface level, the wind observations from these techniques are converted to 10 meter wind using the suitable conversion technique like those used in case of aircraft reconnaissance technique in Atlantic.

The location estimation error has been about 55 km over the sea areas (Mohapatra *et al*., 2012b; Goyal *et al*., 2013). According to Elsberry (2003), the errors in determining the TC centre over the northwest Pacific Ocean can be upto 50 km by satellite fixes, 20-50 km by radar observations and by about 20 km by aircraft reconnaissance. The induction of DWR has reduced the error in fixing the centre of TCs in radar range. The landfall point estimation error has reduced to about 25 km by 2010 mainly due to installation of coastal AWS. The average error in MSW estimation has reduced over the years. It could have been T0.5 (05-20 knots or 3-10 mps) with the introduction of Dvorak's classification of intensity since 1974.

7.4. *Track and intensity forecasting*

A variety of observational data have been used in India till 1960s to forecast the track intensity and landfall of TCs. Satellite era, since 1960s, added another feature. There has been rapid development in objective techniques since 1970s and especially in recent years for forecasting tracks and intensity of TCs in the NIO. To summarise, currently for TC track and intensity forecasting, IMD uses statistical technique (Analogue, Persistence, Climatology, Climatology and persistence (CLIPER)), synoptic technique, satellite techniques, radar techniques, NWP models and dynamical statistical models

In the synoptic method, prevailing environmental conditions like wind shear, low to upper level wind and other characteristics are considered. All these fields in the NWP model analyses and forecasts are also considered. The development of characteristic features in satellite and radar observations is also taken into consideration. While, the synoptic, statistical and satellite/radar guidances help in short range forecast (upto 12/24 hrs), the NWP guidance is mainly used for 24-120 hr forecasts. Consensus forecasts that gather all or part of the numerical forecast tracks and intensity and uses synoptic and statistical guidance are utilised to issue official forecast.

7.4.1. *Operational NWP models*

There are three types of NWP models, *viz*., individual deterministic models, multi-model ensemble (MME) and single model ensemble prediction system (EPS) for different ranges of forecast (Regional Specialised
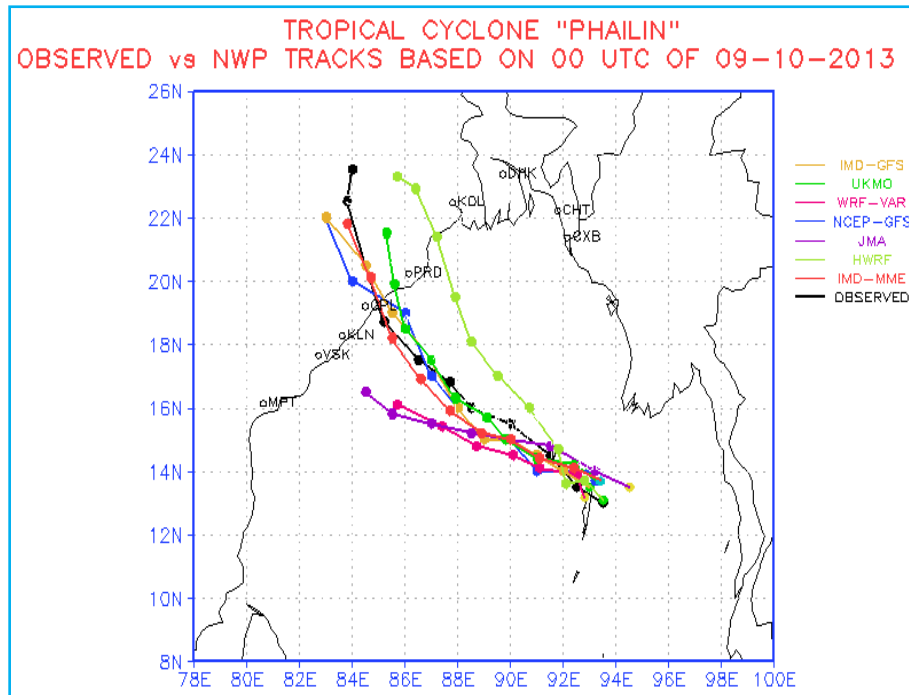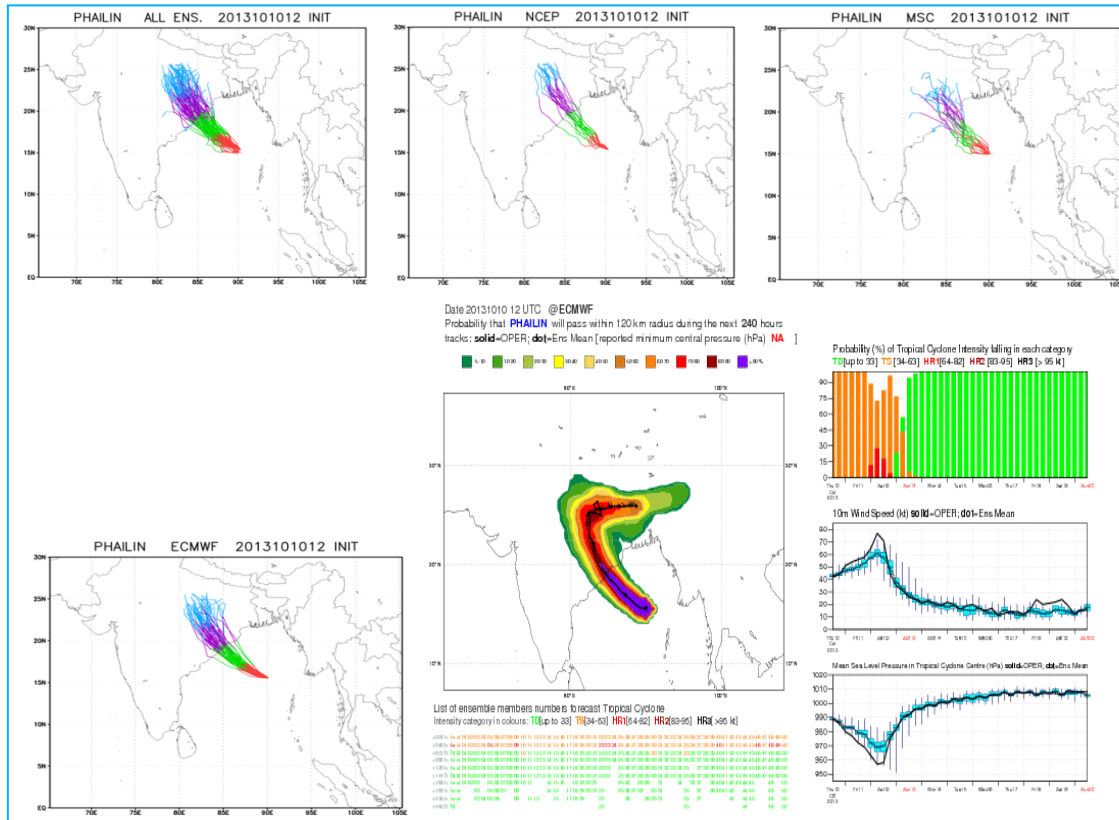
Fig. 7. Observed track and forecast track of NWP models based on 0000 UTC of 9th October, 2013

Meteorological Centre (RSMC), New Delhi, 2019). It include (*i*) Global forecasting system (GFS) global model (horizontal resolution of 12 km and forecast upto 10 days), (*ii*) Unified model (horizontal resolution of 12 km and forecast upto 10 days), (*iii*) Global Ensemble Forecasting System (GEFS) global probabilistic model (horizontal resolution of 12 km and forecast upto 10 days), (*iv*) Unified model ensemble prediction system (horizontal resolution of 12 km and forecast upto 10 days), (*v*) Weather research forecast (WRF) Meso scale model (horizontal resolution of 3 and 9 km and forecast upto 3 days, (*vi*) Unified Meso scale regional model (horizontal resolution of 4 km and forecast upto 3 days), (*vii*) Hurricane WRF (HWRF) for cyclone prediction ((horizontal resolution of 2 km and forecast upto 5 days), (*viii*) MME based cyclone track prediction (forecast upto 5 days) (Kotal & Roy Bhowmik, 2011), (*ix*) statistical cyclone intensity prediction (SCIP) model (Kotal *et al*., 2008), rapid intensification (RI) model (Kotal *et al*., 2008), (*x*) Storm surge prediction models including (a) IMD Nomogram (Ghosh, 1977), (b) IIT Delhi Model (Dube *et al*., 2013) and INCOIS, Hyderabad storm surge and coastal inundation model (Murty *et al.*, 2017; Srinivas *et al.*, 2015).

IMD also makes use of NWP products prepared by some other operational NWP centres like, NCEP-GFS, USA, Japan Meteorological Agency (JMA), United Kingdom Meteorological Office (UKMO), Global

Tropical model, Meteo-France etc. The MME technique for cyclone track forecast (Kotal and Roy Bhowmik, 2011) is based on a statistical linear regression approach using five operational NWP models. (ECMWF, GFS (IMD), GFS (NCEP), UKMO and JMA). The single model based ensemble forecast products from ECMWF (50+1 Members), NCEP (20+1 Members), UKMO (23+1 Members) and Meteorological Services, Canada (MSC) (20+1 Members) and JMA (20+1 Members), IMD GEFS and UMEPS are available in near real-time for NIO region. These Products include: Deterministic and ensemble track forecasts of cyclones, strike probability maps and strike probability of cities within the range of 120 km 4 days in advance. The super-ensemble has also been developed based on above ensembles. An example of MME track forecast for TC, Phailin is shown in Fig. 7. Examples of EPS product in case of TC, Phailin are shown in Fig. 8.

There is also facility in cyclone module of forecasters' work station to develop MME using equal weightage to individual model tracks available in cyclone module. According to Heming *et al.*, 2018, there has been significant improvement in track forecasting by RSMC New Delhi in recent years. It is found that the MME outperforms the individual model. The official forecast accuracy is similar to MME forecast accuracy. Considering individual models, it is observed that the HWRF model is a promising tool for TC track forecasting

Fig. 8. Track prediction of VSCS Phailin by EPS based on 1200 UTC of 10th October, 2013

as the error of this model is lowest upto 36 hrs lead period after that of MME. It is followed by ECMWF model for these lead periods. The UKMO model shows lowest errors for the higher lead periods.

According to Osuri *et al*. (2012a), the convection and planetary boundary layer (PBL) processes play significant role in the genesis and intensification of tropical cyclones (TCs). Several convection and PBL parameterization schemes incorporate these processes in the NWP models. Therefore, a systematic inter comparison of performance of parameterization schemes is essential to customize a model. In this context, six combinations of physical parameterization schemes (2 PBL Schemes, YSU and MYJ and 3 convection schemes, KF, BM and GD) of WRF-ARW model are employed to obtain the optimum combination for the prediction of TCs over NIO. Five cyclones are studied for sensitivity experiments and the out-coming combination is tested on real-time prediction of TCs during 2008. The tracks are also compared with those provided by the operational centers like NCEP, ECMWF, UKMO, NCMRWF and IMD. It is found that the combination of YSU PBL scheme with KF convection scheme (YKF) provides a better prediction of intensity, track and rainfall consistently. The average RMSE of intensity (13 hPa in CSLP and 11 m s^{-1} in 10-m wind), mean

track and landfall errors is found to be least with YKF combination. The equitable threat score (ETS) of YKF combination is more than 0.2 for the prediction of 24-h accumulated rainfall up to 125 mm. The vertical structural characteristics of cyclone inner core also recommend the YKF combination for Indian seas cyclones.

8. Model diagnosis

According to Osuri *et al.* (2012b), remote-sensing data are more useful to improve the initial condition of the model and hence the forecast of TCs when they are in the deep Oceans, where conventional observations are unavailable. In their study, an attempt is made to assess the impact of remotely sensed satellite-derived winds on initialization and simulation of TCs over the NIO based on four TCs, namely, 'Nargis', 'Gonu', 'Sidr' and 'KhaiMuk', with 13 different initial conditions. Two sets of numerical experiments, with and without satellite-derived wind data assimilation, are conducted using a high resolution weather research and forecasting (WRF) model. The inclusion of satellite-derived winds through a three-dimensional variational (3DVAR) data assimilation system improves the initial position in 11 cases out of 13 by 34%. The 24-, 48-, 72- and 96-hour mean track forecast improves by 28%, 15%, 41% and 47%, respectively,

based on 13 cases. The landfall prediction is significantly improved in 11 cases by about 37%. The intensity prediction also improves by 10-20%. Kinematic and thermodynamic structures of TCs are also better explained, as it could simulate heat and momentum exchange between sea surface and upper air. Due to better simulation of structure, intensity and track, the 24-hour accumulated rainfall intensity and distribution are also well predicted with the assimilation of satellite-derived winds.

The performance of the Advanced Research version of the Weather Research and Forecasting (ARW) model in real-time prediction of TCs over the NIO at 27-km resolution is evaluated by Osuri *et al.* (2013) on the basis of 100 forecasts for 17 TCs during 2007-11. The analyses are carried out with respect to (*i*) basins of formation, (*ii*) straight-moving and recurving TCs, (*iii*) TC intensity at model initialization and (*iv*) season of occurrence. The impact of high resolution (18 and 9 km) on TC prediction is also studied. The ARW model results showed a bias toward predicting eastward movement for the NIO TCs for both the BoB and AS. This bias is particularly true for straight-moving TCs. In the case of recurving TCs, the model showed a rightward bias up to the 36-h forecast and thereafter a westward bias. The analyses of latitudinal systematic errors as well as along track (AT) errors show that the model forecast positions are biased to the south of (behind) the observed positions. The ARW forecasts are in general slower relative to the actual translation speed of the system for all forecast lengths and they predict a delayed landfall. The magnitude of cross track (CT) errors is less in comparison with AT errors in the ARW model. Hence the ARW model is more accurate in predicting TC landfall location than landfall time. The model is more skillful in track prediction when initialized at the intensity stage of severe cyclone or greater than at the intensity stage of cyclone or lower. The higher-resolution (18 and 9 km) predictions yield an improvement in mean track error for the NIO Basin by about 4%-10% and 8%-24%, respectively. The 9-km predictions were found to be more accurate for recurving TC track predictions by; 13%-28% and 5%-15% when compared with the 27- and 18-km runs, respectively. The 9-km runs improve the intensity prediction by 15%-40% over the 18-km predictions. With respect to season of occurrence, the model exhibits less error and 3%-15% more gain in skill for post monsoon TCs than for pre monsoon TCs. The model underestimates the peak intensities of systems of VSCS or higher intensity and experiences maximum errors in the case of these systems. The intensity prediction of CS and SCS is reasonably simulated, however. The error can be further reduced by improving the initial intensity and structure of the TC vortex by increasing the observational network of buoy, ships and aircraft reconnaissance over the NIO region or through advanced vortex initialization

techniques and Ocean–atmosphere coupling for better heat, moisture and momentum exchanges.

A genesis potential parameter (GPP), for the NIO has been developed (Kotal and Bhattacharya, 2013) as the product of four variables, namely vorticity at 850 hPa, middle tropospheric relative humidity, middle tropospheric instability and the inverse of vertical wind shear. The GPP is operationally used for predicting cyclogenesis at their early development stages. The grid point analysis and forecast of the genesis parameter up to seven days are generated on real time. Region with GPP value equal or greater than 30 is found to be high potential zone for cyclogenesis.

Whenever any low level circulation (LLC) forms over the Indian Seas, the prediction of its intensification into a TC is very essential to provide longer lead time for the management of TC disaster. Satellite Application Centre (SAC) of Indian Space Research Organization (ISRO), Ahmedabad, has developed a technique to predict TCs based on scatterometer-derived winds from the polar orbiting satellite, QuikSCAT and Oceansat-II. The IMD has acquired the technique and verified it for the years 2010-2013 for operational use (Goyal *et al.*, 2016a). The model is based on the concept of analogs of the sea surface wind distribution at the stage of LLC or vortex (T1.0) as per Dvorak's classifications, which eventually leads to cyclogenesis (T2.5). The results indicate that the developed model could predict cyclogenesis with a probability of detection of 61% and critical success index of 0.29. However, it shows high over-prediction. The model is better over the BoB than over AS and during post-monsoon season (September-December) than in pre-monsoon season (March-June).

A statistical-dynamical model (SCIP) (Kotal *et al.*, 2008) has been implemented for real time forecasting of 12 hourly intensity upto 72 hours. The model parameters are derived based on model analysis fields of past cyclones. The parameters selected as predictors are mainly initial storm intensity, intensity changes during past 12 hours, storm motion speed, initial storm latitude position, vertical wind shear averaged along the storm track, vorticity at 850 hPa, divergence at 200 hPa and SST. For the real-time forecasting, model parameters are derived based on the forecast fields of IMD GFS model. However, being a statistical model, it has limitations in predicting rapid intensification and rapid weakening of TCs.

A rapid intensification index (RII) is developed for tropical cyclones over the BoB (Kotal and Bhattacharya, 2013). The RII uses large-scale characteristics of tropical cyclones to estimate the probability of rapid intensification

(RI) over the subsequent 24-h. The RI is defined as an increase of intensity 30 kt (15.4 ms^{-1}) during 24-h. The RII technique is developed by combining threshold (index) values of the eight variables for which statistically significant differences are found between the RI and non-RI cases. The variables are: Storm latitude position, previous 12-h intensity change, initial storm intensity, vorticity at 850 hPa, divergence at 200 hPa, vertical wind shear, lower tropospheric relative humidity and storm motion speed. The forecasts are made available in real time from 2013. However, the verification of RII indicates limitation in RI prediction. Hence it needs modification.

The study on VSCS, Madi during December, 2013 over the Bay of Bengal by Sabade and Mohapatra (2017) endorsed that the SST (> 26 °C), TCHP (> 50 kJ/cm^2), vertical wind shear (low to moderate, < 20 knots), relative vorticity (> 10 × 10^{-5} per second) and mid-tropospheric relative humidity (≥ 50%) is essential for tropical cyclogenesis and intensification. The lower Ocean thermal energy, higher wind shear together with lower SST were responsible for weakening of the system before landfall. The study further suggests that TPW can be utilised as a precursor for predicting intensification/weakening of the system. The intensity of the TC and track are related to each other, as the steering flow changes with change in intensity and with the change in track, the factors for intensification change. In case of Madi, when the system was of VSCS intensity, it was steered by the upper-tropospheric anti-cyclonic circulation and when it was SCS, it was steered by mid- and upper-tropospheric anti-cyclonic circulation. The change in the track of Madi during its life period could be attributed to above impact of TC on steering flow. The track of the TC in turn also plays a dominant role in determining the intensity of the system. The initial north/north-northeastward track of Madi helped in increasing beta effect and favourable outflow leading to intensification. It's southwestward movement in the later part of the life cycle led to weakening, due to low SST, Less TCHP (< 50 kJ/cm^2), high wind shear (> 20 knots) and dry and cold air intrusion from the Indian sub-continent. Similarly, Sharma and Mohapatra (2013), analysing the explosive intensification of VSCS Giri (2010) over the BOB found that the cyclone, GIRI being situated in an area of weak wind shear and accompanied by strong poleward outflow, experienced additional strengthening on 22nd October 2010 despite its proximity to land with an increase in associated sustained maximum wind speed from 45 knots at 1200 UTC of 21st October to 105 knots at 0900 UTC of 22nd October, 2010.

The super cyclone of Orissa maintained the intensity of cyclonic storm for about 30 hours after landfall (Mohapatra *et al*., 2002). Because a dense population resides at or near the Indian coasts, the decay forecast has direct relevance to relief and rescue operation apart from response actions by disaster managers. In view of this, the decay model (Roy Bhowmik *et al*., 2005) has been used for real time forecasting of decaying intensity (after landfall) of TCs. However, the verification of this model indicates limited skill and hence, it needs improvement.

9. **Operational forecast and warning services products**

9.1. *Track forecast*

Considering recent development in prediction capability, IMD introduced the objective cyclone track forecast valid for next 72 hrs in December, 2008 (Mohapatra *et al*., 2013d) and upto 120 hrs in 2013 from the stage of deep depression onwards (RSMC New Delhi, 2015). During 2018, objective track forecast has been introduced from the stage of depression onwards for a lead period of 72 hours at an interval of 12 hrs each (RSMC New Delhi, 2019). The track forecast is issued 5 times a day from the stage of depression onwards based on 0000, 0300, 0600, 1200 and 1800 UTC observations and 8 times a day from the stage of cyclonic storm based on 0000, 0300, 0600, 0900, 1200, 1500, 1800 and 2100 UTC observations. The forecasts are issued about three hours after the above mentioned observation time. An example of the product during ESCS Mekunu is shown in Fig. 9(a).

9.2. *Cone of uncertainty in track forecast*

The "cone of uncertainty (COU)" - also known colloquially as the "cone of death", "cone of probability" and "cone of error" - represents the forecast track of the centre of a cyclone and the likely error in the forecast track based on predictive skill of past years. The COU in the forecast of IMD has been introduced with effect from the TC, 'WARD' during December, 2008 (Mohapatra *et al*., 2012c). A typical example of COU forecast is shown in Fig. 10. Due to improvement in track forecast errors during 2009-13, the radii of cone of uncertainty for various forecast periods was reduced to 10, 20, 30, 45, 60, 80, 100, 120, 135, 150, 160, 170 and 180 nautical miles for 06, 12, 18, 24, 36, 48, 60, 72, 84, 96, 108 and 120 hr forecast periods respectively with effect from VSCS Hudhud in October 2014 (Mohapatra *et al*., 2017b). The observed track lies within the forecast COU in about 60-70% of the cases like other Ocean basins like northern Atlantic and Pacific Oceans.

Again based on the track forecast errors during 2014-18, the same has been revised in 2019. The revised radii used to construct the COU have shrunk by 20-30% for 24-120 h forecast period due to improved TC track forecast
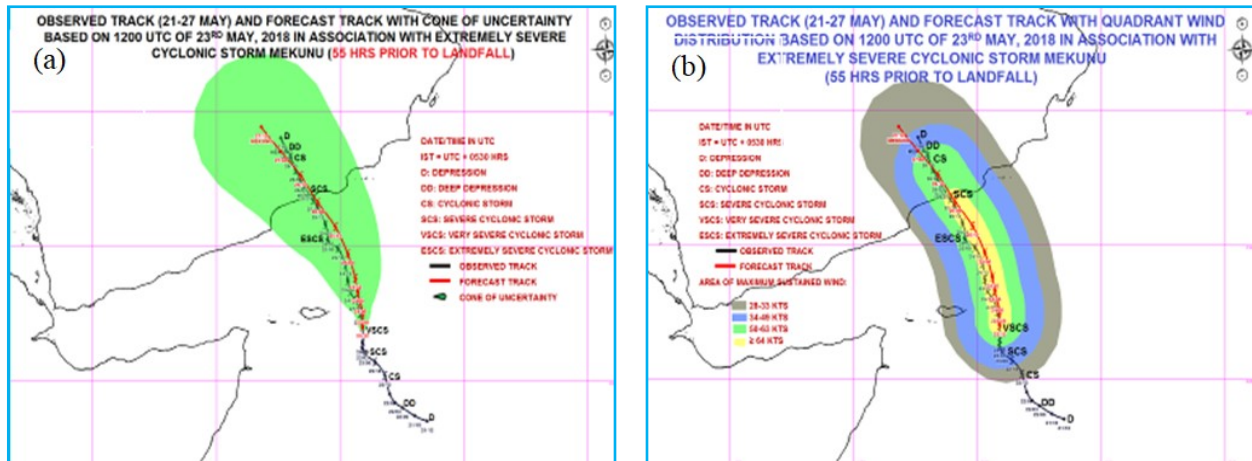
Figs. 9(a&b). (a) A typical example of observed and forecast track alongwith cone of uncertainty and (b) graphical presentation of quadrant wind forecast during VSCS Mekunu based on 1200 UTC of 23rd May, 2018

errors during the recent years (2014-2018). For the newly constructed COU, the radii of circles pertaining to 24, 48,72, 96 and 120 h forecasts are 45, 70, 95, 130 and 160 nm respectively based on the errors during 2014-18, against 65, 105, 140, 170 and 200 nm respectively, for the previous COU based on track errors during 2009-2013. The accuracy of the newly constructed forecast COU is 70-80% and is comparable with those of other leading TC forecasting centres of the world.

There is a need for development of COU forecast using dynamical model forecasts of the track of TCs. IMD is utilizing the global EPS products through TIGGE database (THORPEX Interactive Grand Global Ensemble) with the help of Japan Meteorological Agency and WMO. The National Centre for Medium Range Weather Forecasting (NCMRWF), Noida, is running 20-member ensemble, GEFS and UMEPS. These ensemble predication products could be utilized for developing dynamical COU forecast.

9.3. *Quadrant wind radii forecasting and gale wind warning*

The cyclone wind radii representing the maximum radial extent of winds reaching 34 kts, 50 kts and 64 kts in each quadrant (NW, NE, SE, SW) of cyclone are generated as per requirement of ships. The initial estimation and forecast of the wind radii of TC is rather subjective and strongly dependent on the data availability, climatology and analysis methods. The subjectivity and reliance on climatology is amplified in NIO in the absence of aircraft observations. However, recently with the advent of easily accessible remotely sensed surface and near surface winds (e.g., Ocean Sat., Special Sensor Microwave Imager (SSMI), low level atmospheric motion vectors and Advanced Microwave Sounder Unit (AMSU)

retrieval methods, DWR, coastal wind observations and advances in real time data analysis capabilities, IMD introduced TC wind radii monitoring and prediction product in October, 2010 (Mohapatra and Sharma, 2015). A typical example of the quadrant wind radii product is shown in Fig. 9(b).

This operational product, generated from multiplatform satellite derived winds and NWP products, contains analysed and forecast wind field (wind radii in four geographical quadrants, *viz*., NW, NE, SW and SE for thresholds of 28, 34, 50 and 64 knots) valid for next 72 hrs since 2010 and 120 hrs since 2013. Forecasts are issued every six hrs based on 0000, 0600, 1200 and 1800 UTC. However, this product is not validated by IMD at present, like other Ocean basins (WMO, 2013) due to the uncertainties in the best track estimates. Even currently the structure parameters are not included in best track archives of RSMC, New Delhi. Since storm structure represents many aspects of TCs and their impacts, it would be desirable to understand the errors in the wind fields. As data assimilation methods for TCs improve and the ability of the observation systems to represent the wind structure improves, it is hoped that measurement of the radii will become less uncertain, which will make evaluation of these variables more meaningful.

The forecast of gale wind includes (*i*) time of commencement, (*ii*) duration, (*iii*) area of occurrence and (*iv*) magnitude of gale wind. The methods for prediction of gale wind include (*i*) synoptic, (*ii*) climatological, (*iii*) satellite, (*iv*) Radar, (*v*) NWP and (*vi*) dynamical statistical techniques. In the satellite method region of maximum reflectivity and mesoscale vortices are assumed to be associated with higher wind. In radar technique, the direct wind observation are available though uniform wind
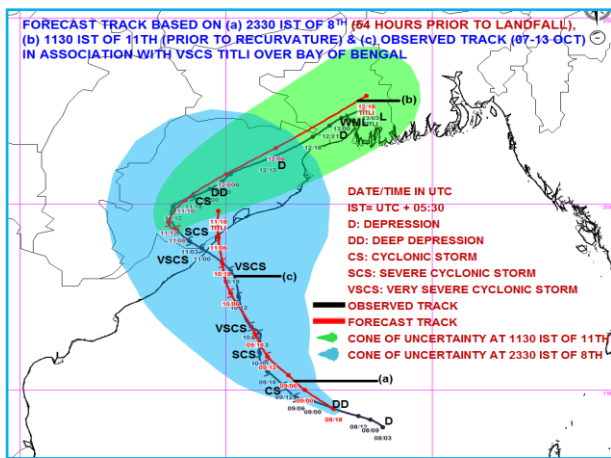
Fig. 10. Observed track of VSCS Tiltli and forecast based on 1800 UTC of 8th and 0600 UTC of 11th October, 2018 (prior to recurvature)

technique, ppv2 product and radii velocity measurements. The wind estimates from satellite and radar and other observations are extrapolated to forecast the wind. MSW is also available from other sources like Scatteometry wind from satellite, Buoy, Ships apart from estimate by Dvorak technique. Though the wind forecasts by the NWP models are underestimated the initial condition of wind from the model can be corrected based on actual observations and accordingly model forecast wind can be modified. The forecast based on dynamical statistical model also can be utilised in the similar manner.

10. Cyclone warning organisation

At present, the cyclone warning organization of IMD has three-tier system to cater to the needs of the maritime states at national, regional and local levels and to carry out international responsibility.

The liaison with the Central Government organizations and other agencies as well as co-ordination and supervision of cyclone warning activities are done by Cyclone Warning Division (CWD) at New Delhi. CWD, New Delhi is also functioning as Regional Specialised Meteorological Centre - Tropical Cyclones (RSMC - Tropical Cyclones), New Delhi and provides the TC advisories to WMO/ESCAP Panel countries, *viz*., Bangladesh, Myanmar, Thailand, Sri Lanka, Maldives, Pakistan, Oman, Yemen, Saudi Arabia, UAE, Qatar and Iran. It also acts as a TC Advisory Centre (TCAC) for international civil aviation as per the requirement of International Civil Aviation Organisation (ICAO) and issues the TC advisories to Airoport meteorological Offices over NIO and Pacific region as well as Middle East for issue of significant meteorological (SIGMET) information to different civil aviation authorities and airlines.

There are three Area Cyclone Warning Centres (ACWCs) at Chennai, Mumbai and Kolkata and four Cyclone Warning Centres (CWCs) at Visakhapatnam, Ahmedabad, Bhubaneswar and Thiruvananthapuram. The ultimate responsibility for operational storm warning work for the respective area rests with the ACWCs and CWCs. Area of responsibility of various ACWCs and CWCs is shown in Table 2.

10.1. *Bulletins issued for international users*

(*i*) **Tropical Weather Outlook for WMO/ESCAP Panel countries** is issued once daily at 0600 UTC based on 0300 UTC observation and analysis. It contains convective activity; meteorological situation over the basin; observed and expected lows; their potential of intensification within the next 120 hours.

(*ii*) **Special Tropical Weather Outlook for WMO/ESCAP Panel countries** is issued five times a day (based on 0000, 0300, 0600, 1200, 1800 UTC) when a depression forms over NIO. It contains current location and intensity, past movement, convective activity; T number, estimated central pressure and MSW, sea condition, 120 hrs (00, 06, 12, 18, 24, 36, 48, 72, 96 and 120 hrs) forecast track and intensity (text and graph) from deep depression stage onwards and 72 hrs forecast track and intensity from depression stage till the weakening of the system. It also contains diagnostic and prognostic features.

(*iii*) **Tropical Cyclone Advisory Bulletin for WMO/ESCAP Panel countries** is issued every three hourly (based on 0000, 0300, 0600, 0900, 1200, 1500, 1800 and 2100 UTC). It contains current location and intensity, past movement, convective activity, T number, estimated central pressure and MSW, sea condition, 120 hrs (00, 06, 12, 18, 24, 36, 48, 72, 96 and 120 hrs) forecast track and intensity (text and graph), storm surge guidance, diagnostic and prognostic features

(*iv*) **TCAC bulletin for issue of SIGMET by Met. Watch Offices** is issued as soon as any disturbance over the NIO attains or likely to attain the intensity of cyclonic storm. These bulletins are issued at six hourly intervals based on 0000, 0600, 1200, 1800 UTC synoptic charts and the time of issue is HH+03 hrs. These bulletins contain information about current location of cyclone in Lat./ Long., MSW (in knots), speed and direction of forecast movement & estimated central pressure, forecast position in Lat./Long and forecast winds in knots valid at HH+6, HH+12, HH+18 and HH+24 hrs in coded form.

(*v*) **TC Vital bulletin for modeling group** are prepared every six hourly from depression stage onwards and

TABLE 2

Area of Responsibility of ACWC/CWC

	Area of Responsibility		
Centre	Sea area	# Coastal area	Maritime State
ACWC Kolkata	Bay of Bengal	West Bengal, Andaman & Nicobar Islands	West Bengal & Andaman & Nicobar Islands.
ACWC Chennai		Tamil Nadu, Puducherry	Tamil Nadu, Puducherry,
ACWC Mumbai	Arabian Sea	Maharashtra, Goa	Maharashtra, Goa.
CWC Bhubaneshwar	-	Odisha	Odisha
CWC Visakhapatnam	-	Andhra Pradesh	Andhra Pradesh
CWC Ahmedabad	-	Gujarat, Diu, Daman, Dadra & Nagar Haveli	Gujarat, Diu, Daman, Dadra & Nagar Haveli
CWC Thiruvananthapuram	-	Kerala & Karnataka	Kerala, Karnataka & Lakshadweep

Coastal strip of responsibility extends upto 75 km. from the coast line

provided to various NWP modeling groups in India for generation/relocation of vortex in the model so as to improve the track and intensity forecast by the numerical models. It is issued in text and coded form. It contains information about the location, intensity, size, distribution of 28/34 kts winds around the system centre in four geographical quadrants and depth of system.

10.2. *Bulletin issued at national level*

The cyclone warnings are issued to central and state government officials in four stages by ACWCs/ CWCs and CWD at HQ. The **First Stage** warning known as **"PRE CYCLONE WATCH" is** issued at least 72 hours in advance contains early warning about the development of a cyclonic disturbance in the north Indian Ocean, it's likely intensification into a cyclone and the coastal belt likely to experience adverse weather. This early warning bulletin is addressed to the Cabinet Secretary and other senior officers of the Government of India including the Chief Secretaries of concerned maritime states. The **Second Stage** warning known as "CYCLONE ALERT" is issued at least 48 hrs in advance of the expected commencement of adverse weather over the coastal areas. It contains information on the location and intensity of the storm likely direction of its movement, intensification, coastal districts likely to experience adverse weather and advice to fishermen, general public, media and disaster managers. The **Third Stage** known as "CYCLONE WARNING" is issued at least 24 hours in advance of the expected commencement of adverse weather over the coastal areas. Landfall point is forecast more precisely at this stage along with the latest position of cyclone and its intensity, likely point and time of landfall, associated heavy rainfall, strong wind and storm surge alongwith their impact and advice to general public, media, fishermen and disaster managers.

The **Fourth Stage** known as "POST LANDFALL OUTLOOK" is issued by the concerned ACWCs/ CWCs/and CWD at HQ at least 12 hours in advance of expected time of landfall. It gives likely direction of movement of the cyclone after its landfall and adverse weather likely to be experienced in the interior areas.

However, the above procedure is applicable to the cyclones developing over the open sea area. In case the genesis takes place near the coast and thus restricts the lead time before the landfall, the above procedure may not be applicable. The cyclone warning may be issued directly bypassing the pre-cyclone watch and cyclone alert.

At national level, the bulletins are issued from the stage of depression onwards. During the stage of depression/deep depression; it is issued based on 0000, 0300, 0600, 1200 and 1800 UTC observations. When the system intensifies into a cyclonic storm, these bulletins are issued based on 0000, 0300, 0600, 0900, 1200, 1500, 1800 and 2100 UTC (every three hourly interval) observations. An example of graphical presentation of track forecast alongwith the cone of uncertainty and actual observed track in case of cyclone Titli is presented in Fig. 10. Frequent hourly updates are issued 12 hrs before landfall to various national & state level disaster managers based on the radar and other observations since VSCS Hudhud (October, 2014). Regular press releases and press conferences are held to provide latest updates to general public through media.

Types of bulletins and warnings issued in the interest of Mariners in cyclone specific situations are: (*i*) Sea area bulletins for shipping on high seas, (*ii*) Coastal weather bulletin for ships plying in coastal waters (upto 75 km off the coast line), (*iii*) Bulletins for Indian Navy, (*iv*) Port
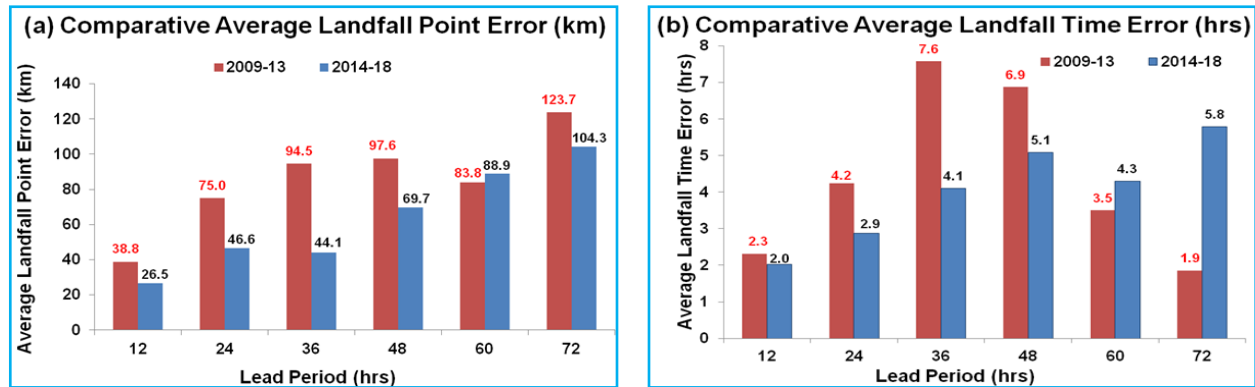
Figs. 11(a&b). Average landfall (a) point forecast error (km) and (b) time forecast error (hrs) during 2014-18 as compared to that during 2009-13

warnings, (*v*) Fishermen warnings, (*vi*) warning for fisheries officials, (vii) Four stage warning for disaster managers, (*viii*) Bulletin for all India radio (AIR), (*ix*) Warnings for Designated/Registered users, (*x*) Bulletins for Press etc.

The cyclone warnings are furnished on real time basis to the Control Room in the Ministry of Home Affairs, Government of India, besides other Ministries & Departments of the Central Government, Doordarshan and All India Radio (AIR) at New Delhi and other electronic and print media and concerned state Governments. Different colour codes are being used since post monsoon season of 2006 at different stages of the cyclone warning bulletins (cyclone alert-yellow, cyclone warning-orange and post landfall outlook-red), as desired by the Government. Cyclone warnings are disseminated to various users through telephone, fax, email SMS, Global Telecom System (GTS), WMO Information System (WIS), All India Radio, FM & community radio, Television and other print & electronic media, press conference & press release. These warnings/advisories are also put on the website (www.rsmcnewdelhi.imd.gov.in) of IMD. Since 2009, IMD has started SMS based weather and alert dissemination system through AMSS (Transmet) at RTH New Delhi. To further enhance this initiative, IMD has taken the leverage of Digital India Programme to utilize - Mobile Seva of Department of Electronics and Information Technology (DeitY), Ministry of Communication and Information Technology; Govt. of India for SMS based Warnings/Weather information dissemination for a wide range of users, since 2015. Global Maritime Distress and Safety System (GMDSS) message is also put in RSMC, New Delhi website (URL: www.rsmcnewdelhi.imd.gov.in) as well as transmitted through GTS. The WIS Portal - GISC New Delhi is another system for cyclone warning dissemination. The user can access the warning messages through the -URL: http://www.wis.imd.gov.in. IMD has also started issuing NAVTEX bulletins for the coastal region along east as

well as the west coast of India for the ships from 30th March, 2016. In addition IMD also issues SMS to farmers through Kisaan portal and fishermen through INCOIS.

11.   TC forecasting skill accuracy over NIO

All these initiatives as mentioned in previous sections have resulted in improved cyclone warning service delivery, timeliness of the warning and reduction in loss of lives as the outcome. Significant improvement in forecast errors was observed after the implementation of modernisation programme in IMD in 2009.

11.1.   *Landfall forecast accuracy*

Mohapatra *et al*. (2015b) analysed accuracy of TC landfall forecast with respect to basin of formation (BoB, AS and NIO as a whole), specific regions of landfall, season of formation [pre-monsoon and post-monsoon seasons), intensity of TCs (cyclonic storm (CS) and severe cyclonic storm (SCS) or higher intensities] at the time of initiation of forecast and type of track of TCs (climatological/straight moving and recurving/looping type). The landfall point forecast error (LPE) is less over the BOB than over the AS for all forecast lengths up to 72 hrs. Similarly, the LPE is less during the post-monsoon season than during pre-monsoon season. The LPEs are less for climatologically moving/straight moving TCs than for the recurving/looping TCs. The LPE over the NIO has decreased significantly during 2003-2018 for 24-hr forecasts. The landfall time error (LTE) shows relatively less improvement for 24-hr forecast during the same period. The LPE during 2014-18 has been 47, 70 and 104 km against 75, 98 and 124 km during 2009-13 [Fig. 11(a)] for 24, 48 & 72 hours lead period. Thus, 38%, 29% and 16% improvement in LPE was observed during 2014-18 compared to 2009-13 for 24, 48 and 72 hours lead period. The LTE dropped significantly during 2014-18 upto 48 hours lead period [Fig. 11(b)] and has been 2.9 and 5.1 hrs against 4.2 and 6.9 hrs during 2009-13
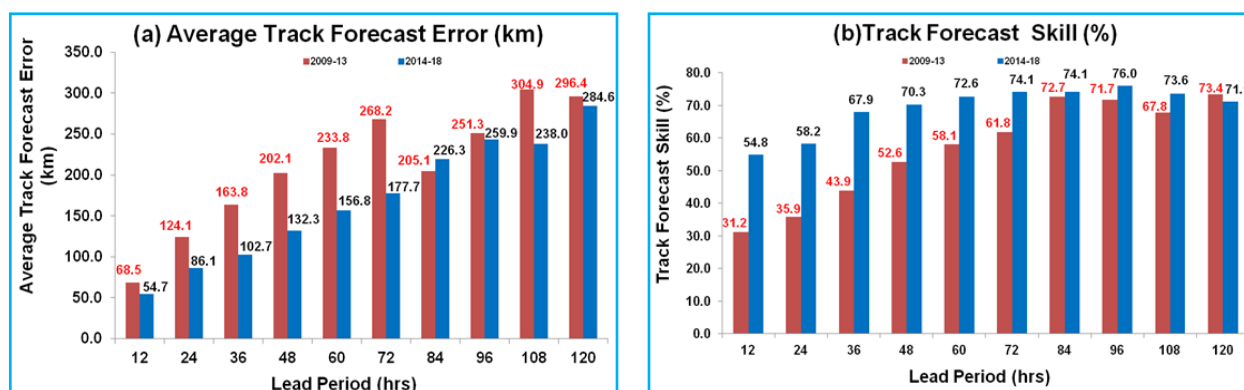
Figs. 12(a&b). Average track forecast (a) error (km) and (b) skill (%) during 2009-13 and 2014-18

for 24 & 48 hrs lead period respectively with an improvement of 32% and 26%.

However, there is still scope for further reduction of LPE to 30, 60, 90 km by 2030 for 24, 48 & 72 hrs respectively over the NIO as per the strategy document of MoES (2017) with the introduction of latest technology including aircraft reconnaissance, deployment of buoys and assimilation of more observational data from satellite and Doppler weather radars, etc. in the NWP models.

11.2. *Track forecast accuracy*

IMD introduced the objective tropical cyclone (TC) track forecast valid for next 24 hr over the north Indian Ocean (NIO) in 2003. It further extended the validity period up to 72 hr in 2009. Mohapatra *et al.* (2013d) evaluated the TC track forecast issued by IMD during 2003-2011 (9 years) by calculating the direct position error (DPE) and skill in track forecast. The accuracy of TC track forecast was also analysed with respect to basin of formation (BoB, AS and NIO as whole), season of formation (pre-monsoon and post-monsoon seasons), intensity of TCs (cyclonic storm and severe cyclonic storm or higher intensities) and type of track of TCs (climatological/straight moving and recurving/looping type). The error is higher over the AS than over the BOB and higher in premonsoon season than in post-monsoon season. The error is also higher in case of recurving track than in case of straight moving track. The track forecast error during 2014-18 has been 86, 132, 178 km against 124, 202, 268 km during 2009-13 for 24, 48 and 72 hrs lead period respectively [Fig. 12(a)]. The period during 2014-18 registered a decrease in track forecast error by 31, 35 & 34% as compared to 2009-13 for 24, 48 and 72 hours lead period respectively. Similarly skill also improved significantly during 2014-18 [Fig. 12(b)] and has been 58, 70 & 74% during 2014-18 against 36, 53 & 62% during 2009-13 for 24, 48 and 72 hrs lead period respectively.

There is scope for improvement in TC track forecast verification methods adopted for the NIO basin. The ensemble prediction system (EPS) which provides the strike probability and dynamical cone of uncertainty also need to be validated. The CLIPER model could be updated with the latest past data to serve as a better reference model.

A new approach called the Track Forecast Integral Deviation (TFID) integrates the track error over an entire forecast period (Yu *et al.*, 2013). This can be attempted over NIO. An alternative approach to examining the average errors is to consider the distributions of errors. Box plots are used to summarize the distributions of errors in forecasts. One obvious characteristic is the increase in the variability of the errors with increasing lead time. It can help in finding out the outliers. A number of other types of displays (e.g., scatter plots depicting the combined direction and magnitude errors around the actual storm location) also can be used to gain a better understanding of track error. Use of confidence intervals and statistical significance tests is also highly recommended for application to all aspects of operational forecast and model comparisons (Brown and Gilleland, 2011).

11.3. *Intensity forecasting accuracy*

According to Mohapatra *et al.* (2013e), IMD introduced the objective TC intensity forecast valid for next 24 hr over the north Indian Ocean (NIO) in 2003, extended up to 72 hr in 2009. In this study, an attempt was made to evaluate the TC intensity forecast issued by IMD during 2005-2011 (7 years) by calculating the absolute error (AE), root mean square error (RMSE) and skill in intensity forecast in terms of MSW. The accuracy of TC intensity forecast was also analysed with respect to basin of formation (BoB, AS and NIO as whole), season of formation (pre-monsoon and post-monsoon seasons), intensity of TCs (cyclonic storm and severe cyclonic storm or higher intensities) and type of track of TCs
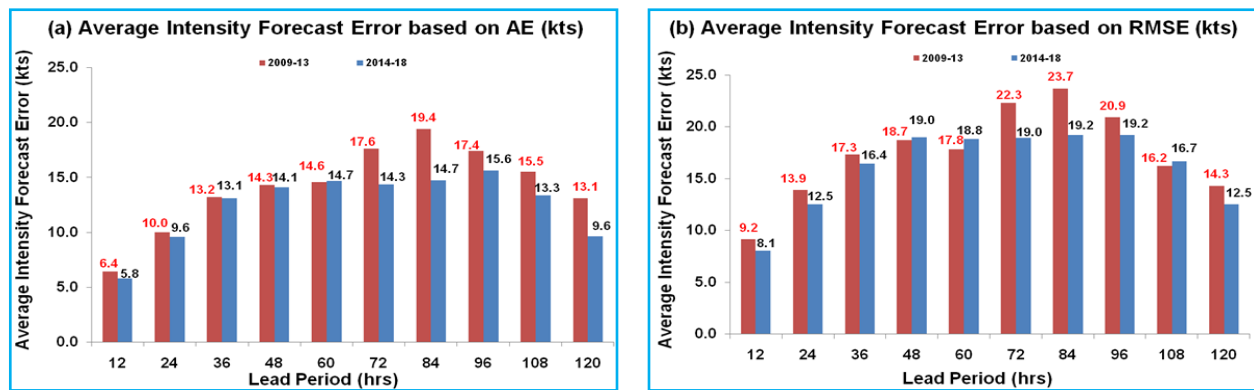
Figs. 13(a&b). Average intensity forecast error (knots) based on (a) AE and (b) RMSE during 2009-13 and 2014-18

(climatological/straight moving and recurving/looping type). The study shows that there is no significant improvement in terms of reduction in AE and RMSE of MSW forecast over the NIO like that over the northwest Pacific and northern Atlantic Oceans during 2005-2018.

Comparative analysis of intensity forecast errors based on AE & RMSE relative to persistence error is shown in Figs. 13(a&b). The intensity forecast errors based on AE during 2014-18 have been 9.6, 14.1 & 14.3 knots against 10.0, 14.3 & 17.6 knots during 2009-13 for 24, 48 and 72 hrs lead period respectively. An improvement of 4%, 2% and 19% has been observed in intensity forecast errors for 24, 48 and 72 hours lead period. Thus the improvement in TC intensity forecast is less as compared to that of landfall and track forecast like other Ocean basins.

Extreme winds in TCs can cause a large amount of structural damage when a TC makes landfall. Hence there is need for verification of forecast wind at landfall. It is at present verified by IMD in a qualitative method by comparing the forecast class and observed class of wind along the coast during the landfall of a TC. Wind speeds in TCs are difficult to measure accurately due to instrument measurement error and damage or even destruction of the instrument. Even with proper instrument, wind speed and direction are sensitive to local topographical effects, obstructions and spatial variations in TC structure (Otto, 2012). Deterministic forecasts for wind speed can be verified using approaches for continuous and categorical forecasts. Categorical verification of wind speed exceeding certain thresholds, for example, 34, 50 and 64 kt, is an approach that is commonly used. Verification of extreme wind speeds in TCs could be done using the Extremal Dependency Index (EDI) score.

There is scope for further reduction in intensity forecast error over the NIO in view of improved data availability in coming years. There can be (*i*) more accurate determination of MSW based on advanced high resolution satellite based wind estimation techniques, DWR observations, buoy and HWSR data etc. (*ii*) determination of maximum and minimum errors and hence range in errors in intensity estimation every year would serve to assess the improvements and consistency in intensity forecasts. (*iii*) The extreme wind values need to be validated with more authenticity and documented for records. (*iv*) A CLIPER model for intensity prediction similar to the Statistical Hurricane Intensity Forecast (SHIFOR) developed for the North Atlantic need to be developed for the NIO basin for using it as the reference model for analysing the skill in the intensity forecasts. (*v*) One important aspect of performance is missed by the traditional approach for evaluating TC intensity. In particular, this approach ignores possible "misses" and "false alarms" that might be associated with the forecasts (particularly if the forecasts are produced by NWP systems). Specifically, forecast TCs that do not exist in the best track data (e.g., that are projected to continue to exist after the actual storm has dissipated) should be counted as false alarms. Secondly, a storm that is projected to weaken and dissipate at an earlier time than the actual time of dissipation should be counted as a "miss". (*vi*) Aberson (2008) suggested using an m × m contingency table to show counts associated with different combinations of forecast and observed intensity, including cells for situations when either the forecast storm and/or the observed storm dissipated. This idea was applied by Yu *et al*. (2013), who extended the technique to be based on the contingency table for TC category forecasts. From a table like this, contingency table statistics like false alarm rate (FAR), probability of detection (POD) and Heidke Skill Score (HSS) could be computed to measure the impact of false alarms and misses and provide an appropriate measure of skill. Mohapatra *et al*. (2013e) have applied the method based on Aberson (2008) to demonstrate the utility of this method over the NIO. This method can be adopted operationally by IMD for intensity
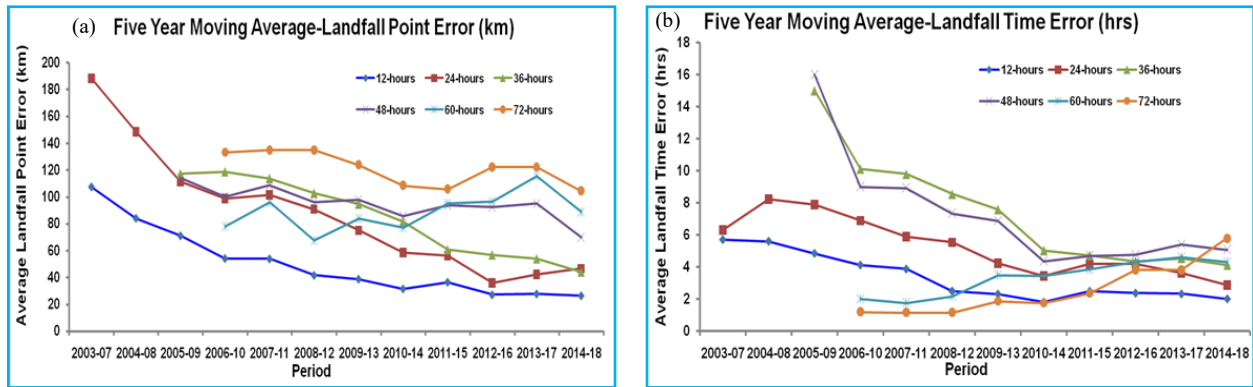
Figs. 14(a&b). Five Year Moving Average (a) Landfall Point Error (km) and (b) Landfall Time Error (hours)
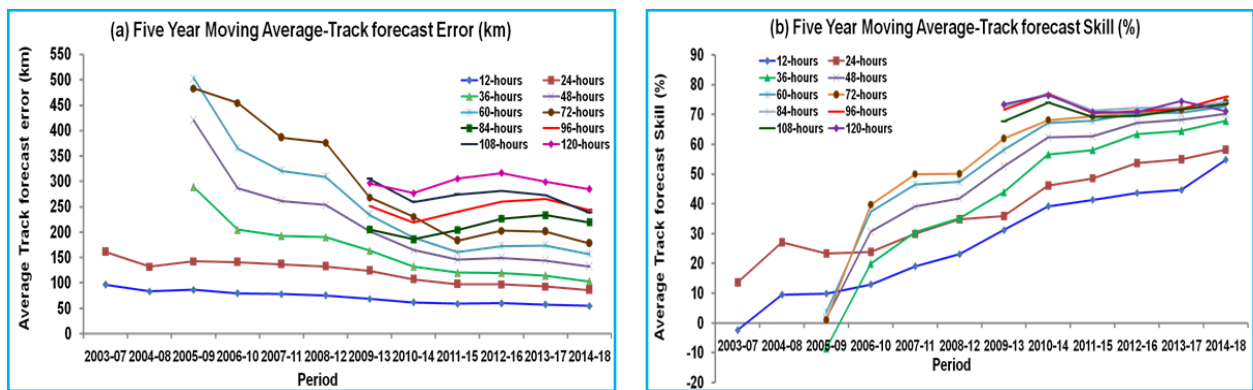
Figs. 15(a&b). Five Year Moving Average Track Forecast (a) Error (km) and (b) Skill (%)

forecast verification. (*vii*) The time evolution of TC intensity often is of interest; in particular, forecasters are often concerned about rapid changes in intensity - either increasing or weakening over the NIO like other Ocean basins. Typically this characteristic is measured by setting a threshold for a change in intensity over a 24-h period (e.g., 30 knots for rapid intensification and weakening). Normally this variable is treated as a Yes/No phenomenon (*i.e.*, either the rapid change occurred or it did not occur and it either was or was not forecast). In that case, basic categorical verification approaches can be applied to compute statistics such as POD and FAR. To obtain more complete information about the forecasts' ability to capture these events, the actual timing and intensity change errors associated with these forecasts could be measured and summarized (WMO, 2013).

11.4. *Five year moving averages of errors and skill*

It can be seen from Figs. 14(a&b) &15(a&b) that there has been continuous improvement in forecast accuracy with decrease in landfall and track forecast errors and increase in track forecast skill over the years. It is seen that due to modernization programme of IMD and other initiatives of MoES, the improvement has been more

significant since 2009. As the 36-72 hours forecasts commenced from 2009, the five year period of 2005-09, 2006-10, 2007-11, 2008-12 for these forecast times contain only 1, 2, 3 and 4 years of data respectively. However, the rate of improvement in intensity forecast over the years has been marginal as can be seen from Figs. 16(a&b).

12. Adverse weather warning

12.1. *Heavy rainfall warning*

The forecast/warning of heavy rainfall includes (*i*) time of commencement, (*ii*) duration, (*iii*) area of occurrence and (*iv*) intensity of heavy rainfall. The methods for prediction of heavy rainfall include (*i*) synoptic, (*ii*) climatological, (*iii*) satellite, (*iv*) radar and (*v*) NWP techniques. While NWP models provide prediction of rainfall for different lead period; satellite and radar provides quantitative precipitation estimates during past 3/12 hrs. The intensity and spatial distribution of rainfall estimated by satellite and radar are extrapolated to issue forecast. In synoptic and climatology method, synoptic climatology of rainfall intensity and spatial distribution are used. The final forecast is the consensus
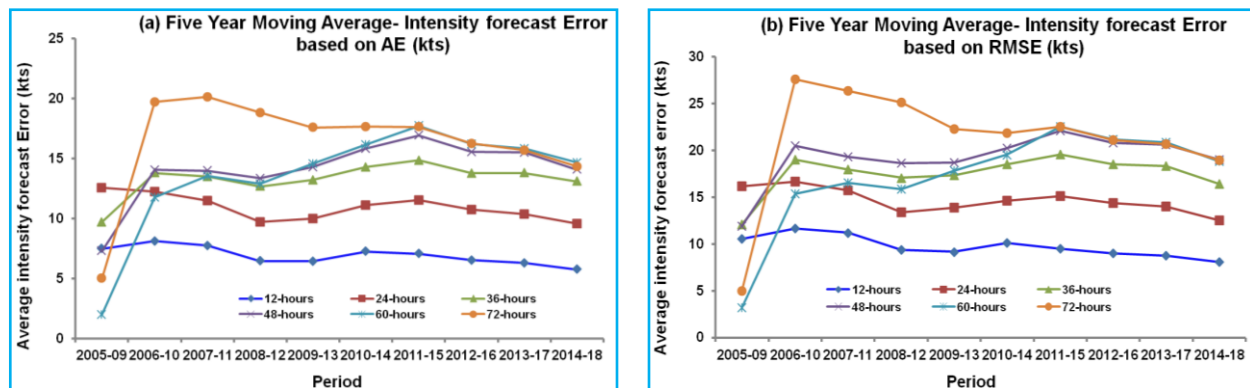
Figs. 16(a&b). Five Year Moving Average Intensity Forecast Error based on (a) AE and (b) RMSE

arrived from various methods as mentioned above. Though heavy rainfall prediction is very challenging, the HWRF model is a promising tool for heavy rainfall prediction (Ray *et al*., 2017; Mohanty *et al*. 2015). The percentage correct (PC) of 24 hour quantitative precipitation forecast (QPF) issued by IMD is about 33% *i.e*., the forecast issued by IMD is correct in about 1/3rd occasions, while the actual rainfall lies in the same range of forecast rainfall (Mohapatra, 2015c). It is seen that number of over-warning is less than the number of under-warning cases. Though, it is always advisable to have over-warning than under-warning in case of high impact weather events like TC rainfall which usually causes flood over the river catchment. The results of the study suggests, the need for further improvement in QPF to minimize over and under-warnings and hence to improve accuracy in forecast. There is scope for improvement in TC rainfall forecast verification. At present, heavy rainfall warnings issued in connection with landfalling TCs is verified on case by case basis only. A rigorous statistical verification procedure consolidating heavy rainfall forecasts of various categories could be adopted to assess the skill scores of the heavy rainfall forecasts. Rainfall associated with a TC when it is out in the sea also needs to be understood for improving our warnings. Daily satellite gauge merged rainfall dataset is being generated since 2013 by IMD and NCMRWF (Mitra *et al*., 2009) for the NIO region. This dataset could be used for objective verification over the sea and land region also. QPF is currently verified for a river catchment based on the area weighted average of point rainfall. Instead, satellite and rain gauge based merged rainfall data can be used for verification of QPF. A rainfall forecast model such as R-CLIPER (based on rainfall climatology and persistence) using the satellite based rain estimates could be developed for the NIO basin to serve as the baseline for verification of the skill of forecast. Verification of EPSgram is not carried out at present. Similarly, the location specific meteogram and local forecasts for TC related rainfall needs to be verified. NWP based QPFs could be verified based on

errors in the location as well as in the intensity of rainfall. For verifying extreme rain in the tails of the distribution, a new family of metrics called the "Extremal Dependency" scores has better statistical behaviour than standard contingency table scores (Ferro and Stephenson, 2011). The simplest of these scores is the EDI. Details are available in WMO (2013). The same can be attempted by RSMC, New Delhi. Marchok *et al*. (2007) describe a verification framework specifically geared for validating total storm rainfall in TCs in terms of rainfall pattern, mean rain intensity and volume and intensity distribution. They evaluated the radial distribution of precipitation by comparing forecast and observed intensity distributions within concentric rings centered on a storm (0-100 km, 100-200 km, etc.), including comparisons of the extreme (0.95th percentile) values of the forecasts and observations to test whether the heaviest rain in the forecast matches with that in the observations. This procedure can also be adopted over the NIO.

12.2.   *Storm surge warning*

Storm surge is the rise of sea water above the astronomical tide due to cyclone. The storm surge depends on pressure drop at centre, radius of maximum wind, point of landfall and interaction with sea waves, astronomical tide, rainfall, river run off, bathymetry, coastal geometry etc. (Dube *et al*., 2013). The forecast of storm surge includes (*i*) time of commencement, (*ii*) duration, (*iii*) area of occurrence and (*iv*) magnitude of storm surge. The methods for prediction of storm surge include (*i*) IMD Nomogram (Ghosh model), (*ii*) IIT Delhi Model (Dube *et al*., 2013) and INCOIS, Hyderabad model.

IMD has started issuing coastal inundation forecast based on coastal inundation forecast model run by INCOIS, Hyderabad since 2013 (Srinivas *et al*., 2015; Murty *et al*., 2017). It provides the combined effect of storm surge and astronomical tide. It needs to be further augmented with integration of hydrostatic models to take

care of past rainfall and forecast rainfall, river runoff and river discharge which also contribute to the net inundation over an area due to landfalling cyclone.

According to Srinivasa Kumar *et al.* (2015), the model marginally underestimated the magnitude with respect to observations of storm surge in case of TC Phailin (2013), which can be attributed to the lack of wave setup in the model and uncertainty in wind and pressure information. The experiment also involved the use of two idealized scenarios, that is, variation of landfall timings with the ebbing and high tide phase. These scenarios were required for better understanding the sensitivity of inundation to the phase of tide in the model. Simulation with landfall at flooding (ebbing) tide showed greater (lower) inundation than the real scenario. Results from idealized scenarios confirmed the significance of the accuracy needed in forecasting landfall time.

According to Mohapatra (2015c), verification of storm surge prediction is being carried out using a network of 50 tide gauges (36- by Survey of India and 14- by NIOT, India) along the coastal belt of India. However, objective verification is not practically possible if the TC landfall occurs over places unrepresented by the tide gauge network. As such, most storm surge verification is done manually by post landfall survey teams based on the saline water marks etc. Verifying storm surge warning during 2009-13, Mohapatra (2015c) found that there has been considerable over-warning of storm surge especially in case of TCs that weakened before landfall. It may be due to the fact that the accuracy of storm surge forecast depends on the accuracy level of track and intensity forecast of the meteorological inputs for storm surge. Higher the error in track and intensity forecasts, higher is the error in storm surge forecast. Further, the assessment of radius of maximum wind and hence the size of the storm need to be accurate for correct assessment of the storm surge.

There is scope for improving storm surge forecast over the NIO basin as per the following: (*i*) Denser network of tide gauges is very much essential for objective determination of storm surges. (*ii*) Further, it is difficult to verify coastal inundation due to storm surge. At present, it is estimated based on postcyclone survey. (*iii*) Verification of probabilistic storm surge prediction may have to be carried out when such forecasts would be issued by IMD. (*iv*) LANDSAT data and products could be used to determine coastal inundations objectively.

13. Significant outcome

Early Warning System is a major component of disaster management due to cyclone. Increase in lead time alongwith increase in accuracy of the forecast of genesis, track, intensity and adverse weather help in better management of disaster due to cyclone. Following are the significant outcome of improvement in cyclone warning services in the country:

(*i*) Reduction in loss of life: Though the damage due to cyclones cannot be minimized, the loss of life has been drastically reduced being limited to double digit figure in the recent years, like 64 deaths due to cyclone Fani (2019), 78 due to Titli (2018), 46 due to Hudhud (2014) and 21 due to Phailin (2013) as compared to 9885 due to Odisha Super Cyclone (October, 1999).

(*ii*) Reduction in cost of evacuation: Improvement in forecasting skills has drastically reduced the area of evacuation from about 500 km during 1999 Odisha Super Cyclone to 180 km during VSCS Phailin (2013). As a result the cost of evacuation has also reduced significantly being Rs. 180 crores during Phailin (2013) against Rs. 500 crores during Odisha Super Cyclone (1999). (Assuming the cost of evacuation as Rs. 1 crore per km for both the years).

(*iii*) Reduction in payment of ex-gratia by the Govt.: The ex-gratia paid by Govt. during Odisha Super Cyclone (1999) could be Rs. 593 crores with the death of about 9885 persons as against Rs. 1.24 crores during VSCS Phailin (2013) with the death of about 21 persons. (Assuming that ex-gartia @ Rs. 6 lakhs was paid by Govt. in both the years).

(*iv*) Consequent upon the success in monitoring, prediction and early warning services in case of VSCS Phailin (2013), Hudhud (2014), Vardah (2016), Sagar, Mekunu, Titli & Luban (2018) and Fani (2019), IMD received applause from various sectors. A number of appreciations and recommendations have been received at national and global level including appreciation from Hon'ble President of India, Hon'ble Prime Minister of India, Indian Science Congress, Parliamentary Standing Committee, WMO & United Nations, Regional Assiociation II, national level disaster managers including NDMA, NDRF, various coastal state governments, media and general public.

14. Conclusions

According to Mohapatra (2017b) and Heming *et al.*, 2018), there are some difficult situations wherein TC forecasting is still tricky and more challenging (such as recurving and rapidly intensifying/weakening TCs near the landfall point) than in other situations. IMD is regularly upgrading its observational and analytical capabilities to meet these challenges and to improve its forecasting skills further in the near future. With proposed ongoing modernisation programme, the error is likely to reduce by about 20% by 2025 from the base year of 2010.

The track forecast errors are higher over the Arabian Sea than over the Bay of Bengal, as Arabian Sea is more data sparse. The error is also higher in case of recurving and looping TCs than in case of straight moving TCs (Mohapatra *et al.*, 2013d).

The track forecast error is more difficult when there is rapid change in track near landfall. Such difficult situations include the (*i*) recurving TCs, (*ii*) rapid movement of TCs during landfall, (Slow movement/ stationarity of TC near the coast. It is found that the error is higher by about 5 to 20% for 12 hr to 72 hr lead period of forecasts in case of TCs with rapid track changes as compared to the mean track forecast errors based on the data of 2003-13 (Heming *et al.*, 2018). Comparing the track forecast errors of cyclones with sudden changes in track direction, rapid movement and slow movement, the error is maximum in case of sudden change in direction followed by rapidly moving TCs.

The intensity forecast error is higher for intense TCs than in weaker TCs. Intensity prediction is more difficult over Arabian Sea than over Bay of Bengal as it is more data sparse leading to poor initial conditions in NWP models. There is no DWR in AS rim countries. Number of buoys are also very less.

There are cases, when, the TC maintains its intensity with very slow decaying process after landfall. It specially occurs, when the TC moved over a plain surface, especially over deltaic region and during post-monsoon season (October-December). It occurs in post-monsoon season due to availability of moisture over the land surface and atmosphere due to monsoon circulation which prevailed during June-September and may extend to October during its withdrawal phase. A statistics based decay model for intensity prediction after landfall using the intensity at the time of landfall has been developed by IMD (Roy Bhowmik *et al.*, 2005). The error statistics shows that the model has still limitations. For the cyclone PHAILIN as an example, decay (after landfall) prediction curve (6-hourly up to 30 hr) showed fast decay compared to observed decay. As the model is statistical in nature, it does not take into consideration various dynamical and hydro-dynamical processes governing the decay of a TC after landfall. Hence prediction of decay of intensity of TC after landfall is still a challenge.

Another interesting part is the dissipation/rapid weakening of systems over NIO. It poses a great challenge to a forecaster as it very often leads to wrong/over-warning. The dissipation/rapid weakening over the sea may happen due to various reasons including colder Ocean thermal energy, entrainment of dry and cold continental air into the core of TC and increase in vertical wind shear in the horizontal wind. An example of very severe cyclonic storm, Lehar (23-28 November, 2013) over Bay of Bengal (Sharma and Mohapatra, 2017), which rapidly weakened before the landfall. It rapidly weakened over the sea from the stage of very severe cyclonic storm (75 knots) to depression (25 knots) in 18 hrs. It had landfall near Machillipatnam (Andhra Pradesh) as a depression. It did not cause any significantly heavy rainfall over Andhra Pradesh. The intensity forecast errors were very high. The error in intensity prediction led to large error in prediction of rainfall, wind and storm surge. However, the situation was managed by providing frequent update and immediate revision of forecasts with the sign of weakening envisioned through synoptic analyses. There is a need for development of dynamical statistical model for rapid weakening of TCs over the sea.

Due to absence of aircraft reconnaissance, detailed structural characteristics like wind & temperature distribution along the vertical and horizontal structure of eye and eye wall etc. over the NIO are not yet known. Studies made so far in this respect are mainly based on satellite and radar observations (Raghavan, 2013; Bhatia and Sharma, 2013). In recent years, the microwave imageries from the polar orbiting satellites have helped further to understand the structure of TC as it can provide the imageries in different levels of the TC (Jha *et al*., 2013). The structure of TC varies with respect to area of genesis, *viz.*, Bay of Bengal and Arabian Sea, season of formation (pre-monsoon and post-monsoon seasons), intensity of TCs (Mohapatra and Sharma, 2015)

Over the past several years, there have been large improvements in track forecast skill (Mohapatra *et al*., 2013d) and modest improvements in the intensity skill (Mohapatra *et al*., 2013e) like other Ocean basins. These errors, particularly the intensity errors negatively affect wind radii forecasts. The poor intensity forecast is particularly pronounced when intensity forecast fail to or falsely forecast winds that exceed the 34 kts, 50 kts and 64 kts thresholds.

There is shifting of convection and wind maxima during landfall sometimes leading to error in predicting heavy rainfall and wind over the land regions. To overcome this problem, R&D activities have been taken up to develop R-CLIPER for prediction of rainfall, QPE estimates based on Radar and INSAT 3D, introduction of HWRF etc.

IMD continuously expands and strengthens its activities in a collaborative mechanisms within and outside the country (Rathore *et al.*, 2017) in relation to observing strategies, forecasting techniques, disseminating methods and research relating to different aspects of

TCs to ensure most critical meteorological support through observations, analysis, predictions and warnings to disaster managers and decision makers not only in India but also to the NIO rim countries. Some of the planned activities include (*i*) augmentation of observational network, (*ii*) implementation of coupled HWRF model, (*iii*) introduction to probabilistic wind forecast, (*iv*) location of specific heavy rainfall forecast, (*v*) operationalisation of coastal inundation model, (*vi*) hydrological models and (*vii*) observed and satellite/ radar-based merged data set for TC rainfall etc.

The FDP on landfalling cyclones over the BoB has been taken up to minimise the error in prediction of TC track and intensity forecasts and hence adverse weather. During FDP (15 October-30 November, 2008-2018), several national institutions participated for joint observational, communicational & NWP activities resulting in improved forecast and delivery of services (Mohapatra *et al.*, 2013b). With possible manned/ unmanned aircraft reconnaissance it will help in improving TC track and intensity forecasting and hence the adverse weather warning, as demonstrated in Atlantic and Pacific Ocean basins.

Currently an effort is underway in which high resolution HWRF model with the support from NCEP, USA is being used in track & intensity predictions. It is being operationalised with inclusion of ocean component, which is being customized by INCOIS, Hyderabad. Attempt will be made to assimilate more observational data, especially remotely sensed satellite and DWR data as it has become necessary to provide adequate and realistic observations for frequent initialization of NWP models for short to medium range forecasting of track, intensity and associated adverse weather.

Acknowledgements

References

Aberson, S. D., 2008, "An alternative tropical cyclone intensity forecast verification technique", *Weather Forecasting*, **23**, 1304-1310, doi:10.1175/2008WAF2222123.1.

Bhatia, R. C. and Sharma, A. K., 2013, "Recent advances in observational support from space-based systems for tropical cyclones", *Mausam*, **64**, 97-104.

Brown, B. G., Gilleland, E. and Ebert, E. E., 2011, "Forecasts of spatial fields", *Forecast Verification: A Practitioner's Guide in Atmospheric Science*, 2nd Edition, Edited by Jolliffe, I. T. and Stephenson, D. B., Published by John Wiley & Sons, Ltd., 95-117.

Cerveny, Randall S., Bessemoulin, Pierre, Burt, Christopher C., Cooper, Mary Ann, Cunjie, Zhang, Dewan, Ashraf, Finch, Jonathan, Holle, Ronald L., Kalkstein, Laurence, Kruger, Andries, Lee, Tsz-cheung, Martínez, Rodney, Mohapatra, M., Pattanaik, D. R., Peterson, Thomas C., Sheridan, Scott, Trewin, Blair, Tait, Andrew and Abdel Wahab, M. M., 2017, "WMO Assessment of Weather and Climate Mortality Extremes: Lightning, Tropical Cyclones, Tornadoes and Hail", *American Meteorological Society*, **9**, 487-497, https://doi.org/10.1175/WCAS-D-16-0120.1.

Chinchole, P. S. and Mohapatra, M., 2017, "Some Characteristics of Translational Speed of Cyclonic Disturbances Over North Indian Ocean in Recent Years", *Tropical Cyclone Activity over the North Indian Ocean*, Ed. Mohapatra, M., Bandyopadhyay, B. K. and Rathore, L. S., Co-published by Capital Publishers, New Delhi and Springer, Germany, 165-179.

Chourasia, Manjusha, Ashrit, R. G. and George, John P., 2013, "Impact of cyclone bogusing and regional assimilation on tropical cyclone, track and intensity predictions", *Mausam*, **64**, 135-148.

Dube, S. K., Rao, A. D., Poulose, Jismy, Mohapatra, M. and Murty, T. S., 2013, "Storm surge inundation in south Asia under climate change scenario", *In: Monitoring and prediction of tropical cyclones over Indian Ocean and climate change,* Edited by Mohanty, U. C., Mohapatra, M., Singh, O. P., Bandyopadhyay, B. K. and Rathore, L. S. (In Press).

Dvorak, V. F., 1984, "Tropical cyclone intensity analysis using satellite data", Technical Report (NOAA TR NESDIS 11), *National Oceanic and Atmospheric Administration, National Environmental Satellite, Data and Information Service*, p47.

Elsberry, R. L., 2003, "Track forecast guidance improvement for early warnings of tropical cyclones", Early warning system for natural disaster reduction, Ed. Jochen Jschau and Andreas N Kuppers, Springer publication, New York, 167-184.

Elsner, J. B. and Kocher, B., 2000, "Global tropical cyclone activity: A link to the North Atlantic Oscillation", *Geophys. Res. Lett.*, **27**, 1, 129-132.

Ferro, C. A. T. and Stephenson, D. B., 2011, "Extremal dependence indices: Improved verification measures for deterministic forecasts of rare binary events", *Weather Forecast.*, **26**, 699-713.

Ghosh, S. K., 1977, "Prediction of storm surges on the east coast of India", *Indian J. Meteorol. Geophys.*, **28**, 157-168,

Gonnert, G., Dube, S. K., Murty, T. and Siefert, W., 2001, "Global storm surges: Theory, observations and applications", *Die Kueste*, p623.

Goyal, S., Mohapatra, M., Dube, S. K., Kumari, P. and De, I., 2016b, "Mesoscale convective systems in association with tropical cyclones over Bay of Bengal", *Natural Hazards*, **82**, 2, 963-979.

Goyal, S., Mohapatra, M., Kumar, A., Dube, S. K., Rajendra, K. and Goswami, P., 2016a, "Validation of a satellite-based cyclogenesis technique over the North Indian Ocean", *Journal of Earth System Science*, **125**, 7, 1353-1363.

Goyal, S., Mohapatra, M., Kumari, P., Dube, S. K. and Rajendra, K., 2017, "Validation of Advanced Dvorak Technique (ADT) over north Indian Ocean", *Mausam*, **68**, 4, 689-698.

Goyal, Suman, Mohapatra, M. and Sharma, A. K., 2013, "Comparison of best track parameters of RSMC, New Delhi with satellite estimates over north Indian Ocean", *Mausam*, **64**, 25-34.

Gray, W. M., 1968, "Global view of origin of Tropical disturbance and storms", *Mon. Wea Rev.*, **96**, 669-700.

Heming, Julian, Prates, Fernando, Bender, Morris, Cangialosi, John, Caroff, Phillippe, Doyle, James, Dube, Anumeha, Faure, Ghislain, Howell, Brian, Igarashi, Yohko, McTaggart-Cowan, Ron, Mohapatra, M., Moskaitis, Jon, Murtha, Jim, Rivett, Rabi, Sharma, Monica, Short, Chris, Singh, Amit, Tallapragada, Vijay, Titley, Helen and Xiao, Yi, 2018, "Review of Recent Progress in Tropical Cyclone Track Forecasting & Expression of Uncertainties", WMO/TCP/WWW Ninth International Workshop On Tropical Cyclones held at Honolulu, USA during December, 2018.

IMD, 1976, "Weather Radar Observations Manual", published by IMD.

IMD, 2003, "Cyclone Manual", published by IMD.

IMD, 2008, "Track of storm and depressions over the Indian Seas during 1891-2007", *Cyclone e-Atlas of IMD*, published by IMD.

IMD, 2013, "Cyclone Warning Services: Standard Operation Procedure", Published by Cyclone Warning Division, IMD, New Delhi.

Jha T. N., Mohapatra, M. and Bandyopadhyay, B. K., 2013, "Estimation of intensity of tropical cyclone over Bay of Bengal using microwave imagery", *Mausam*, **64**, 105-116.

Knaff, J. A., DeMaria, M. D., Molenar, A., Sampson, C. R. and Seybold, M. G., 2011, "An automated, objective, multi-satellite platform tropical cyclone surface wind analysis", *Journal of Applied Meteorology and Climatology*, **50**, 10, 2149-2166.

Knutson, Thomas, Camargo, Suzana J., Chan, Johnny C. L., Emanuel, Kerry, Ho, Chang-Hoi, Kossin, James, Mohapatra, Mrutyunjay, Satoh, Masaki, Sugi, Masato, Walsh, Kevin and Wu, Liguang, 2019, "Tropical Cyclones And Climate Change Assessment", *Bulletins of American Meteorological Society*, 1987-2007, BAMS-D-18-0189.

Kotal, S. D. and Bhattacharya, S. K., 2013, "Tropical cyclone Genesis Potential Parameter (GPP) and it's application over the north Indian Sea", *Mausam*, **64**, 149-170.

Kotal, S. D. and Roy Bhowmik, S. K., 2011, "A multimodel ensemble technique for cyclone track prediction over north Indian Sea", *Geofizika*, **28**, 275-291.

Kotal, S. D., Roy Bhowmik, S. K., Kundu, P. K. and Das, A. K., 2008, "A statistical cyclone intensity prediction model for Bay of Bengal", *J. Earth Syst. Sci.*, **117**, 157-168.

Kumar, S. V. J., Ashthikar, S. S. and Mohapatra, M., 2017, "Life Period of Cyclonic Disturbances Over the North Indian Ocean During Recent Years", *In: Tropical Cyclone Activity over the North Indian Ocean*, Ed. Mohapatra, M., Bandyopadhyay, B. K. and Rathore, L. S., Co-published by Capital Publishers, New Delhi and Springer, Germany, 181-198.

Lakshmanan, N., Gomathinayagam, S., Harikrishna, P., Abraham, A. and Chitra, Ganapathi S., 2009, "Basic wind speed map of India with long-term hourly wind data", *Current Science*, **96**, 911-922.

Mandal, G. S. and Prem Krishna, 2009, "Global warming, climate change and cyclone related destructive winds - Discussion of results from some selected studies with emphasis on the north Indian Ocean", *Global Environmental Research*, **13**, 141-150.

Marchok, T., Rogers, Robert and Tuleya, Rober E., 2007, "Validation Schemes for Tropical Cyclone Quantitative Precipitation Forecasts: Evaluation of Operational Models for U.S. Landfalling Cases", *Weather and Forecasting*, **22**, 726-746, doi:10.1175/WAF1024.1.

Mishra, D. K. and Gupta, G. R., 1976, "Estimates of maximum wind speed in tropical cyclones occurring in the Indian Seas", *Ind. J. Met. Geophys.*, **27**, 285-290.

Mitra, A. K., Bohra, A. K., Rajeevan, M. N. and Krishnamurti, T. N., 2009, "Daily Indian precipitation analyses formed from a merged of rain-gauge with TRMM TMPA satellite derived rainfall estimates", *Journal of the Meteorological Society of Japan*, **87A**, 265-279.

Mohanty, U. C., Osuri, Krishna K., Routray, A., Mohapatra, M. and Pattanayak, Sujata, 2010, "Simulation of Bay of Bengal Tropical Cyclones with WRF Model: Impact of Initial and Boundary Conditions", *Marine Geodesy*, **33**, 4, 294-314, doi:10.1080/01490419.2010.518061.

Mohanty, U. C., Osuri, Krishna K., Tallapragada, Vijay, Marks, Frank D., Pattanayak, Sujata, Mohapatra, M., Rathore, L. S., Gopalakrishnan, S. G. and Niyogi, Dev, 2015, "A Great Escape from the Bay of Bengal "Super Sapphire-Phailin" Tropical Cyclone: A Case of Improved Weather Forecast and Societal Response for Disaster Mitigation", *Earth Interactions*, **19**, 17, 151104123042003, doi:10.1175/EI-D-14-0032.1.

Mohapatra M., Bandyopadhyay, B. K. and Tyagi, Ajit, 2013c, "Construction and Quality of best tracks parameters for study of climate change impact on Tropical Cyclones over the North Indian Ocean during satellite era, Monitoring and Prediction of Tropical Cyclones in the Indian Ocean and Climate Change", Edited by: Mohanty, U. C., Mohapatra, M., Singh, O. P., Bandyopadhyay, B. K. and Rathore, L. S., 3-17, Capital Publishing Co. and Springer Publications Ltd.

Mohapatra, M. and Adhikary, S., 2011, "Modulation of cyclonic disturbances over the north Indian Ocean by Madden - Julian oscillation", *Mausam*, **62**, 375-390.

Mohapatra, M. and Kumar, V. V., 2017, "Interannual variation of tropical cyclone energy metrics over North Indian Ocean", *Climate Dynamics*, **48**, 1431-1445.

Mohapatra, M. and Mohanty, U. C., 2004, "Some characteristics of low pressure systems and summer monsoon rainfall over Orissa", *Current Science*, **87**, 9, 1245-1255.

Mohapatra, M. and Ranalkar, Manish, 2014c, "Utility of automatic weather station (AWS) data for monitoring and prediction of cyclonic disturbances during monsoon season, 2013", *IMD Met. Monograph, Synoptic Meteorology No. 1/2014*, 161-172, IMD, Pune.

Mohapatra, M. and Sharma, Monica, 2015, "Characteristics of surface wind structure of tropical cyclones over the north Indian Ocean", *Journal of Earth System Science*, **124**, 7, 1573-1598. doi:10.1007/s12040-015-0613-6.

Mohapatra, M., 2015a, "Cyclone hazard proneness of districts of India", *Journal of Earth System Science*, **124**, 3, 515-526, doi:10.1007/s12040-015-0556-y.

Mohapatra, M., 2015b, "Monitoring and prediction of tropical cyclones", *Monitoring and prediction of tropical cyclones over north Indian ocean*, Edited by: Mohanty, U. C., Mohapatra, M., Singh, O. P., Bandyopadhyay, B. K., Rathore, L. S., Capital Publishing Co. and Springer Publications Ltd., 3-17.

Mohapatra, M., 2015c, "Tropical cyclone forecast verification by India Meteorological Department For north Indian Ocean: A review", *Tropical Cyclone Research and Review*, **3**, 1-14.

Mohapatra, M., 2017a, "Monitoring and Forecasting of Tropical Cyclones over North Indian Ocean", In: *Advanced Numerical Modeling and Data Assimilation Techniques for Tropical Cyclone Prediction*, Ed. Mohanty, U. C. and Gopalakrishnan, S. G., Co-published by Capital Publishers, New Delhi and Springer, Germany, 409-447.

Mohapatra, M., 2017b, "Tropical Cyclone Track, Structure and Intensity Changes at Landfall", *Tropical Cyclone Activity over the North Indian Ocean*, Ed. Mohapatra, M., Bandyopadhyay, B. K. and Rathore, L. S., Co-published by Capital Publishers, New Delhi and Springer, Germany, 97-116.

Mohapatra, M., Bandyopadhyay, B. K. and Nayak, D. P., 2013e, "Evaluation of operational tropical cyclone intensity forecasts over north Indian Ocean issued by India Meteorological Department", *Natural Hazards*, **68**, 2, 433-451, doi:10.1007/s11069-013-0624-z.

Mohapatra, M., Bandyopadhyay, B. K. and Rathore, L. S., 2014a, "Very Severe Cyclonic Storm (VSCS), "Phailin" over the Bay of Bengal during 08-14 October 2013: A Demonstration of Early Warning Capability of India Meteorological Department", Proceedings of Third International Workshop on Tropical Cyclone Landfall Processes, WMO/CAS/WWW, 1-20

Mohapatra, M., Bandyopadhyay, B. K. and Tyagi, Ajit, 2012b, "Best track parameters of tropical cyclones over the North Indian Ocean: A review", *Natural Hazards*, **63**, 3, 1285-1317, doi:10.1007/s11069-011-9935-0.

Mohapatra, M., Bandyopadhyay, B. K. and Tyagi, Ajit, 2013a, "Status and Plans for operational Tropical Cyclone Forecasting and Warning Systems in the North Indian Ocean region, Monitoring and Prediction of Tropical Cyclones in the Indian Ocean and Climate Change", Edited by: Mohanty, U. C., Mohapatra, M., Singh, O. P., Bandyopadhyay, B. K., Rathore, L. S., 149-168, Capital Publishing Co. and Springer Publications Ltd.

Mohapatra, M., Bandyopadhyay, B. K., Ray, Kamaljit and Rathore, L. S., 2014b, "Early Warning Services for Management of Cyclones over North Indian Ocean : Current status and future scope, High Impact Weather Events over SAARC Region", Ed. Ray, Kamaljit, Mohapatra, M., Bandyopadhyay, B. K. and Rathore, L. S., Capital Publishing Co. and Springer Publications Ltd.

Mohapatra, M., Geetha, B. and Sharma, M., 2017b, "Reduction in uncertainty in tropical cyclone track forecasts over the North Indian Ocean", *Current Science*, **112**, 9, 1826-1830.

Mohapatra, M., Geetha, B., Balachandran, S. and Rathore, L. S., 2015a, "On the Tropical Cyclone Activity and Associated Environmental Features over North Indian Ocean in the Context of Climate Change", *Journal of Climate Change*, **1**, 1-26.

Mohapatra, M., Gupta, D. C., Chanchalani, N. K. and Dastidar, S. K., 2002, "Orissa Super Cyclone, 1999 - A case study", *Journal of Indian Geophysical Union*, **6**, 93-106.

Mohapatra, M., Kumar, Naresh and Ranalkar, Manish, 2011, "Utility of automatic weather station (AWS) data for monitoring and prediction of cyclonic disturbances during 2010", *IMD Met. Monograph, Synoptic Meteorology No. 10/2011*, 189-203, IMD, Pune.

Mohapatra, M., Kumar, Naresh and Ranalkar, Manish, 2012d, "Utility of automatic weather station (AWS) data for monitoring and prediction of cyclonic disturbances during monsoon season, 2011", *IMD Met. Monograph, Synoptic Meteorology No. 1/2011*, 161-172, IMD, Pune.

Mohapatra, M., Mandal, G. S., Bandyopadhyay, B. K., Tyagi, Ajit and Mohanty, U. C., 2012a, "Classification of cyclone hazard prone districts of India", *Natural Hazards*, **63**, 3, 1601-1620, doi:10.1007/s11069-011-9891-8.

Mohapatra, M., Nayak, D. P. and Bandyopadhyay, B. K., 2012c, "Evaluation of Cone of Uncertainty in Tropical Cyclone Track Forecast over North Indian Ocean Issued by India Meteorological Department", *Tropical Cyclone Research and Review*, **1**, 331-339.

Mohapatra, M., Nayak, D. P., Sharma, Monica, Sharma, R. P. and Bandyopadhyay, B. K., 2015b, "Evaluation of official tropical cyclone landfall forecast issued by India Meteorological Department", *Journal of Earth System Science*, **124**, 4, 861-874, doi:10.1007/s12040-015-0581-x

Mohapatra, M., Nayak, D. P., Sharma, R. P. and Bandyopadhyay B. K., 2013d, "Evaluation of official tropical cyclone track forecast over north Indian Ocean issued by India Meteorological Department", *Journal of Earth System Science*, **122**, 3, 589-601; doi:10.1007/s12040-013-0291-1.

Mohapatra, M., Ranalkar, M. R. and Devi, S. Sunitha, 2015c, "Validation of automatic weather station (AWS) data for monitoring and prediction of the low pressure systems during the monsoon season", *IMD Met. Monograph: ESSO Document No.: ESSO/IMD/SYNOPTIC MET/01(2015)/17*, 171-188, IMD, Pune.

Mohapatra, M., Sikka, D. R., Bandyopadhyay, B. K. and Tyagi, Ajit, 2013b, "Outcomes and challenges of Forecast Demonstration Project (FDP) on landfalling cyclones over Bay of Bengal", *Mausam*, **61**, 1, 1-12.

Mohapatra, M., Srivastava, A. K., Balachandran, S. and Geetha, B., 2017a, "Inter-annual Variation and Trends in Tropical Cyclones and Monsoon Depressions Over the North Indian Ocean", *Observed Climate Variability and Change over the Indian Region*, Ed. Rajeevan, M. and Nayak, Shailesh, published by Springer, Germany, 89-106.

Murty, P. L. N., Padmanabham, J., Srinivasa Kumar, T., Kiran Kumar, N., Ravi Chandra, V., Shenoi, S. S. C. and Mohapatra, M., 2017, "Real-time storm surge and inundation forecast for very severe cyclonic storm 'Hudhud'", *Ocean Engineering*, **131**, 25-35.

Nayak, D. P. and Mohapatra, M., 2017, "Rapid Movement of Cyclone Viyaru Just Before Landfall - A Case Study", *Tropical Cyclone Activity over the North Indian Ocean*, Ed. Mohapatra, M., Bandyopadhyay, B. K. and Rathore, L. S., Co-published by Capital Publishers, New Delhi and Springer, Germany, 149-163.

Osuri, Krishna K., Mohanty, U. C., Routray, A. and Mohapatra, M., 2012b, "The impact of satellite-derived wind data assimilation on track, intensity and structure of tropical cyclones over the North Indian Ocean", *International Journal of Remote Sensing*, **33**, 5, 1627-1652,doi:10.1080/01431161.2011.596849.

Osuri, Krishna K., Mohanty, U. C., Routray, A. and Mohapatra, M., 2013, "Real-Time Track Prediction of Tropical Cyclones over the North Indian Ocean Using the ARW Model", *Journal of Applied Meteorology and Climatology*, **52**, 11, 2476-2492.

Osuri, Krishna K., Mohanty, U. C., Routray, A., Kulkarni, Makarand A. and Mohapatra, M., 2012a, "Customization of WRF-ARW model with physical parameterization schemes for the simulation of tropical cyclones over North Indian Ocean", *Natural Hazards*, **63**, 3, 1-23, 1337-1359; DOI:10.1007/s110 69-011-9862-0.

Otto, P., 2012, "Tropical Cyclone Wind Field determination: Challenges and Possibilities", *Tropical Cyclone Research and Review*, **1**, 118-129.

Pattanaik, D. R. and Mohapatra, M., 2016, "Seasonal Forecasting of Tropical Cyclogenesis over the North Indian Ocean", *Journal of Earth System Science*, **125**, 231-250, doi:10.1007/s12040-016-0663-4.

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*, **25**, 1523-1530.

Raghavan, S., 2013, "Observational aspects including weather radar for tropical cyclone monitoring", *Mausam*, **64**, 89-96.

Rathore, L. S., Mohapatra, M. and Geetha, B., 2017, "Collaborative Mechanism for Tropical Cyclone Monitoring and Prediction over North Indian Ocean", *Tropical Cyclone Activity over the North Indian Ocean*, Ed. Mohapatra, M., Bandyopadhyay, B. K. and Rathore, L. S., Co-published by Capital Publishers, New Delhi and Springer, Germany, 3-27.

Ray, K., Mohapatra, M., Chakravarthy, K., Ray, S. S., Singh, S. K. and Das, A. K., 2017, "Hydro-Meteorological Aspects of Tropical Cyclone Phailin in Bay of Bengal in 2013 and the Assessment of Rice Inundation due to Flooding", *Tropical Cyclone Activity over the North Indian Ocean*, Ed. Mohapatra, M., Bandyopadhyay, B. K. and Rathore, L. S., Co-published by Capital Publishers, New Delhi and Springer, Germany, 29-43.

Roxy, Mathew Koll, Modi, Aditi, Murtugudde, Raghu, Valsala, Vinu, Panickal, Swapna, Kumar, S. Prasanna, Ravichandran, M., Vichi, Marcello and Levy, Marina, 2015, "A reduction in marine primary productivity driven by rapid warming over the tropical Indian Ocean", *Geophysical Research Letters*, **43**, 2, 826-833, https://doi.org/10.1002/2015GL066979.

Roy Bhowmik, S. K., Kotal, S. D. and Kalsi, S. R., 2005, "An empirical model for predicting decaying rate of tropical cyclone wind speed after landfall over Indian region", *J. Appl. Meteor.*, **44**, 179-185.

RSMC, New Delhi, 2015, "Report on cyclonic disturbances over north Indian Ocean during 2014", published by Cyclone Warning Division, IMD, New Delhi.

RSMC, New Delhi, 2019, "Report on cyclonic disturbances over north Indian Ocean during 2018", published by Cyclone Warning Division, IMD, New Delhi.

Sabade, B. and Mohapatra, M., 2017, "Very Severe Cyclonic Storm MADI over Bay of Bengal, 6-13 December 2013: A Diagnostic Study", *Tropical Cyclone Activity over the North Indian Ocean*, Ed. Mohapatra, M., Bandyopadhyay, B. K. and Rathore, L. S., Co-published by Capital Publishers, New Delhi and Springer, Germany, 117-130.

Sharma, M. and Mohapatra, M., 2013, "Possible causes of explosive intensification of VSCS GIRI over the Bay of Bengal", Proceedings of International Conference on Indian Ocean Tropical Cyclone and Climate Change (14-17 February 2012)

New Delhi, India, published by WMO, WWRP 2013-14, 131-138.

Sharma, M. and Mohapatra, M., 2017, "Standard Operation Procedure for Tropical Cyclone Vital Parameters over North Indian Ocean", *Tropical Cyclone Activity over the North Indian Ocean*, Ed. Mohapatra, M., Bandyopadhyay, B. K. and Rathore, L. S., Co-published by Capital Publishers, New Delhi and Springer, Germany, 367-381.

Sharma, R. P. and Mohapatra, M., 2017, "Rapid Weakening of Very Severe Cyclonic Storm 'Lehar' - A Case Study", *Tropical Cyclone Activity over the North Indian Ocean*, Ed. Mohapatra, M., Bandyopadhyay, B. K. and Rathore, L. S., co-published by Capital Publishers, New Delhi and Springer, Germany, 131-147.

Singh, Kasturi, Panda, Jagabandhu, Sahoo, Monalisa and Mohapatra, Mrutyunjay, 2018, "Variability in Tropical Cyclone Climatology over North Indian Ocean during the Period 1891 to 2015", *Asia-Pacific Journal of the Atmospheric Sciences*, **55**, 2, 269-287, doi:10.1007/s13143-018-0069-0.

Srinivasa Kumar, T., Murty, P. L. N., Pradeep Kumar, M., Krishna Kumar, M., Padmanabham, J., Kiran Kumar, N., Shenoi, S. C., Mohapatra, M., Nayak, Shailesh and Mohanty, Prakash, 2015, "Modeling Storm Surge and its Associated Inland Inundation Extent Due to Very Severe Cyclonic Storm Phailin", *Marine Geodesy*, **38**, 4, 345-360, doi:10.1080/01490419.2015.1053640.

Tyagi, Ajit, Mohapatra, M., Bandyopadhyay, B. K. and Kumar, Naresh, 2010, "Inter-annual variation of frequency of cyclonic disturbances landfalling over WMO/ESCAP Panel Member Countries", WMO Technical Document, WMO/TD-No. 1541 WWRP-210-2, 1-7, WMO, Geneva.

Uhlhorn, E. W. and Black, P. G., 2003, "Verification of remotely sensed sea surface winds in hurricanes", *J. Atmos. Ocean. Technol.*, **20**, 99-116.

Velden, C. S., Harper, B., Wells, F., Beven II, J. L., Zehr, R., Olander, T., Mayfield, M., Guard, C. C., Lander, M., Edson, R., Avila, L., Burton, A., Turk, M., Kikuchi, A., Christian, A., Caroff, P. and McCrone, P., 2006, "The Dvorak tropical cyclone intensity estimation technique: A satellite-based method that has endured for over 30 years", *Bull. Amer. Met. Soc.*, **87**, 1195-1210.

Wang, B., 1995, "Interdecadal changes in El Nino onset in last four decades", *J. Climate*, **8**, 267-285.

WMO, 2013, "Verification methods for tropical cyclone forecasts", WWRP/WGNE Joint Working Group on Forecast Verification Research WWRP 2013-17, 2013, p89, [Available online at http://www.wmo.int/pages/prog/arep/wwrp/new/documents/WWRP_2013_7_TC_verification_15_Nov_en.pdf.].

WMO, 2016, "Tropical Cyclone Operation Plan-21, 2016 Edition", WMO/TD No. 84.

Yu Hui, Chen, Guomin and Brown, Barbara, 2013, "A New Verification Measure for Tropical Cyclone Track Forecasts and its Experimental Alication", *Tropical Cyclone Research and Review*, **2**, 4, 185-195.