MAUSAM, **76**, 1 (January 2025), 103-124

MAUSAM

DOI : https://doi.org/10.54302/mausam.v76i1.6940
Homepage: https://mausamjournal.imd.gov.in/index.php/MAUSAM

UDC No.551.515.2:504.4(540)

Evolution of cyclone monitoring and forecasting system in India: A review

M. MOHAPATRA, M. SHARMA and D. R. PATTANAIK

India Meteorological Department, MoEs, Lodi Road, New Delhi - 110 003, India

e mail : mohapatraimd@gmail.com

सार – भारत के पूर्वी तट पर एक के बाद एक दो भयंकर चक्रवाती तूफान आए, जिससे मानव जीवन और संपत्ति की भारी क्षति हुई - पहला अक्टूबर में कोलकाता में आया और दूसरा नवंबर, 1864 में मछलीपट्टनम में आया। इन आपदाओं से चिंतित होकर, सरकार ने एक समिति नियुक्त की 1865 में एक चक्रवात चेतावनी प्रणाली विकसित करने की योजना तैयार की गई, विशेषकर कोलकाता भाग के लिए। तब से, भारत मौसम विज्ञान विभाग (आईएमडी) अवलोकन नेटवर्क में वृद्धि, बुनियादी ढांचे और संगठनात्मक सेट अप, संचार प्रणाली, मॉडलिंग सहित प्रारंभिक चेतावनी प्रणाली (ईडब्ल्यूएस) के सभी घटकों को संबोधित करने के लिए विभिन्न चरणों में बहुत व्यवस्थित तरीके से आगे बढ़ा। उष्णकटिबंधीय चक्रवातों (टीसी) की निगरानी और भविष्यवाणी, मानक संचालन प्रक्रिया के निरंतर उन्नयन के साथ-साथ निगरानी, पूर्वानुमान और चेतावनी सेवाओं के लिए नई तकनीक का परिचय और कार्यान्वयन। परिणामस्वरूप, आईएमडी टीसी बिपरजॉय (जून 2023) के दौरान गुजरात राज्य में शून्य मृत्यु और न केवल भारत में बल्कि बंगाल की खाड़ी (बीओबी) और अरब सागर (एएस)। की सीमा से लगे 13 देशों में किसी भी टीसी के कारण पिछले दशक में 100 से कम मौतें हासिल कर सका। इन सबके परिणामस्वरूप क्षेत्र में सामाजिक-आर्थिक स्थितियों में समग्र सुधार हुआ है और न केवल आईएमडी बल्कि भारत को भी नाम और प्रसिद्धि मिली है। यह पांडुलिपि भारत में चक्रवात चेतावनी प्रणाली के विकास के विभिन्न चरणों की जानकारी प्रदान करती है।

ABSTRACT. Two severe cyclonic storms hit the east coast of India in quick succession causing enormous loss of human lives and property – the first one struck Kolkata in October and the second one struck Machilipatnam in November, 1864. Concerned with these disasters, the Government appointed a committee in 1865 to formulate a scheme to develop a cyclone warning system, especially for Kolkata part to begin with. Since then, the India Meteorological Department (IMD) moved ahead in a very systematic manner in different stages to address all components of early warning system (EWS) including enhancement of observational network, development of infrastructure & organizational set up, communication system, modeling, monitoring & prediction of tropical cyclones (TCs), introduction & implementation of new technology for monitoring, forecasting and warning services along with continuous upgradation of standard operating procedure. As an outcome, the IMD could achieve zero death in Gujarat state during TC Biparjoy (June 2023) and less than 100 deaths due to any TC not only in India but also in the 13 countries bordering the Bay of Bengal (BoB) and the Arabian Sea (AS) in last decade. All these have resulted in overall improvements in socio-economic conditions in the region and also earned name & fame not only to IMD but also to India. This manuscript provides an insight into various phases in the development of Cyclone Warning System in India.

Key words – Tropical cyclones, Early warning system.

1. Introduction

The warm tropical north Indian Ocean (NIO), is a breeding ground for the disastrous tropical cyclone (TC). Historically, in terms of loss to human life, the Bay of Bengal (BoB) TCs accounted for deaths exceeding thousands (Dube *et al*., 2013). The India Meteorological Department (IMD) under the Ministry of Earth Sciences (MoES) has prepared a map of the cyclone hazard proneness of the coastal districts of India based on frequency of cyclones, their intensity, actual/estimated maximum wind strength, Probable Maximum Storm Surge (PMSS) associated with the cyclones and Probable Maximum Precipitation (PMP) for all districts along the coastline (Mohapatra *et al*., 2012a, Mohapatra, 2015a). 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,

TABLE 1.

Criteria for classification of cyclonic disturbances over the North Indian Ocean

Sr. No.	Type of disturbance	Associated maximum sustained wind (MSW)
1.	Low Pressure Area	Not exceeding 17 knots (<31 kmph)
2.	Depression	17 to 27 knots (31-49 kmph)
3.	Deep Depression	28 to 33 Knots (50-61 kmph)
4.	Cyclonic Storm	34 to 47 Knots (62-88 kmph)
5.	Severe Cyclonic Storm	48 to 63 Knots (89-117 kmph)
6.	Very Severe Cyclonic Storm	64 to 119 Knots (118-221 kmph)
7.	Super Cyclonic Storm	120 Knots and above (≥222 kmph)

and Kolkata of West Bengal, Balasore, Bhadrak, Kendrapara and Jagatsinghpur districts of Odisha, Nellore, Krishna and east Godavari districts of Andhra Pradesh and Yanam of Puducherry. (Mohapatra *et al*., 2012 a). According to MD's criteria, (IMD, 2024 and Sharma and Mohapatra, 2017), the cyclonic disturbances have been classified into various categories based on associated maximum sustained wind speed (Table 1).

However, during recent years, there has been significant reduction in loss of life, cost of evacuation and loss in government exchequer towards payment of ex-gratia *etc*. through the proactive involvement of three-tier disaster management agencies at central, state and district levels based on accurate and timely warnings by IMD (IMD, 2024, Sharma & Mohapatra, 2017 and Mohapatra *et al*., 2012b). According to Mohapatra *et al*., 2020, Mohanty *et al*., 2015, Mohapatra *et al*., 2022 and NDMA 2008, it has been possible due to continuous upgradation of all the components of early warning based on latest technology for effective management of TCs. The early warning component includes skill in monitoring and prediction of TCs, research and development leading to introduction of scientific methods, tools and technology, effective warning products generation and dissemination, coordination with emergency response units and the public perception about the credibility of the official predictions and warnings (Mohapatra *et al*., 2012b; IMD, 2024). The cyclone warning system has undergone many changes over the years starting from 1865. A review is made about the cyclone warning system including cyclone monitoring, prediction, physical understanding and warning services over the Bay of Bengal and Arabian Sea region, gap areas and future scope for further improvement.

The details of the origin of cyclone warning system and the evolution of the cyclone warning organization and institutional mechanism are discussed in Section 2 and 3 respectively. Section 4 discusses the evolution of monitoring and forecasting system. Section 5 discusses the frequency of cyclones in each version of prediction system. Section 6 and 7 respectively discuss comparative analysis of losses in various versions and accuracy compared to other international centers. Conclusions and future scope are discussed in Section 8.

2. Origin of cyclone warning system

In 1864, two severe cyclonic storms hit the east coast of India in quick succession causing enormous loss of human lives and property - the first one struck Kolkata in October and the second one struck Machilipatnam in November (IMD, 2024). Concerned with these disasters, the Government appointed a committee in 1865 to formulate a scheme to develop a system of cyclone warnings (IMD 2013, 2021). On the recommendations of the committee, Kolkata became the first port where a storm warning system was established in 1865 (IMD, 2024). Thus, cyclone prediction system originally started in India in 1865. It is noteworthy to mention that the storm warnings from Kolkata Port started even before the establishment of the IMD in 1875. The storm warning scheme for west coast ports (Mumbai, Karachi, Ratnagiri, Vengurla, Karwar and Kumta) came into force in 1880. In 1882, besides Kolkata, the ports at Sagar Islands, Mud Port and Diamond Harbour were also included in the list of ports getting storm warning messages. By 1886, the system of early warnings against cyclones was extended to cover all Indian ports (IMD, 2003 b). Upto 1898, two different systems of storm warning signals (one for the east coast ports and another for west coast ports) were in use. Different systems of signals, created confusion. Hence a uniform system of storm warning signals was introduced at all the Indian ports in 1898 (IMD, 2000).

3. Evolution of Organizational structure/ institutional mechanism

Kolkata office was responsible for issuing storm warning to all the ports (including those of Burma now Myanmar) around the Bay of Bengal since 1865, while the west coast ports were served by the Bombay Meteorological Reporter initially since 1886 and later from Shimla which was then the headquarters of IMD (Mohapatra *et al*., 2012b). In 1928, the headquarter of IMD was shifted from Shimla to Pune (Mohapatra *et al*., 2012b, IMD, 2000) and the storm warning work for west coast also shifted to Pune. Till 1945, the storm warning work was managed by Kolkata and Pune offices for Bay of Bengal and Arabian Sea respectively (IMD, 2000).

With the formation of Regional Meteorological Centres soon after the World War II, the storm warning work for the Bay ports on the east coast from southwards of Kalingapatnam was transferred to Chennai (Meenambakkam) in 1945 (IMD, 2024). Similarly, the responsibility for the Arabian Sea ports was taken over by the Meteorological Office at Santacruz (Mumbai) in 1947 (IMD, 2024). As the combination of the meteorological activities for aviation and marine interests in the same office had some drawbacks, these two activities were bifurcated to achieve a more efficient functioning of the storm warning service. Separate storm warning centres were established at Colaba (Mumbai) in 1956 and at Nungambakkam (Chennai) in 1969 (IMD, 2024). The responsibility for the ports on the west coast from Karwar southwards was also transferred from Mumbai to Chennai in 1969 (IMD, 2024).

In 1969, the Government of India appointed Cyclone Distress Mitigation committee (CDMC) for Andhra Pradesh to examine various measures to mitigate human sufferings and reduce loss of life and property due to cyclones (IMD, 2024). Subsequently, similar committees were set up for Orissa and West Bengal. The CDMCs for Andhra Pradesh and Orissa recommended establishment of separate storm warning centres at Visakhapatnam and Bhubaneshwar for issuing cyclone warnings to coastal Andhra Pradesh and coastal Odisha respectively (IMD, 2024) during 1971-72. Consequently, a storm warning centre was set up at Visakhapatnam in 1974, and at Bhubaneshwar in 1973 for catering to the needs of Andhra Pradesh and Odisha respectively. In pursuance of the recommendations of Cyclone Review Committee (CRC), another Storm Warning Centre was established at Ahmedabad in 1988 for catering the needs of Gujarat state and Union Territory of Diu, Daman, Dadra & Nagar Haveli. Subsequent to the adverse impact of TC, Ockhi in December, 2017 over south Arabian Sea and southern states of Kerala & South Tamil Nadu, it was decided to establish a cyclone warning centre in Thiruvananthapuram in 2018 to cater to maritime weather service requirements of Kerala, Karnataka & Lakshadweep Islands (IMD, 2021).

Consequent upon the notorious Bhola cyclone which crossed Bangladesh coast in 1970 and caused death of about 300,000 people, WMO constituted a committee headed by Dr. P. Koteswaram, then Director General of IMD to formulate World Tropical Cyclone Programme (TCP). As per the recommendations of the committee, the TCP was constituted to coordinate the meteorological, hydrological, disaster preparedness and prevention, research and training activities in different Ocean basins. The World Meteorological Organization (WMO) and the Economic and Social Commission for Asia and the Pacific (ESCAP) jointly established a Panel on Tropical Cyclones in 1972 as an intergovernmental body. Its membership comprised countries affected by tropical cyclones in the Bay of Bengal and the Arabian Sea. Originally its member countries were Bangladesh, India, Myanmar, Pakistan, Sri Lanka and Thailand (WMO, 2018). Later Maldives joined this Panel in 1982 followed by Sultanate of Oman in 1997, Yemen joined in 2016 and Iran, Qatar, Saudi Arabia & United Arab Emirates joined in 2018 (RSMC New Delhi, 2018).

Fig. 1. Cyclone warning – organizational structure.

Since 1973, IMD acts as Regional Meteorological Centre for WMO/ESCAP Panel (PTC) member countries and provides TC advisories to these countries. As per the recommendations of the CRC, a Cyclone Warning Directorate (CWD) was established in the Office of the Director General of Meteorology, New Delhi to co-ordinate the cyclone warning work in the country in totality and also to carry out international coordination. Accordingly, in the year 1988, Regional Meteorological Centre (RMC) New Delhi was redesignated as Regional Specialized Meteorological Centre (RSMC) Tropical Cyclones New Delhi (IMD, 2024). It also acts as a Tropical Cyclone Advisory Centre (TCAC) since 2003 for International Civil Aviation and provides 6 hourly advisory bulletins during TC period (IMD, 2024)

3.1. *Current organizational structure*

Nationally, IMD has a three tier organizational structure for cyclone warnings with Cyclone Warning Division (CWD) at IMD headquarter, 3 Area Cyclone Warning Centres (ACWCs) at Chennai, Mumbai & Kolkata and 4 Cyclone Warning Centres (CWCs) at Bhubaneswar, Visakhapatnam, Thiruvananthapuram & Ahmedabad to cater to the country's requirements (Fig. 1). The area of responsibility of each Centre is shown in Table 2. Internationally, IMD acts as one among 6 Regional Specialized Meteorological Centres (RSMCs) to provide

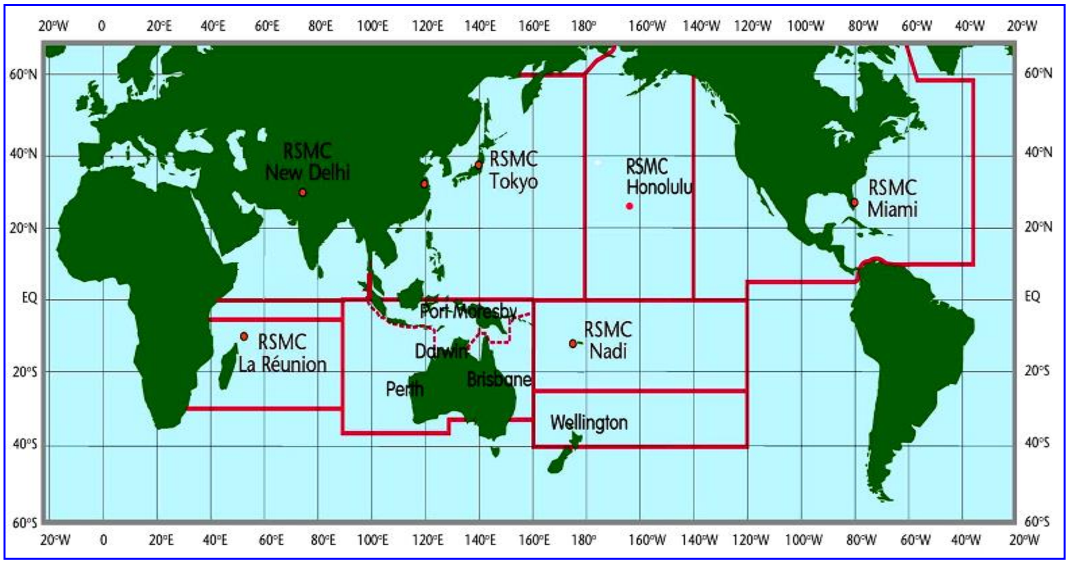

Fig. 2: Area of responsibility of RSMC New Delhi

TABLE 2

Area of responsibility of Area Cyclone Warning Centres (ACWCs) and Cyclone Warning Centres (CWCs)

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

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

tropical cyclone and storm surge advisories for the area to the north of equator between 40º E and 100º E to 13 WMO/ESCAP Panel member countries including Bangladesh, India, Iran, Maldives, Myanmar, Oman, Pakistan, Saudi Arabia, Sri Lanka, Qatar, Thailand, United Arab Emirates and Yemen. IMD also acts as 1 among the 7 Tropical Cyclone Advisory Centres (TCACs) to provide tropical cyclone advisories for international civil aviation to Asia Pacific and Middle East countries. IMD also acts as 1 among 16 centres across the globe to provide warnings for ships in deep sea for Met Area VIII(N). The area of the Indian Ocean enclosed by lines from the India/Pakistan frontier at 23° 45' N 68° E to 12° N 63° E, thence to Cape Gardafui and the east African coast southward to the Equator, thence to 95° E, to 6° N, thence north east to the Myanmar/Thailand frontier at 10° N 98° 30' E (IMD, 2013, 2021).

3.2. *Bulletins issued by CWD, CWC, ACWC*

The weather associated advisories and warnings are issued by various forecasting offices of IMD as per user's requirement in a customized format (IMD, 2003a, 2013, IMD 2021, 2024 WMO, 2022). Various types of bulletins issued by IMD are as follows.

(*i*) Bulletins issued by RSMC, New Delhi

- Extended Range Outlook (ERO) issued every Thursday valid for next two weeks
- Tropical Weather Outlook (TWO) issued daily once (based on 0300 UTC) valid for next seven days in normal weather,
- Special Tropical Weather Outlook (S-TWO) five times a day (based on 00, 03, 06, 12 and 18 UTC) in case of depression/deep depression.
- Tropical Cyclone Advisories (TCA) issued 8 times a day (every three hours *i.e.* based on 00, 03, 06, 09, 12, 15, 18 and 21 UTC)) during the cyclone period.
- Tropical Cyclone Advisories for international civil aviation issued during cyclone period every six hrs (based on 00, 06, 12 and 18 UTC).

- Global Maritime Distress Safety System (GMDSS) bulletin issued twice a day in normal weather, three times a day (based on 03, 12 and 18 UTC) in case of depression and deep depression and six times a day (based on 00, 03, 06, 12, 15 and 18 UTC) during cyclone period.

(ii) Bulletins issued by Cyclone Warning Division and Marine Services Division.

- Special Message on formation of low pressure area once a day based on 03 UTC.

- Bulletin for India coasts five times a day (based on 00, 03, 06, 12 and 18 UTC) in case of depression/deep depression and 8 times a day (every three hours i.e. based on 00, 03, 06, 09, 12, 15, 18 and 21 UTC)) during the cyclone period.

- Track & intensity in graphical format alongwith cone of uncertainty and wind distribution around centre in four geographical quadrants from the stage of depression/deep depression.

- TC Vital Bulletin for numerical weather prediction (NWP) and storm surge Modeling Group for generating synthetic vortex or relocating the vortex in NWP models and creating wind stress for storm surge model.

- Bulletin for offshore/onshore industries (based on 00, 03, 06, 12 and 18 UTC) in case of depression/deep depression and 8 times a day (every three hours i.e. based on 00, 03, 06, 09, 12, 15, 18 and 21 UTC)) during the cyclone period.

- Special Bulletin from Director General of Meteorology to high officials Once a day from the stage of pre-cyclone watch till dissipation of the system.

- Press Release daily once.

- Bulletins for Indian Navy issued twice a day in normal weather, three times a day (based on 03, 12 and 18 UTC) in case of depression and deep depression and six times a day (based on 00, 03, 06, 12, 15 and 18 UTC) in case of a cyclone.

(*iii*) Bulletins issued by ACWCs/ CWCs

- Four Stage Warning Bulletins
- Sea Area Bulletins
- Coastal Weather Bulletins
- Warnings to Ports
- Warnings for Fisheries
- Bulletins for All India Radio (AIR)
- Coastal Bulletins for AIR news cycle
- Registered/designated warnees
- Press Bulletins
- Aviation Warnings
- Bulletins for Indian Navy

All the above bulletins are issued twice a day in normal weather, three times a day (based on 03, 12 and 18 UTC) in case of depression and deep depression and six times a day (based on 00, 03, 06, 12, 15 and 18 UTC) in case of a cyclone.

4. Evolution of cyclone monitoring and forecasting system

Over the years, India's cyclone warning system has seen significant improvements in policy, planning, organizational structure, institutional mechanisms and standard operating procedures. These changes have greatly enhanced cyclone monitoring, analysis, modeling, forecasting, and the early warning communication and dissemination system. As a result, there has been notable progress in detecting cyclonic disturbances, improving forecast accuracy for cyclone track, landfall, intensity, and associated severe weather like heavy rainfall, high winds, and storm surges. Additionally, the generation, presentation, and dissemination of warning products, along with the Standard Operating Procedure (SOP), have evolved through various stages of enhancement.

The evolution phases described here have been compared with the global evolution of weather forecasting. According to Benjamin *et al*. (2019), the 100-yr period (1919-2018) of evolution of operational weather forecasting in the World can be divided into four eras: 1) ‘‘Era 1’’ (1919-39: maps only; observations and extrapolation/advection techniques), 2) ‘‘Era 2’’ (1939-56: increasing science understanding; application especially to aviation; birth of computers), 3) ‘‘Era 3’’ (1956-85: the advent of NWP and dawn of remote sensing), and 4) ‘‘Era 4’’ (1985-2018: weather forecasting, and especially NWP, mature and penetrate virtually all areas of human activity). The comparison indicates that the evolution of cyclone warning system in India was either contemporary or ahead of the rest of the World in certain cases.

4.1. *Version-1 (1865-1876): Era of manual estimation of observations, limited surface observatories and commencement of port warnings through method of extrapolation of observations.*

Version 1 of cyclone warning system commenced with establishment of first Port Warning System at Kolkata Port in 1865 after the disastrous cyclones that hit Kolkata killing about 80,000 and another that hit Andhra Pradesh killing about 40,000 people in 1864 **(**IMD 2000**)**. There were no instrumental observations over the sea area during that period. The wind was estimated based on the Beaufort scale (BS) which estimates wind intensity based on sea wave conditions. The ships plying in the Bay of Bengal (BoB) and Arabian Sea (AS) maintained log books and entered the type of sea condition and intensity of winds based on BS which was qualitative in nature. There were only 7 surface meteorological observatories along the coast and no upper air observations in the country by the end of 1876 (Mohapatra *et al*., 2012a).

The cyclonic disturbances were monitored and detected from the observations taken at different times and entered in log books by ships plying in BoB & AS and the limited meteorological observations taken along the coast. The analysis was based on these limited data which were received very late. Intensity estimation was based on wind estimates as per BS. It was highly qualitative. BS < 7 was equivalent to depression category. BS value 8 and 9 represented cyclonic storm and BS > 10 represented severe cyclonic storm. As there was no classification in BS beyond 12, there were only 3 categories of cyclonic disturbances (IMD, 1964) against 7 such categories at present (IMD, 2021). Detection of cyclonic disturbances was highly underestimated with an average of 1 TC being detected per year during the period against an average of 12 cyclonic disturbances (CDs) including 5 tropical cyclones (TCs) in a year (Mohapatra *et al*., 2012a). There was high error in intensity estimation with either under-estimation or over-estimation and intensity estimation was limited to three categories (D, CS and SCS) only and was highly subjective based on BS.

There was no numerical modeling for predicting the cyclonic disturbances and the forecast was based on extrapolation of observations upto 24 hrs only. Only Port warning was issued limited to next 24 hours which commenced in 1865 for Kolkata port only. The post, news paper, Telegram and hoisting of signals at ports were the means of dissemination of warnings. The forecast and warning products were subjective in nature lacking clarity, consistency and accuracy. No forecast was verified quantitatively and hence no estimation of forecast errors are available for this period.

The postal service started in country 1766. The express telegram was used to exchange the meteorological data for preparing port warnings for Kolkata port since 1865 prior to establishment of IMD. Express telegrams were used for speedy exchange of information among meteorological observatories, meteorological centers and end users and for about 6 decades this mode remained the only means of quick communication.

4.2. *Version-2 (1877-1890): Standardisation of observations, preparation of surface weather charts and forecast based on methods of extrapolation of observations with understanding (Synoptic meteorology).*

Version 2 commenced in 1877 with the introduction of simultaneous observations at 1000 hrs IST and systematic preparation of daily weather charts. There was augmentation of surface observatories to 22 and there were no upper air observations. The cyclonic disturbances were monitored and detected from the log books maintained by ships and the enhanced surface observations. With the publication of 1st Meteorological Report in India and establishment of the IMD in 1875, systematic preparation of daily weather charts commenced in 1877 to identify the weather systems (Mohapatra *et al*., 2012b). Accordingly, the frequency of genesis and tracks (Paths) of cyclonic disturbances are available in IMD since 1877 (IMD, 2008).

Synoptic models/method commenced with the preparation of weather charts at surface level over Indian region and sea areas. In this method, the simultaneous observations taken at a fixed time are analysed in terms of pressure and wind to identify the low pressure systems including cyclone. During this period the cyclonic disturbances continued to be classified into only three categories like D, CS and SCS due to limited data. During (1877-1890), the cyclone detection error was high with average frequency of 6.3 CDs and 2.6 TCs against normal of 12 CDs and 5 TCs in a year during 1961-2020 (Mohapatra *et al*., 2021). There was no detection to the south of 10º N over the south Bay of Bengal, south Arabian Sea and south Andaman Sea (Mohapatra *et al*., 2012b, IMD 1964, IMD 2008). Hence, there could have been missing of CDs with shorter life and also over and under estimation of intensity.

Based on the analysis as discussed above forecast was generated by extrapolating the behavior of the low pressure systems over the Sea. The forecast was issued for a limited period upto 24 hrs. Only Port Warnings continued with validity of next 24 hours. The port warning was extended to all ports in the country in 1886 (IMD, 2013). The post, news paper, Telegram and hoisting of signals at ports were the means of dissemination of warning. The meteorological service in India utilized telegram system as early as 1878. Though no forecast was verified quantitatively, the subjective forecast as track and intensity could have had large errors at that time.

4.3. *Version 3: 1891-1963: Augmented surface and upper air observations, wind finding radar and development of Cyclone track atlas, climatological and analog methods of forecasting in addition to synoptic method*

Version 3 was introduced with publication of India Weather Review in 1891 (Mohapatra *et al*., 2012b). Cyclone Track Atlas was published for the first time in 1925 (Normand 1925, 1926). It was further updated in 1943 (IMD, 1943) and 1964 (IMD, 1964). There was augmentation of observational network in 1940s and 1950s (Mohapatra *et al*., 2012b). The optimum representation of surface observatories was obtained during 1940s and 1950s for the entire coastline except Kerala, Andaman & Nicobar Islands and Lakshadweep (Mohapatra *et al*., 2012 b). 1st Surface Observatory at Bay Island was established in 1952. There was augmentation of surface observatories from 24 during 1891-1900 to 58 in 1960 (IMD, 1986). 1st Pilot Balloon Observatory got established at Pune in 1915(IMD 2013, IMD 2021). There was augmentation of Pilot balloon stations for upper air wind observation from 2 during 1911-1920 to 16 in 1960 and radiosonde and radio-wind stations from zero till 1950 to 6 during 1951-1960 for upper air temperature and wind observations (Mohapatra *et al*., 2012b). The first wind finding radar was established at Dumdum, Kolkata in 1950 (Mohapatra *et al*., 2012b).

The cyclonic disturbances were monitored and detected from the log books maintained by ships equipped with meteorological instruments as well as BS and the enhanced surface and upper air observations along the coast. Simultaneous observations at 0300 UTC and 1200 UTC commenced in 1891 (IMD, 2000). India Daily weather report (IDWR) was published from 1891 with systematic preparation of daily weather charts based on 0830 and 1730 IST observations to identify the weather systems (IMD, 2000). Accordingly, the detection frequency of genesis and tracks (Paths) of cyclonic disturbances improved since 1891. The cyclone detection error was still high, though reduced. On an average 11.8 CDs including 5.4 TCs were detected in a year during the period against an average of 12 CDs and 5 TCs in a year. However, there was no tracking of CDs to the south of 5º N. Hence, there could have been missing of CDs with shorter life tracks to the South of 5º N and also over and under estimation of intensity. The track of CDs could have been smooth, but for lack of observations and less frequent observations (Mohapatra *et al*., 2012 b).

Synoptic models/method continued with the preparation of weather charts at surface level over Indian region and sea areas. With the continuous observations, the climatology of CDs was prepared and published in regular intervals. The synoptic climatology could be developed as a method to predict TC. Thus, compared to previous period, IMD used synoptic, synoptic climatology and climatology methods to predict CDs, track and intensity. There was no NWP method and also no statistical model for prediction of TCs. Forecast valid for next 24 hours were issued twice a day at noon and evening.

Globally, the initial NWP technique for track prediction relied on a single-level barotropic model. Various versions of this model were presented in papers by Japanese and U. S. scientists from the mid-1950s to the early 1980s (Kasahara (1957); Vanderman (1962); Soyono and Yamasaki (1966); Sanders and Burpee (1968); De Maria (1985); and others).

The port warning was made uniform with introduction of uniform port warning signal in 1898 for all ports in the country (IMD 2013, IMD 2021and IMD 2003a). The early warning for coastal states commenced with establishment of Storm Warning Centres at Kolkata and Mumbai in 1945, 1956 respectively. Early warning was provided to coastal states twice a day at noon and evening based on 0830 and 1730 observations and analysis with validity period of 24 hrs (IMD 2013, IMD 2021). The post, news paper, Telegram, teleprinter, Telex, Police wireless, All India Radio and hoisting of signals at ports were the means of dissemination of warning. In 1920 wireless communication system commenced for ship shore communication. Prior to that police wireless was used for cyclone warning. The All India Radio commenced weather warning dissemination in 1935.

The forecast error could have reduced during this era. However, there was still over/underestimation of intensity apart from the relatively higher error in location estimation and the track of CDs. There were only 3 categories of intensity viz. D, CS and SCS based on BS and hence high error in intensity estimation and forecast. No forecast was verified quantitatively (Mohapatra *et al*., 2012b).

4.4. *Version 4: 1964-1973: Era of polar orbiting satellite, wind finding radar and Cyclone forecast based on synoptic, synoptic-climatology, climatology-persistence and satellite observations, commencement of research on NWP for cyclone and storm surge prediction*

The version 4 was introduced with the onset of satellite era in 1960. Also, during this period there was an appointment of Cyclone Distress Mitigation Committee for Andhra Pradesh, Odisha and West Bengal in 1969 (IMD 2013, 2021).

1st Polar orbiting satellite was launched by USA in April, 1960 (Mohapatra *et al*., 2012b). Real-time reception of satellite imagery commenced in December 1963 through an automatic picture transmission (APT) station at Mumbai. Thus, satellite support commenced form 1964. Satellite imageries were available every 12 hourly. However, as the swath area was limited, all CD could not be monitored. It was a matter of opportunity to monitor CD with the satellite imageries. The method of analysis included satellite imageries apart from further enhanced surface and upper air observations as mentioned above. Analog method could be developed to find the analogous CDs in the past so as to predict track and intensity of CDs.

Detection error reduced significantly. On an average 10.8 CDs including 4.7 TCs were detected in a year during the period against an average of 12 CDs and 5 TCs in a year during 1961-2020. There was decrease in genesis of CDs over North Bay of Bengal as it was overestimated in pre-satellite era. Still there could be missing and over/underestimation of intensity as satellite imagery was not available round the clock and also not over entire Ocean basins.

The analog method along with synoptic, synoptic-climatology, climatology-persistence and satellite observations based method were used for forecasting. Forecast and warning based on above methods continued in general being issued twice a day at noon and evening based on 0830 and 1730 observations and analysis with validity period of next 24 hrs. However, as and when as a matter of opportunity, the cyclone could be detected by the satellite imagery, the information about the cyclone could be given with a little higher lead period.

Globally around the mid-1970s, there was a belief that utilizing a model integrated with vertically averaged winds (baroclinic), as opposed to winds at a single level (barotropic), would offer a more accurate track estimate. Development of an objective technique for forecasting track of tropical cyclones began in 1972. Concurrently, statistical dynamical models such as NHC-73 were developed, as highlighted in the work of Neumann and Lawrence (1975). However, marginal success over the single level barotropic model was noticed and the multi-level baroclinic models were also not that much useful to give significantly better track forecast. Shukla and Saha (1970) developed a non-divergent barotropic model with 500 hPa winds as input for dynamical weather prediction in India. Sikka (1975) used this model for several case studies for predicting tropical cyclones but the results for 24 – hour predictions were similar to those of earlier method based on persistence and climatology.

The storm surge, which reached a height of 10 meters above astronomical tides and struck the Bangladesh coast in 1970 (Bhola cyclone), resulted in the tragic loss of over 300,000 lives. This devastating event prompted significant efforts in India to develop advanced storm surge prediction models (Das, 1972).

The port warning, coastal weather and sea area information could be provided to coastal population, coastal ships and ships in high seas by this era. The early warning for coastal states continued with establishment of Storm Warning Centers at Chennai in 1969 in addition to Kolkata and Mumbai in 1945, 1956 respectively (IMD, 2013, IMD 2021). The post, newspaper, telephone, telegram, teleprinter, Telex, Police wireless, All India Radio and hoisting of signals at ports continued to be the means of dissemination of warning.

4.5. *Version 5: 1974-1983: Augmented surface and upper air observations, cyclone detection radars along the coast, geo-stationary satellite, Dvorak technique and forecast based on synoptic, climatology, analog and CLIPER model, Commencement of running of NWP model with first HPC, Nomogram for storm surge forecasting*

After the devastating cyclones affecting east coast in 1970 and 1971, a cyclone distress mitigation committee headed by Cabinet Secretary was formed to suggest the remedial measures (IMD 2013 & IMD 2021). As per its recommendation, the version 5 came into existence. It was marked with the establishment of 11 cyclone detection radars (analog type) in 1974 all along east and west coasts of the country. It covered entire coastline except Andaman & Nicobar and Lakshadweep Islands. The Cyclone Detection Radar along the east and west coasts helped in better monitoring of cyclones upto a distance of about 400 km from the coast. The hourly radar based cloud imagery helped in better determination of location and intensity and hence tracking of cyclones crossing the coast or coming nearby the coast. There were 66 surface, 21 pilot balloon and 14 radio wind observatories by the end of this period. The geostationary satellite was introduced in the globe which provided the cloud imageries of the cyclones every three hours. The support was received from Geostationary satellites of NASA and NOAA through secondary data utilization centre and 3 hourly images were printed on photographic paper. The introduction of Dvorak technique in 1972 (Dvorak, 1972) for interpretation of satellite images made significant contribution in determining the location and intensity of CDs. Further the augmented surface and upper air observations along the coast helped in better monitoring and analysis of cyclones, especially the landfall point and time as well as associated adverse weather every three hours.

With the augmented observational network and analysis techniques, IMD introduced very severe cyclonic storm category (then known as severe cyclonic storm with core of hurricane winds) with wind speed or 64 knots or more in the classification of cyclones and severe cyclonic storm was redefined as storm with wind speed of 48-63 knots from its previous definition of 48 knots or more (WMO, 2016). Detection error reduced significantly with detection of 11 CDs and 5 TCs per year during the period. However, as visible imagery was available in day time only and Dvorak technique was applicable to visible images, the error was more in night in terms of location and intensity identification of cyclonic disturbances beyond the radar range.

Satellite and Radar based guidance were additional tools in this version apart from the tools discussed in previous version for cyclone prediction. Also, the statistical model based on climatology and persistence (CLIPER) was developed to predict track of cyclones over the Bay of Bengal and Arabian Sea (Neuman and Mandal, 1978). Sikka (1975) used non-divergent barotropic model using wind as the basic input at 500 hPa for the numerical forecasting of tropical storms in the Bay of Bengal and the Arabian Sea during the storm seasons of 1970, 1971 and 1972. The results of this study showed that it was possible to get the forecast about the movement of tropical storms using a barotropic model upto 24 hours. The High Power Computing (HPC) system IBM 360/44 with memory of 512 KB was established in 1978 to run the numerical model. Mathur (1974 and 1975) developed a semi-Lagrangian iteration of a multilevel Potential Energy (P.E.) model, incorporating parameterization for physical processes to predict hurricane movement. Dr. P. K. Das, Dr. S. K. Ghosh and their co-workers (Das *et al*., 1974, Ghosh, 1977 and Das 1994) have made several investigations on storm surge prediction. At the IMD, Ghosh (1997) adopted the SPLASH model, after Jelesniaski (1972), for storm surge prediction and development of monograms in the IMD for quick calculation of the storm surge along different coastal belts of India. IMD started storm surge warning for the Indian coasts based on Ghosh Nomograms in the year 1978 (Ghosh, 1977),

The forecast based on above methods continued in general being issued twice a day at noon and evening with validity period of next 24 hrs. However, as and when the cyclone could be detected by the satellite and radar imageries, the information about the cyclone could be given with a higher lead period. As the Radar has a tracking range upto 400-500 km and a cyclone normally moves 300 km per day, the establishment of Radar could have helped in increasing the lead period from one day to two days in conjunction with other observational guidance. Track and intensity forecast errors also reduced significantly due to introduction of Dvorak technique (Dvorak 1984) and radars (Raghavan, 1997). However, lack of tools at night for interpretation of satellite imagery for determining location of centre and intensity, especially in deep sea region could have led to higher forecast error. Similarly, non-availability of wind information from radar also led to only subjective estimation of intensity and hence more error in intensity forecast, even when the cyclone is nearer to the coast (Raghavan, 1997).

The Port warning, coastal weather and sea area information could be provided to coastal population, coastal ships and ships in high seas. The early warning for coastal states continued with augmented information based on satellite and Radar and statistical model. The early warning could be provided to coastal states four times a day every six hours based on 0830, 1130, 1730 and 2330 observations and analysis with validity period of 48 hrs (IMD, 2003a). However, as and when as a matter of opportunity, the cyclone could be detected by the satellite imagery, the information about the cyclone could have been given with a little higher lead period.

The post, newspaper, telephone, telegram, teleprinter, Telex, Police wireless, All India Radio and hoisting of signals at ports continued to be the means of dissemination of warning. Only a few kilo bytes (KB) data were exchanged during the period. The bulletin continued to be textual with limited information. However, information based on satellite and Radar observations, could be provided.

4.6. *Version 6: 1984-1989: Introduction of INSAT series, establishment of NCMRWF, Super Computing System and augmentation of NWP*

The version 6 commenced with the introduction of Indian National Satellites (INSAT) in 1983 (Mohapatra *et al*., 2012b) and automatic weather stations in 1984 (Mohapatra *et al*., 2011). There was establishment of 100 data collection platforms (DCPs) across India and introduction of Dvorak technique for infrared imageries (Dvorak, 1984) to monitor location and intensity of cyclones. In 1984, INSAT series was in operation which was launched in 1983. The 3 hourly images were available for monitoring of TCs. As the INSAT was located over north Indian Ocean, the parallex error was less and hence the determination of location of centre and hence intensity was more accurate. There were 11 radars, 69 surface, 21 pilot balloon and 14 radio wind observatories along the coast by the end of this period. However, the DCPs being new and having large estimation error lacked confidence of the forecasters and could not be used well to improve the cyclone analysis (IMD, 1988). The detection error improved and the missing events were almost negligible during this period. The track and intensity estimation as well as landfall point & time determination improved significantly.

A model based on climatology and persistence (CLIPER) was introduced in 1984 (Pike and Neumann, 1987). In addition to analog, synoptic, Radar and satellite methods, CLIPER based forecast was also available. HPC VAX-1I/730 computer system was in use with 1 CPU 4 M bytes memory in 1988. Singh and Sugi (1986) pioneered the use of a multi-level parameterization model for dynamic weather prediction over the Indian region. The National Centre for Medium Range Weather Forecasting (NCMRWF) was established in 1989 to augment NWP modeling.

The forecast was issued for next 48 hours with improved methodology and accuracy. However, as and when the cyclone could be detected by the INSAT satellite and radar imageries, the information about the cyclone could be given with a higher lead period. It also helped in improving the heavy rainfall, wind and storm surge forecast and warning in terms of lead period upto 48 hrs and accuracy.

The port warning, coastal weather and sea area information could be provided to coastal population, coastal ships and ships in high seas. The early warning for coastal states continued with augmented information based on satellite and Radar and statistical model. Early warning could have been provided to coastal states four times a day every six hours based on 0830. 1130, 1730 and 2330 observations and analysis with validity period of 48 hrs. However, as and when the cyclone could be detected by the satellite imagery, the information about the cyclone could be given with a little higher lead period. Hourly update based on radar tracking could be provided along with three hourly tracking information based on INSAT imageries**.** The track and intensity errors reduced due to introduction of CLIPER model, Dvorak technique for infrared imageries, satellite and radar based techniques apart from other methods as discussed above.

The warning dissemination through FAX commenced in 1988 (IMD, 1989) apart from the post, newspaper, telephone, telegram, teleprinter, Telex, Police wireless, All India Radio and hoisting of signals at ports were the means of dissemination of warning. The bulletin continued to be textual with limited information. However, information based on satellite and Radar observations could be provided. Around 3 MB data was exchanged daily during cyclone period (IMD, 1989).

4.7. *Version 7: 1990-1997: Uniformity and further standardization in cyclone warning, enhanced national and international coordination, operational run of NWP models and introduction of damage potential*

The version 7 commenced with establishment of Cyclone Warning Directorate in the office of the Director General of Meteorology, IMD, New Delhi in 1990 (IMD, 2024) as per the recommendations of Cyclone Distress Mitigation Committee (CDMC). IMD also introduced three stage cyclone warning system in 1991 (IMD (pre-cyclone watch, cyclone alert and cyclone warning about 72, 48 and 24 hours ahead of landfall and impact based forecast & risk based warning of cyclones based on historical damages in 1992.

In addition to the 3 hourly satellite imageries, derived products like cloud motion vectors were available in 1993 (RSMC New Delhi, 1994). There were 11 radars, 70 surface, 21 pilot balloon and 14 radio wind observatories along the coast by the end of this period. The CDMC recommended establishment of weather stations in the police stations along the east coast in 1990 to record the mean sea level pressure and wind (IMD, 2003a). The availability of cloud motion vectors in different layers of the atmosphere helped in monitoring the internal structure of cyclones in terms of its wind distribution in horizontal and vertical and hence the shape and size of the cyclone every three hours. It helped in improving the accuracy of monitoring the location and intensity, associated adverse weather and also helped in improving the forecast. Detection error improved. Negligible missing events were observed during this period.

After rigorous research for more than 20 years at the US National Meteorological Centre, Mathur (1991) developed the model further by including a synthetic vortex in the data over the hurricane. The study of the numerical simulation of a tropical storm boundary layer by J. C. Mandal (1997) and the role of the convection scheme for the tropical cyclone simulation by Bhaskar Rao (1997) and many others were also important milestones in tropical cyclone modelling. Studies by Mohanty & Gupta (1997), Gupta & Mohanty (1997) and Gupta & Bansal (1997) employed multi-level P. E. models with parameterized physical processes for dynamical weather prediction over the Indian region. Gupta and Bansal (1997), utilizing the global T-80 NCMRWF model, found limited skill in tropical cyclone prediction due to inaccuracies in representing the initial vortex position in the coarse-resolution T-80 model. Prasad (1997) and Prasad *et al*., (2000) reviewed the application of numerical models for cyclone track prediction in India. They utilized a high-resolution limited area model (LAM) based on the NMC USA model, achieving reasonably accurate predictions up to 48 hours when employing a synthetic analytical vortex based on satellite information. Apart from all the models as mentioned in previous version, a numerical weather prediction model adapted from USA was run operationally with a horizontal resolution of 250 km since 1991 (RSMC New Delhi, 1991). It could provide the forecast upto 48 hrs. However, it took about 12 hrs to run the model and get the forecast products. It was not consistent and had less confidence. The HPC VAX-1I/730 computer system was in use with 1 CPU 4 M bytes memory in 1991 (RSMC New Delhi, 1991).

Forecast was issued for next 48 hours with improved methodology and accuracy based on NWP model, CLIPER, synoptic method, statistical method, climatology, persistence, synoptic climatology and analog method. However, as and when the cyclone could be detected by the INSAT satellite and radar imageries, the information about the cyclone could be given with a higher lead period. It also helped in improving the heavy rainfall, wind and storm surge forecast and warning in terms of lead period upto 48 hrs and accuracy. Track and intensity forecast errors reduced due to introduction of Dvorak technique for infrared imageries (IR) and enhanced IR imageries (Dvorak, 1984), radars and data collection platforms and statistical prediction models. In addition to the early warning system as discussed in previous section, early warning could be provided to coastal states every three hours based on 0230, 0530, 0830. 1130, 1430, 1730, 2030 and 2330 observations and analysis with validity period of 72 hrs to all stakeholders including ports, ships, Indian Navy, IAF, press and electronic media, central and state agencies, NHAI, Indian railways, civil aviation, marine community, fisherman and fishery officials, farmers *etc*. However, as and when the cyclone could be detected by the satellite imagery, the information about the cyclone could be given with a little higher lead period. Hourly update based on radar tracking could be provided alongwith three hourly tracking information based on INSAT imageries (IMD, 2003a).

The three stage cyclone warning system for disaster managers was introduced in 1991 (IMD, 2013). According to this system, pre-cyclone watch, cyclone alert and cyclone warning was issued 72, 48 and 24 hrs in advance of commencement of adverse weather along the coast. However, the bulletin continued to be subjective and qualitative and lacked objective information on track and intensity as well as landfall.

The damage potential for tropical cyclones was published by IMD in 1992 (IMD, 1992). It was used by IMD to provide the impact based forecast of cyclones based on historical damages in terms of expected damages to crops, houses, transport and infrastructures *etc*.

Apart from various dissemination techniques as mentioned in previous section, IMD in collaboration with ISRO introduced the satellite based cyclone warning dissemination system in 1994 (RSMC New Delhi, 1995). These systems were established along the coast in the office of special relief commissioners, district collectors, Block Development Officers and Tehsildars. The cyclone warning was communicated in local language, English and Hindi every hour. However, it was a one way communication system. The VSAT came into use during this period (IMD, 2003a) for data communication among the forecasting centres.

4.8. *Version 8: 1998-2008: Enhancement of observations through Buoys, Quikscat, Doppler Weather Radar, High wind speed recorder, Quasi-Lagrangian model, Limited Area Model, GFS model(T-80), Objective track and intensity forecast upto 24 hrs in 2003 and 72 hrs with cone of uncertainty in 2008, Prognosis and diagnosis and forecast demonstration project since 2008.*

Version 8 marked the upgradation of automated weather stations (AWS) and installation of buoys over north Indian Ocean, 14 automatic weather stations (AWS), scatterometer and derived products based on Quickscat were introduced in 1997 (Mohapatra *et al*., 2012b). In 1998, super cyclonic storm category was introduced (IMD, 1999) based on decisions of annual cyclone review meeting held in 1998. By 2008, there were 125 AWSs countrywide and 12 moored buoys over north Indian Ocean. In addition, there were 11 radars and 70 surface, 21 pilot balloon & 15 radio wind observatories along the coast in this period. 3 hourly satellite imageries were also available alongwith 12 hourly imageries from Polar orbiting satellites. No. of buoys increased to 20 in 2002 (IMD, 2003b). Quickscat imageries were also available during 1999-2009 (https://manati.star.nesdis.noaa.gov/datasets/QuikSCATData.php). Microwave imageries were introduced in 2000 for operational monitoring (Mohapatra *et al*., 2012b and Jha *et al*., 2013). High wind speed recorders were introduced in some places along the coast. First Doppler weather radar (DWR) was established in Chennai in 2002, in Kolkata in 2004, Machillipatnam and Visakhapatnam in 2006 (RSMC New Delhi, 2003, 2005 and 2007).

The monitoring and analysis improved further with augmented observations as mentioned above. Hourly analysis could be possible with energy in 10 minutes DWR images, hourly buoy and AWS data apart from 3 hourly synoptic analysis. As the DWR provides radar reflectivity, rainfall rate and radial wind, it helped in better monitoring and analysis of internal structure of cyclone, shape and size, intensity and associated heavy rainfall. It also helped to improve the input for storm surge model and hence the storm surge forecasting. Detection error improved. Negligible missing events were observed during this period.

In both Japan and the USA, moving grid-multiple nested parameterization models were examined. Elsberry and Carr (2000) conducted an assessment of multi-level parameterization model applications, while Aberson and Simpson (2003) delved into the predictability of tropical cyclone tracks. Apart from the models mentioned in previous version, Quasi-Lagrangian Model (QLM) adopted from USA was made operational for track forecasting upto 72 hours in 1999 (RSMC New Delhi, 2000). GFS model (T 80) was adapted from USA with horizontal resolution of 150 km for track forecasting upto 72 hours in 1997 (Prasad 1997 and Prasad *et al*., 2000).

Forecast was issued for next 72 hours with improved methodology and accuracy based on NWP models, GFS (T80), QLM, CLIPER, synoptic method, statistical method, climatology, persistence, synoptic climatology and analog method since 2008. It helped in improving the heavy rainfall, wind and storm surge forecast and warning in terms of lead period upto 72 hrs and accuracy. The prognosis and diagnosis of the cyclone was introduced with effect from cyclone Nargis in April 2008 (IMD, 2009). The forecast demonstration Project (FDP) over the Bay of Bengal and Arabian Sea commenced on 15th Oct. 2008 (Mohapatra *et al*., 2012 a). Track and intensity forecast errors further reduced due to introduction of GFS model, QLM apart from other tools as mentioned in the previous section. The systematic verification of forecast commenced in 2008 and forecast for past years since 2003 were verified. The 24 hrs average track forecast error was about 203 km in 2003 (with the introduction of first digital track forecast) (IMD, 2013).

The warning process as mentioned in previous section was further augmented with introduction of 4 stage warning system in 1999 (IMD, 1999). According to this system, pre-cyclone watch, cyclone alert, cyclone warning was issued 72, 48, 24 hrs in advance of commencement of adverse weather along the coast. The post landfall outlook was issued 12 hours prior to landfall to warn the interior districts of affected states. However, the bulletin for disaster management continued to be subjective and qualitative and lacked subjective information on track and intensity as well as landfall till 2008. In 2008 first objective track forecast was introduced for TC ward which crossed Sri Lanka coast. The impact based forecast based on historical damage continued in textual form. Apart from various dissemination techniques mentioned in previous section, email to disaster managers was introduced in the year 2010 (WMO, 2011).

4.9. *Version 9: 2009-12: Augmented observation and Objective Decision Support System (DSS), Multi-model ensemble (MME), IIT Delhi storm surge model based guidance to WMO/ESCAP Panel countries, genesis potential parameter, ensemble prediction system and extended range modeling, Quadrant wind forecast upto 3 days from 2010.*

Version 9 marks the launch of Modernisation Programme of IMD in 2008 and made operational in 2009 (Mohapatra *et al*., 2013a). This period also marked improvements in models with introduction of Multi Model Ensemble (MME) technique (Kotal and Bhowmik, 2011) and genesis potential parameter in 2013 (Kotal and Bhattacharya, 2013). Warning products included 72 hour quantitative track and intensity forecast and graphical track alongwith cone of uncertainty (Mohapatra *et al*., 2013 b, 2013 c and Mohapatra 2015).

559 surface observatories, 62 Pilot balloon & 39 radiosonde/ radiowind observatories, 11 S band radars, 3 hourly satellite imageries from Kalpana-1 & INSAT 3A and 12 hourly imageries from polar orbiting satellites depending upon area of coverage were used for analysis. Sea surface wind was available from Ocean Sat II in 2009 (RSMC New Delhi, 2010). Fully automated indigenously developed digital Meteorological Data Processing System was launched in 2008 (RSMC New Delhi, 2009). In 2009, high end decision support system was installed at IMD New Delhi with tropical cyclone module for analyzing various observations and model guidance on a single platform and generate graphical products in GIS platform (Mohapatra *et al*., 2013a). The analog method of manual analysis was replaced by automated analysis system in a digital platform in 2009. Missing rate reduced to almost zero. Landfall point estimation error was reduced to 25 km over both basins.

Model guidance was available from 6 different models (*i*) Quasi Lagrangian Model (40 km resolution, run twice/day, lead period 72 hours), (*ii*) Limited Area Model 90 km horizontal resolution, run twice/day, lead period 72 hours), (*iii*) Non-hydrostatic Meso-scale Model MM-5 (45 km resolution, run once, lead period 72 hours), (*iv*) Non-hydrostatic mesoscale model WRF (27km resolution, run once, lead period 72 hours), (*v*) Multi Model Ensemble (run twice, lead period 72 hours), (*vi*) Statistical Dynamical model for Cyclone Intensity Prediction (SCIP, lead period 72 hours) and Storm Surge Model included IIT, Delhi model and Ghosh nomograms in 2009 (RSMC New Delhi, 2010, Dube *et al*., 2009). Cyclone specific Hurricane Weather Research & Forecast (HWRF) model with resolution of 27 km X 9 km was introduced in 2012 (RSMC New Delhi, 2013). Forecast Demonstration Project commenced for the period 15-October to 30 November commenced in 2008 (IMD, 2010 and Mohapatra *et al*., 2013 d). For data exchange IBM HPCS was used with computing power of 14.4 Tera Flops and 300 tera bytes storage in 2009 (RSMC New Delhi, 2010).

Rao *et al*., 2009, discussed about the utilization of meso-scale models like MM5 and WRF, which can be used for prediction of TCs based on suitable combination of appropriate parameterization schemes of physical processes. A preliminary study about the prospects of extended range forecast of tropical cyclogenesis over the north Indian Ocean during the 2010 post-monsoon season was published by Pattanaik *et al*., (2013). The real-time extended range forecasts in terms of weekly mean of dynamical variables were prepared for two weeks based on the coupled model outputs from ECMWF, NCEP and the 2 models average (2MAVE) of both. The ERF of cyclogenesis probability based on ECMWF and CFSv1 dynamical models had a modest beginning in 2010 with reasonable performance in case of severe cyclonic storm 'Jal' formed during the first week of November.

Till 2007, there was only 24 hour objective track and intensity forecast and no quantitative forecast was issued. In 2008, 72 hr forecast of track with Cone of Uncertainty was introduced from cyclone "WARD" (RSMC New Delhi, 2009). Prognosis & Diagnosis were included in the RSMC Bulletin from cyclone "NARGIS" in 2008 (WMO, 2009). The wind structure forecast upto 72 hours was introduced in 2010 with cyclone "GIRI". (WMO, 2011 and RSMC New Delhi, 2011) Storm surge warning was operationally issued for WMO/ESCAP member countries since 2009 (RSMC New Delhi, 2010). Landfall point forecast error was 120 km and track forecast error was 162 km for 24 hours lead period in 2009 (RSMC New Delhi, 2010).

The early warning bulletin was modified with introduction of both text and graphic in 2008 (Cyclone Ward). Media Briefing on cyclones and Press Release commenced in 2008 from cyclone "NARGIS" (IMD, 2024). The graphics bulletin was uploaded in website. The impact based forecast was made more specific apart from all other initiatives mentioned in previous version.

Cyclone warnings were disseminated to various users through telephone, fax, e-mail, GTS, All India Radio, Television and the print & electronic media, website of IMD (www.imd.gov.in), IVRS (Interactive Voice Response system) and 352 Cyclone Warning Dissemination System (CWDS) stations along the coast (IMD, 2013).

4.10. *Version 10: 2013-17: Augmented observations, modeling, forecasting and communication, Cyclone forecast 5 days ahead, Worldwide accolades for early warning of Phailin, 2013, Dedicated website, introduction of SMS and GIS*

Version 10 marked the improvements in observational network, modeling capabilities, increase in lead period of forecast from 3 days to 5 days, introduction of better dissemination techniques including SMS, dedicated website for cyclones and worldwide accolades for accurate prediction of cyclones Phailin (2013) and Hudhud 2014 (IMD, 2021).

By 2013, IMD established 559 surface observatories, 550 automatic weather stations, 1240 automatic rain gauges, 62 Pilot balloon & 39 radiosonde/radiowind observatories, 23 radars countrywide with 16 doppler radars and 20 High Wind Speed Recorders (RSMC New Delhi, 2014) for monitoring of cyclonic disturbances. These were complimented by support from various satellites including INSAT 3A, 3D, Kalpana and polar orbiting satellites. There was nil detection error.

Model guidance was available from 6 different models including (*i*) Global Forecast System (23 km resolution, run twice, 7 days forecast) 23 Km restoration, (*ii*) NCMRWF Model (25 km resolution, run once/day), (*iii*) WRF (ARW) (9 km resolution, run twice, 3 days forecast), (*iv*) QLM model (40 km resolution, run twice, 3 days forecast), (*v*) Hurricane WRF model (9 km resolution, 5 days forecast), (*vi*) Genesis potential Parameter (7 days forecast), (*vii*) Multi Model Ensemble (run twice, 5 days forecast), (*vi*) Statistical Dynamical model for Cyclone genesis and intensity Prediction (SCIP) (Kotal *et al*., 2008) (3 days forecast), (*vii*) rapid Intensification Index and (*viii*) Storm Surge Model included IIT, Delhi model (Dube *et al*., 2013), Ghosh nomograms (Ghosh, 1977) and INCOIS AdCirc Model (Murty *et al*., 2017, Srinivasa *et al*., 2015) for coastal inundation in 2013.

Mohanty *et al*. (2019) discussed research activities with emphasis to NWP methods that led to advance the track prediction of TCs over the North Indian Ocean in the previous two decades. A special Issue on the Proceedings of National Conference on Bay of Bengal Tropical Cyclone Experiment (BOBTEX 2011) was published in the January issue of Mausam 2013 which contains a review of observations, modeling and forecasting tools & techniques and their improvements in recent years.

For data exchange IBM HPCS was used with computing power of 14.4 Tera Flops and 300 tera bytes storage. Introduction of Ensemble Prediction System (EPS) in collaboration with Japan Meteorological Agency (JMA) in 2013 (RSMC New Delhi, 2014). This era also witnessed introduction of experimental coastal inundation and surge forecast by Advanced Circulation (AdCirc) model run by INCOIS experimentally from cyclone "PHAILIN" in 2013 (RSMC New Delhi, 2014, (Srinivasa *et al*., 2015 Murty *et al*., 2017).

In addition to the forecasting process mentioned in previous version, this phase witnessed extension of lead period of track & intensity forecast to next 5 days in 2013 (RSMC New Delhi, 2019 and WMO 2019), introduction of probabilistic cyclogenesis forecast for next 3 days in 2014 (RSMC New Delhi, 2019) and commencement of hourly bulletins, 12 hours before landfall in 2014 (RSMC New Delhi, 2015). The accuracy in forecast further improved with the landfall point, track & intensity forecast errors reaching to 30 km, 110 km and 10 knots for 24 hours lead period in 2013 (RSMC New Delhi, 2014). The uncertainty in track forecast measured in terms of COU reduced from 150, 250 & 350 in 2009 to 80, 135 & 175 nm in 2013 for 24, 48 & 72 hours lead period respectively (WMO, 2010 and WMO, 2014).

In addition to the early warning techniques as mentioned in previous version, the lead period was extended to next 5 days into 2013 (WMO, 2014). In addition to modes of communication and warning dissemination mentioned under Version 10, this phase witnessed the introduction of SMS to fishermen through INCOIS network from cyclone "PHAILIN in 2013, SMS to general public under digital India Programme in 2014 and to farmers through Kisan Portal in 2014 from cyclone Hudhud (RSMC New Delhi, 2014 and 2015). Dedicated website for cyclones was launched in 2014 (WMO, 2015).

4.11. *Version 11: 2018-20: Augmentation of cyclone warning system, introduction of 2 ensemble prediction systems in India and extension of genesis forecast upto 5 days and extended range prediction of genesis upto 2 weeks, fishermen warning text and graphics for NIO in 2018, Worldwide appreciations, communication through social media*

Version 11 marked the improvements in observational network, modeling capabilities with commissioning of ensemble prediction systems, introduction of extended range outlook, increase in lead period of cyclogenesis forecast to next 5 days, upgradation of radars, introduction of social networking platform for warning dissemination, significant improvement in forecast accuracy, worldwide accolades for cyclone FANI (2019) and Amphan (2020).

560 surface observatories, 711 automatic weather stations, 1350 automatic rain gauges, 62 Pilot balloon & 43 radiosonde/radiowind observatories, 24 radars countrywide were used for monitoring analysis. Half hourly imageries from INSAT 3D & 3D (R) and polar orbiting satellites and scatterometer. Model guidance was available from 10 different models (*i*) Global Forecast System (12 km resolution, run twice, 10 days forecast), (*ii*) NCMRWF Unified Model (12 resolution, run once/day), (*iii*) WRF (ARW) (3 km resolution, run twice, 3 days forecast, (*iv*) Ocean coupled Hurricane WRF model (2 km resolution, 5 days forecast) (RSMC New Delhi, 2019), (*v*) Genesis potential Parameter (7 days forecast 12 km restoration) (*vi*) Multi Model Ensemble (run twice, 5 days forecast), (vii) Statistical Dynamical model for Cyclone genesis and intensity Prediction (SCIP) (Kotal *et al*., 2008) (5 days forecast), (*viii*) rapid Intensification Index (Kotal and Bhowmik, 2013), (*ix*) Storm Surge Model included IIT, Delhi model (Dube, 1997), Ghosh nomograms (Ghosh, 1977) and INCOIS AdCirc Model for coastal inundation (Srinivas *et al*., 2015) (*x*) TIGGE ensemble system (RSMC New Delhi, 2012), (*xi*) IMD Global Ensemble Forecasting System (GEFS with resolution of 12 km and forecast upto 7 days (RSMC New Delhi, 2019) and (*xii*) NCMRWF Ensemble Prediction System (NEPS) with resolution of 12 km and forecast upto 7 days (RSMC New Delhi, 2019). For data exchange and modeling, the MoES implemented Bhaskar (1.14 Peta Flops since 2015) & Mihir (2.8 Peta Flops since 2018) at NCMRWF and Aaditya (790 Tera Flops since 2015) & Pratyush (3.9 Peta Flops since 2018) at IITM (MoES, 2019).

Mohanty *et al*. (2019) in their research paper brought out the limitations in understanding of the dynamics of the tropical atmosphere and the interaction of the TCs with its surrounding environment. Some of these problems are partly solved with current advancements in the use of sophisticated numerical methods, advanced physics parameterizations, development of data assimilation methods, parallel computing techniques and so on. With the advent of high performance parallel computing techniques, it became possible to use large area, multilevel, high-resolution models. The implementation of multi-level nesting enabled to resolve the structure of tropical cyclones with a fine mesh grid centered on the storm and the interaction of nested grid structures within a large grid which is used to represent the storm's changing environment. The limitation of initial conditions has been solved to some extent with the use of advanced data assimilation techniques with which all available observations can be incorporated to define the initial state.

There have been many studies on physics sensitivity (Rao & Prasad, 2006; Mandal *et al*., 2004; Mandal & Mohanty, 2006; Trivedi *et al*., 2006; Srinivas *et al*., 2007; Deshpande *et al*., 2010; Osuri *et al*., 2012 a ; Raju *et al*., 2011; Mukhopadhyay *et al*., 2011), on model grid resolution (Rao *et al*., 2009) and impact due to data assimilation (Singh *et al*., 2008, 2012 a & b; Osuri *et al*., 2012b, 2015; Routray *et al*., 2016; Srinivas *et al*., 2010, 2012). These studies have clearly brought out the improvement in TC forecasting in recent times over the North Indian Ocean associated with an increase in resolution, better physics and also incorporation of satellite and radar data in the assimilation cycle.

As discussed in a paper by Pattanaik and Mohapatra (2021), IMD implemented the Climate Forecast System coupled model in 2017 for operational extended range forecast (ERF). Based on this, the generation of the Genesis Potential Parameter (GPP) for tropical cyclogenesis involving the dynamical variables (vorticity, divergence, vertical wind shear, and mid-level relative humidity) from the operational ERF system have been computed every week for next 2 to 4 weeks. Taking a step further, IMD introduced probabilistic extended range outlook for cyclogenesis (formation of depression) during next 15 days, issued once a week every Thursday (WMO, 2019) and extended probabilistic cyclogenesis forecast from 3 to 5, issued daily in 2018. During 2018, IMD introduced 6 hourly forecast of track, intensity and landfall point & time upto next 3 days from the stage of depression and pre-genesis forecast in terms of a special message at the stage of low pressure area (WMO 2019). This period also marked the introduction of TC track and intensity on geospatial platform in 2020 (RSMC New Delhi, 2021; WMO, 2021). For the first time, during super cyclonic storm Amphan, IMD and NDRF jointly conducted press conference in 2020 (IMD, 2020). Fishermen warning both text and graphics was extended for entire Bay of Bengal and Arabian Sea in 2018 (WMO 2019).

The annual average track forecast errors in 2018 had been 88 km, 124 km and 134 km, respectively for 24, 48 and 72 hrs against the past five year average error of 93, 144 and 201 km based on data of 2013-2017 (RSMC New Delhi, 2019). The annual average landfall point forecast errors for the year 2018 have been 44 km, 40 km and 68 km for 24, 48 and 72 hrs lead period against the long period average of 42 km, 95 km and 122 km during 2013-2017. The average absolute errors in intensity (wind) forecast during 2018 have been 8.2 knots, 11.6 knots and 12.9 knots respectively for 24, 48 and 72 lead period of forecast against the past five year average of 10.4, 15.5 and 15.7 knots (RSMC New Delhi, 2019).

In addition to the tools for warning dissemination mentioned in previous section, IMD introduced use of social media including facebook, twitter & whatsapp and launched Mobile App Mausam in 2018 (WMO, 2019; IMD, 2024).

4.12. *Version 12: 2021-23: Introduction of pre-genesis track and intensity forecast since 2022, Web-DCRA for IBF in 2021, nowcast models in 2022*

Version 12 marked the introduction of Web based Dynamic Composite Risk Atlas. Video capsule on daily weather briefing was commenced in 2021. New list of names of tropical cyclones with 169 names from 13 member countries was released in 2021 (IMD, 2024, WMO 2022).

IMD has continuously expanded its infrastructure for meteorological observations, communication system, forecasting and weather services. By the end of 2023, it has a developed a vast network of 560 surface observatories, 925 automatic weather stations, 1383 automatic rain gauges, 5800 rain gauges, 62 Pilot balloon & 56 radiosonde/ radiowind observatories, 39 doppler weather radars and 37 high wind speed recorders (RSMC New Delhi, 2024). There are also two geostationary satellites, INSAT 3D and 3D(R), enabling IMD to get cloud images every 15 minutes in a cascading manner and other derived products like wind, rainfall *etc*. every hour. Sea surface winds from Ocean Sat III are available twice every day since May, 2023 (RSMC New Delhi, 2024). Rapid Scan of TCs (every 6 minutes) was introduced in 2021 (RSMC New Delhi, 2022). The data from various platforms is now more frequent and qualitative with higher spatial and temporal density.

Apart from the models discussed in previous section, this era is marked with introduction of Mean Multi Model Ensemble based products for genesis, track, intensity, landfall point & time and rainfall of forecasting upto 5 days since 2022 and introduction of quantitative pre-genesis track & intensity forecast for next 3 days at the stage of low pressure area from March, 2022 (RSMC New Delhi, 2023). Another major stride was the introduction of indigenously developed decision support system (DSS) for monitoring, analysis and forecasting TCs characteristic features and associated adverse weather (Mohapatra *et al*., 2023). For warning dissemination, short video capsules on weather briefing over Youtube and Facebook commenced in 2021 in English, Hindi and local languages were introduced in 2022.

The annual average track forecast errors in 2023 has been 64 km, 94 km and 135 km against the past five-year average error of 74, 112 and 153 km based on data of 2018-

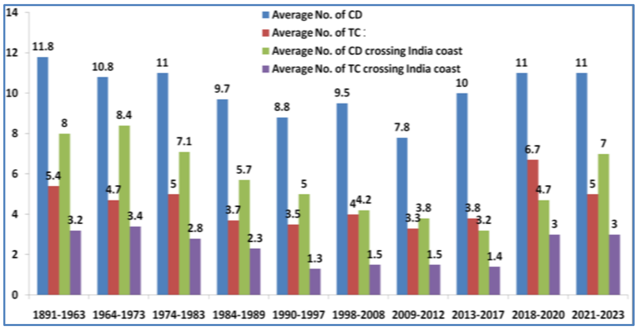

Fig. 3: Total number of cyclonic disturbances (CDs) and tropical cyclones (TCs) during various versions in the evolution of cyclone warning system in India since 1891

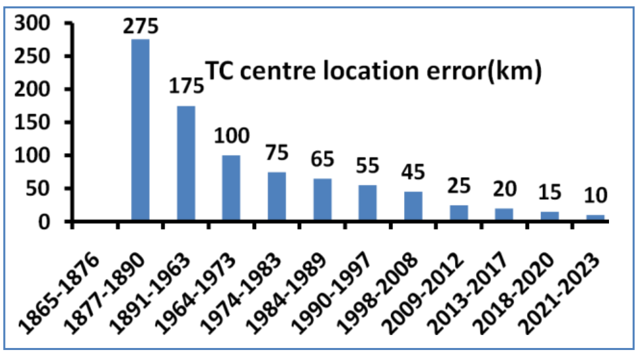

Fig. 4. TC centre location error (km) during different versions of cyclone warning system

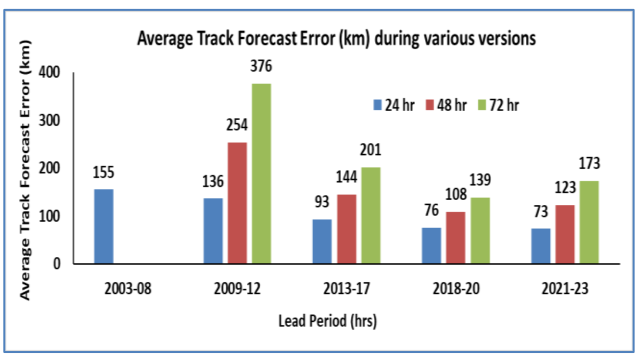

Fig. 5. Average track forecast error during various versions

2022 for 24, 48 and 72 hrs lead period respectively. The annual average landfall point forecast errors for the year 2023 has been 13 km, 27 km and 45 km against the average of past five years of 26 km, 40 km and 76 km for 24, 48 and 72 hrs lead period respectively. The annual average absolute error (AE) in intensity forecast has been 7.3 knots, 10.7 knots and 12.5 knots against the past five years average of 7.4, 10.5 and 14.0 knots for 24, 48 and 72 hrs lead period respectively (RSMC New Delhi, 2024).

5. Frequency of cyclones in each version of prediction system

The total number of CDs and TCs predicted during each version of the forecasting system based on the available record is presented in Fig. 3. TC detection error is the error in locating the centre of TC based on observational data. The TC detection error has reduced significantly since 1891 (Fig. 4).

6. Parameters for comparisons version wise:

The comparison of different versions has been made in terms of cost/loss, loss of lives, track forecast errors and the states impacted by the cyclones.

The improvements in forecast accuracy in different versions are shown in Fig. 5. It shows significant improvement in average forecast errors since the introduction of quantitative forecast in version 8. The 24 hrs forecast error has decreased from 155 km in 2003-08 to 73 km in 2021-23. Similarly, 48(72) hrs forecast errors have decreased from 254(376) km during 2009-12 to 123(173) km during 2021-23

The track forecast errors are given as the running mean errors for each five years during 2003 to 2023. Almost all coastal states are directly or indirectly impacted by the cyclones during different years. There has been significant improvement in cyclone forecast accuracy in recent years (Fig. 6) leading to reduction in loss of human lives. There has been about 40% improvement in forecast accuracy in recent five years (2019-2023) as compared to previous five years (2014-2018) as shown in Fig. 7. The number of loss of human lives has been restricted to less than 100 due to any cyclones hitting coast (Fig. 8). To compare the cost and savings, a comparative analysis showing different parameters with respect to Odisha super cyclonic storm, 1999 and extremely severe cyclonic storm, Phailin which hit Odisha in 2013 are given in Table 3. While total expenditure towards modernization of IMD during 2008-12 was about 437 crores rupees, the saving due to improved early warning for any landfalling cyclone hitting India coast is more than 500 crore rupees. The expenditure towards the saving from ex-gratia payment made by Government and the saving from reduction in evacuation area due to accurate forecast and warning exceeds 500 crore rupees as shown in Table 3.

7. Accuracy of information related to cyclone in comparison to the world

The National Hurricane Centre (NHC) of NOAA, USA was assumed as the benchmark while proceeding for modernization of cyclone warning system in IMD initiated in 2008, as NHC is considered as the best warning centre at that time. Accordingly the forecast errors of Cyclone Warning Division of IMD over north Indian Ocean have been compared with forecast errors of NHC, USA in the following section.

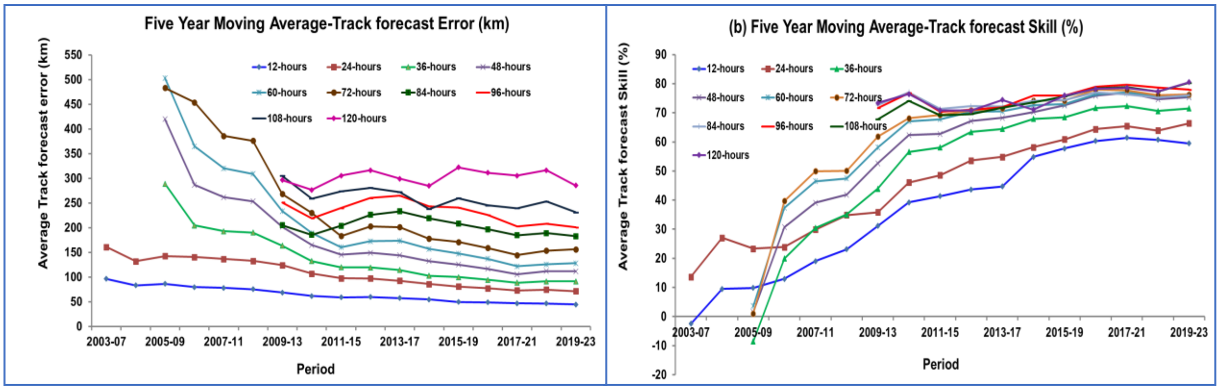

Fig. 6: Five Year Moving Average of cyclone (a) Track Forecast Error (km) and (b) Track Forecast Skill (%) of IMD over North Indian Ocean

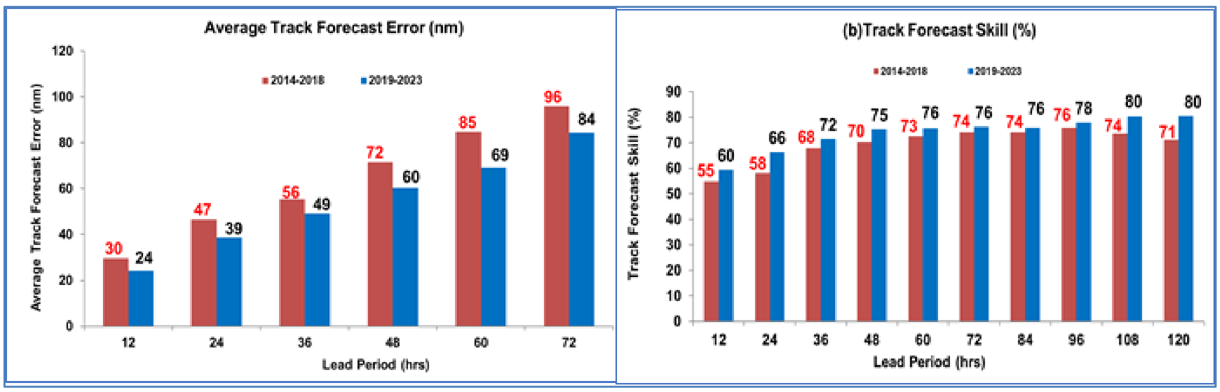

Fig.7: Comparative Average cyclone track forecast (a) error and (b) skill of IMD over the North Indian Ocean during 2019-23 vis-à-vis 2014-18

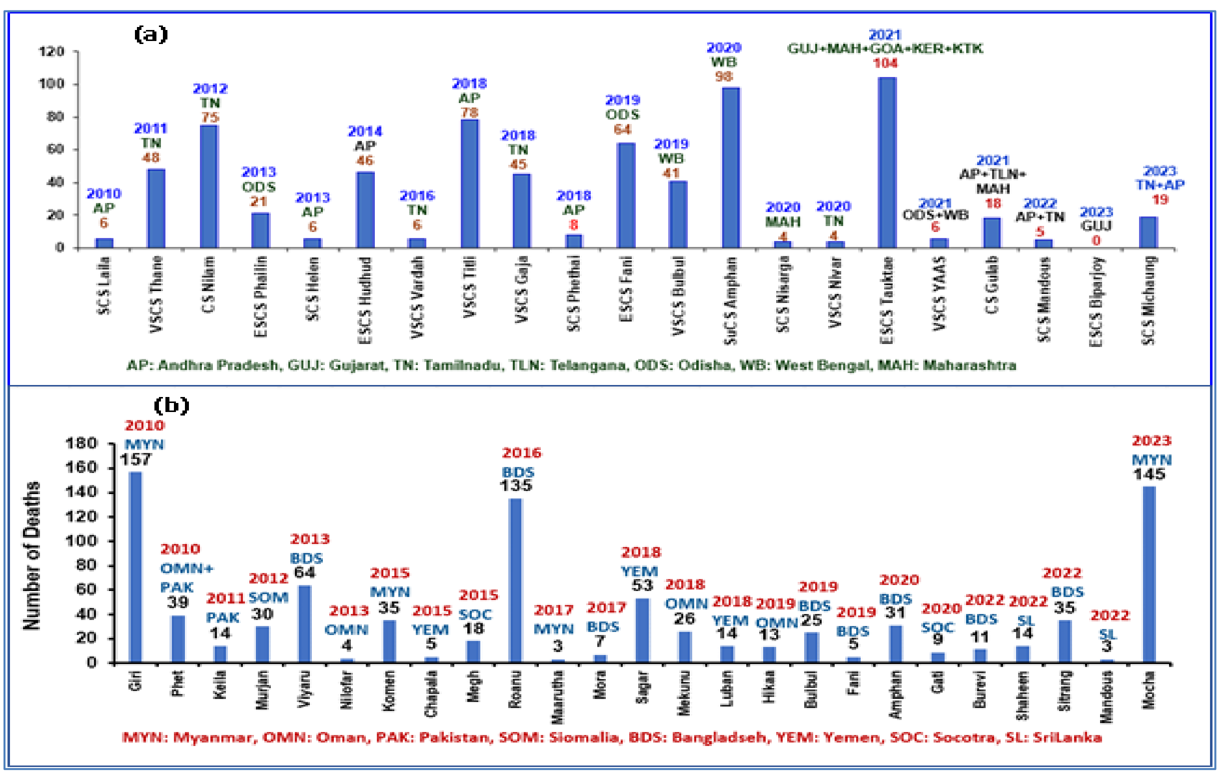

Fig. 8. Number of human deaths due to cyclones during 2010-2023 over (a) India and (b) 13 WMO/ESCAP Panel member countries bordering BoB and AS

TABLE 3

Comparison of losses due to super cyclonic storm 1999 and extremely severe cyclonic storm, Phailin in 2013

Odisha Super cyclone, 1999	Extremely severe cyclonic storm, Phailin, 2013
• No objective forecast • Lead period was less (24 hrs) • Accuracy was moderate • Poor Warning communication and triggering mechanism • Poor response and evacuation (44, 000 people)	• Objective track, intensity and landfall forecast-5 day lead • Accurate impact based warning (Rain, storm surge) • Effective communication and triggering mechanism • Effective response & evacuation (1 Million people)
• Loss of lives: 9887	• Loss of lives : 21
• Ex-gratia paid by Govt. @ Rs 0.6 Million: Rs 5932.2 Million	• Ex-gratia paid by Govt. @ Rs 0.6 Million : Rs 12.6 Million
• Area of evacuation : 500 km • Cost of evacuation(Rs.10 Million/km): 5000 Million	• Area of evacuation : 200 km • Cost of evacuation (Rs 10 Million/km): 2000 Million

Table 4.

Comparison of cyclone forecast with NHC, NOAA USA

	IMD	NHC
Extended range cyclogenesis Forecast	Forecast issued upto two weeks Probabilistic forecast	Forecast issued upto two weeks Probabilistic forecast
Medium range cyclogenesis forecast	Upto five days Probabilistic forecast	Upto five days Probabilistic forecast
Objective Track forecast	From depression stage upto next 72 hours From deep depression stage upto next 120 hours over north Indian Ocean	From cyclone stage upto next 120 hours over north Atlantic Ocean
Track Forecast error	73 km, 106 km & 144 km for 24, 48 and 72 hours lead period during 2017-21 over north Indian Ocean	75 km, 130 km & 185 km for 24, 48 and 72 hours lead period during 2016-20 over north Atlantic Ocean
Intensity Forecast Error	Intensity forecast errors are 8 knots, 12 knots & 14 knots for 24, 48 and 72 hrs lead period during 2017-21 over north Indian Ocean	8 knots, 11 knots & 12 knots for 24, 48 and 72 hours lead period during 2016-20 over north Atlantic Ocean

Comparison with NHC, NOAA USA are given in the following Table 4. On comparison, it can be seen that cyclone forecast accuracy of IMD is at par or better that that of NHC, USA.

8. Conclusions and future scope

Even though there has been tremendous progress with respect to cyclone warning system, still there are gaps in observations, understanding TC processes, modelling, landfall aspects and last mile connectivity. The gap areas are discussed below:

(*i*) Scientific Gaps:

• There is insufficient understanding of the internal structure and dynamics of cyclones, especially in terms of vertical and horizontal wind distribution and the behavior of the eye & eyewall.

• There is lack of comprehensive observational data and advanced modeling capabilities which prevent a full understanding of how cyclones interact with the ocean, atmosphere and land.

• Predicting cyclone intensity, especially rapid intensification or weakening, continues to be a major scientific challenge. However, it is a global challenge.

• The prediction of landfall events and related phenomena (*e.g.*, heavy rainfall, wind, and storm surge) is difficult due to the complexities involved in cyclone dynamics near the coast.

(*ii*) Gaps in Observations:

• Though there has been significant improvement in observational network, the observations from sea are still insufficient, particularly over the Arabian Sea. This impacts the monitoring and forecasting of location and intensity.

• Detailed structural characteristics of cyclones, such as wind and temperature distribution, are not fully understood due to the lack of aircraft reconnaissance over the NIO.

• Shortage of ground-based mobile observing platforms further limit the observational network, hindering the improvement of data density for accurate forecasts.

(*iii*) Gaps in Modeling:

• Predicting rapid changes in cyclone intensity, especially rapid intensification or weakening, is still a challenge.

• There is no probabilistic information available for critical parameters such as landfall timing, heavy rainfall, winds, and storm surge. This limits the ability to assess forecast uncertainty and risk.

• The current statistical decay models for intensity prediction after landfall have limitations and do not account for dynamic processes affecting cyclone weakening post-landfall.

(*iv*) Gaps in Communication:

• There are challenges in disseminating timely warnings to deep-sea fishermen. Efforts to improve communication, through space-based systems like NaVik is under progress.

• Reaching the final recipients, especially in remote regions in an understandable manner remains a challenge.

• Special attention needs to be given to the warning dissemination for physically challenged individuals, such as the deaf, dumb, and blind, to ensure that cyclone warnings reach all sections of society in a comprehensive form.

(*v*) Gaps in Integrated Basin Forecasting (IBF):

• **Collaborative Efforts for Risk-Based Warning Systems**: While dynamic impact-based forecasting and risk-based warning systems have been developed by IMD in collaboration with various stakeholders, the integration of these systems across multiple regions and stakeholders still remains a challenge.

• **Improved Service Delivery**: The need to enhance service delivery to the general public and stakeholders through personalized language and requirements for warnings is a critical gap in IBF systems. Developing more localized and tailored warnings is necessary for improving forecast accuracy and usability across diverse communities.

It is needless to mention that investments for technological upgradation and capacity building are essential to improve forecast accuracy. To further improve the forecast accuracy, following initiatives are required to be taken:

(*i*) Improvement in observational network with more number of radars to cover particularly the west coast, islands, more high wind speed recorders and ship & buoy observations so as to have AWS at each village, wind profiler & RS/RW at each block, Radar at each district, multiple scatterometer to cover hyper spectral microwave radiometer so as to have 3-D temperature, humidity and wind profile every 50 km over BoB & AS every three hours.

(*ii*) Development and deployment of low-cost technologies (*e.g.*, balloons, gliders, uncrewed systems, animal-borne sensors) for collecting in situ measurements of sub-surface, air-sea interface, lower boundary layer and three-dimensional measurements of kinematic and thermodynamic fields in the TC inner core and environment. When possible, make these observations available in real time.

(*iii*) Enhancement of observations for landfalling cyclones through engagement of doppler on wheels, Mobile Mesonet Probe Systems, Mobile Integrated Profiling System, Mobile instrumented tower *etc*.

(*iv*) Introduction of probabilistic information of landfall, heavy rainfall, winds and storm surge at village level.

(*v*) Enhancement of research through Research Test Bed to improve understanding of the conditions, precursors, and processes leading to TC intensity change & landfall process throughout the entire TC life cycle (preformation to decay).

(*vi*) Special focus should be given to rapid intensification and near-coast formation, including onset, duration, and potential intensification rate. As cyclone develop due to interaction of ocean, atmosphere and land, there is need for ocean atmosphere-land interaction coupled models for appropriately forecasting the track & intensity of the CDs.

(*vii*) Encourage the development of skilful seasonal (2 weeks to 3 months) and sub-seasonal (3 months to 1 year) forecasts across all ocean basins that would meet stakeholders' needs through dynamical and statistical methods as well as intercomparison and evaluation of the forecasts.

(*viii*) Implementation of Artificial Intelligence and Machine learning (AI/ML) approach for reliable probabilistic forecasting of tropical cyclone genesis, intensity, track and associated adverse weather, hazard and impact modelling and risk assessment to support Early Warning & Early Action initiative of the country.

(*ix*) Enhancement of ocean observation systems like Buoys, additional data collection platforms (ADCPs), Drifters, tide gauges, ship observations *etc*.

(*x*) Development of automated Tropical cyclone prediction system by using numerical, statistical and AI/ML approach to help forecasters.

(*xi*) Enhancement of mitigation studies based on future TC projections in terms of cyclone intensity, inundation, amount of rainfall.

(*xii*) Study in the climate change related variations in the cyclone characteristics like travelling distance of cyclone, duration, recurvature, path of cyclone in the land region, shift in the cyclogenesis location etc and studies regarding future climatic projections of TC of North Indian Ocean in collaboration with various research institutes nationally and internationally.

(*xiii*) To review the risk assessment and map the risks in a timely manner, The climate policies may be designed in view of the revised multi-hazard risk assessment to reduce loss of life, properties and TC risks. Focus to be given on how to reduce the socio-economic impacts.

(*xiv*) Development of customised sector specific risk based warnings for all sectors including industries, ports, coastal stations, offshore & onshore industries, air force bases, Indian coast, airports, tourist spots, railways, highways *etc*.

(*xv*) Development of a national repository for all-hazard event (associated with Cyclones) and loss data, thereby improving our ability to make informed decisions about where and how to prioritize their resilience investments.

(*xvi*) Enhancement of cooperation and collaboration among meteorologists, researchers, disaster managers, social scientists & workers for effective management of disasters associated with tropical cyclones.

(*xvii*) Further to improve the understanding in the gap & knowledge and improve the forecast, continuous research is required. Thus, there is a need to establish a National Centre for Tropical Cyclone in the country in line with other international centres.

Acknowledgement:

The authors acknowledge the support of Cyclone Warning Division in preparation of the manuscript.

Disclaimer: The contents and views presented in this research article/paper are the views of the authors and do not necessarily reflect the views of the organizations they belongs to.

References

Benjamin, Stanley G., Brown John M., Brunet Gilbert, Lynch Peter, Saito Kazuo and Schlatter Thomas W., 2019, "100 Years of Progress in Forecasting and NWP Applications, Meteorological Monographs", *American Meteorlogical Society*, **13**, 1-13, 67, https://doi.org/10.1175/AMSMONOGRAPHS-D-18-0020.1.

Das P. K., M. C. Sinha and V. Bala Subramanyam, 1974, "Storm surges in the Bay of Bengal", *Quart. J. Roy, Meteor, Soc*., **100**, 437-449

Das, P. K., 1972, "A prediction model for storm surges in the Bay of Bengal", *Nature*, **239**, 211-213.

Das, P. K., 1994, "Prediction of storm surges in the Bay of Bengal", *Pro. Ind. Nat. Sci. Acad*, **60**, 513-533.

De Maria, M., 1985, "Tropical cyclone motion in a non-divergent barotropic model", *Mon. Wea. Rev*., **113**, 1199-1210.

Deshpande, M., Pattnaik, S. and Salvekar, P. S., 2010, "Impact of physical parameterization schemes on numerical simulation of super cyclone Gonu", *Nat. Hazards*, **55**, 211-231.

Dube, S. K., Jain, I., Rao, A. D. and Murty, T. S., 2009, "Storm surge modelling for the Bay of Bengal and Arabian Sea" *Natural Hazards*, **51**, 3-27.

Dube, S. K., Rao, A. D., Jismy Poulose, 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," Ed. by U.C. Mohanty, M Mohapatra, O.P. Singh, B.K. Bandyopadhyay and L.S. Rathore.

Dube, S. K., Rao, A. D., Sinha, P. C., Murty, T. S. and Bahulayan, N., 1997, "Storm surge in the Bay of Bengal and Arabian Sea: the problem and its prediction", *Mausam* (New Delhi), **48**, 283-304.

Dvorak, V. F., 1972, "A technique for the analysis and forecasting of tropical cyclone intensities from satellite pictures", NOAA Tech. memo., NESS 36, Washington, DC.

Dvorak, V. F., 1984, "Tropical cyclone intensity analysis using satellite data", NOAA Tech. Rep., NESPISP, p445.

Ghosh, S. K., 1977, "Prediction of storm surges on the east coast of India", Indian Journal of Meteorology", *Hydrology and Geophysics*, **28**, 157-168.

Gupta, A. and Bansal, R. K., 1997, "Performance of a global spectral model in predicting the track of a hurricane in the Bay of Bengal using synoptic vortex", NCMRWF, New Delhi Tech. Report.

Gupta, A. and Mohanty, U. C., 1997, "Secondary convective rings in an intense asymmetric cyclone of the Bay of Bengal", *Mausam*, **48**, 273-282.

IMD, 1943, Climatological Atlas of India and neighbourhood for Meteorologists and Airmen, IMD, New Delhi

IMD, 1964, Tracks of storms and depressions, IMD, New Delhi.

IMD, 1986, Observational organization, IMD, New Delhi.

IMD, 1989, Standard Brief published by India Meteorological Department, New Delhi, p97.

IMD, 1992, "Damage Potential of tropical cyclones", published by IMD, New Delhi.

IMD, 1999, Annual Cyclone Review Report 1999 published by IMD, Pune.

IMD, 2000, 125 Years of Service to Nation published by India Meteorological Department, Pune.

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

IMD, 2003b, Standard Brief published by India Meteorological Department, New Delhi.

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

IMD, 2009, Standard Brief published by India Meteorological Department, New Delhi, pp-140

IMD, 2010, Forecast Demonstration Project (FDP) for Improving Track, Intensity and Landfall of Bay of Bengal Tropical Cyclones, Implementation of Pilot Phase, 2010: A Report, IMD, New Delhi.

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

IMD, 2020, Preliminary Report on Super Cyclonic Storm Amphan, published by IMD.

IMD, 2021, "Cyclone Warning Services: Standard Operation Procedure", Published by Cyclone Warning Division, IMD, New Delhi.

IMD, 2024, "Cyclone Warning Services: Standard Operation Procedure", Published by Cyclone Warning Division, IMD, New Delhi.

Jelesniaski, C. P., 1972, "SPLASHI landfall storms", NOAA Tech. Memo NWS, TDL-46, NOAA, p52.

Jha, T. N., Mohapatra M., Bandyopadhyay B. K., 2013, "Estimation of intensity of tropical cyclone over Bay of Bengal using microwave imagery", *Mausam*, **64**, 1, 105-116.

Kasahara, A., 1957, "The numerical prediction of hurricane movement with the barotropic model", *J. Met*., **14**, 386-417.

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 techniquefor cyclone track prediction over north Indian Sea", *Geofizika*, **28**, 275-291.

Kotal, S. D. and Roy Bhowmik, S. K., 2013, "Large-scale characteristics of rapidly intensifying tropical cyclones over the Bay of Bengal and a Rapid Intensification (RI) Index", *Mausam*, **64**, 1, 13-24.

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.

Mandal, M. and Mohanty, U. C., 2006, "Numerical experiments for improvement in the mesoscale simulation of Orissa super cyclone", *Mausam*, **57**, 1, 79-96.

Mandal, M., Mohanty, U. C. and Raman, S., 2004, "A study on the impact of parameterization of physical processes on prediction of tropical cyclones over the Bay of Bengal with NCAR/PSU mesoscale model", *Nat. Hazards*, **31**, 2, 391-414.

Mathur, M. B., 1991, "The National Meteorological Center's quasi-Lagrangian model for hurricane prediction, *Mon. Weather Rev*., **119**, 1419-1447.

MoES, 2019, Annual Report of 2018 published by MoES, Government of India.

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, doi : 10.1175/EI-D-14-0032.1.

Mohanty, U. C. and Gupta, A., 1997, "Deterministic methods for prediction of tropical cyclone tracks", *Mausam*, **48**, 257-272.

Mohanty, U. C., R. Nadimpalli, Sama Mohanty, and K. K. Osuri, 2019, "Recent advancements in prediction of tropical cyclone track over north Indian Ocean basin", *MAUSAM*, **70**, 1, 57-70.

Mohapatra, M. and S. Adhikary, 2011, "Modulation of cyclonic disturbances over the north Indian Ocean by Madden - Julian oscillation", *MAUSAM*, **62**, 3, 375-390.

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, "Tropical cyclone forecast verification by India Meteorological Department for North Indian Ocean", *A Review; Tropical Cyclone Research and Review*, **03**, 1- 14.

Mohapatra, M., Bandyopadhyay, B. K. and Tyagi, Ajit, 2012b, "Best track parameters of tropical cyclones over the North Indian Ocean: A review", *Nat. Hazards*, **63**, 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., Capital Publishing Co. and Springer Publications Ltd., 149-168.

Mohapatra, M., Kumar Naresh, Sharma Monica, S. Devi, Sunitha, Senroy, Soma, K. Sathi, Devi, K. K. Singh, 2022, "Short to medium range weather forecasting in India", *In Social and Economic Impact of Earth Sciences by Springer.*

Mohapatra, M., Kumar, N., Ranalkar, M., 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.

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

Mohapatra, M., Monica Sharma and Sunitha Devi, 2020, "Cyclones and Disaster Management", *Journal of Governance*, **22**, 200-220.

Mohapatra, M., Nayak, D. P., Sharma, R. P. and Bandyopadhyay, B. K., 2013c, "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., Sikka, D. R., Bandyopadhyay, B. K. Ajit Tyagi, 2013, "Outcomes and challenges of Forecast Demonstration Project (FDP) on landfalling cyclones over Bay of Bengal", *Mausam*, **61**, 1, 01-12.

Mohapatra, Mrutyunjay, Anshul Chauhan, Avnish Varshney, Suman Gurjar, M. T. Bushair, Monica Sharma, R. K. Jenamani, Kuldeep Srivastava, Pulak Guhathakurta, Rajib Chattopadhyay, Mamta Yadav, Radheshyam Sharma, A. K. Mitra, Ananda Kumar Das, Sankar Nath, Naresh Kumar, Soma Senroy, T Arulalan, Amit Bharadwaj, D. R. Pattanaik, B. P. Yadav, Rahul Saxena, Ashok Kumar Das, Asok Raja, B. Hemlata, KVH Arun, S. Nitha, Atul K. Singh, Shobhit Katiyar, Krishna Mishra, Surendra Pratap Singh, Shashikant Mishra, Akhil Srivastava, B. Geetha, M. Rahul, K. Nagaratna, H R Biswas, Manorama Mohanty, R Thapliyal, Shivinder Singh, Sonam Lotus, Sandeep KumarSharma, V. K. Mini, Sunit Das, G. K. Das, Abhishek Anand, Gayatri KVani, 2023, Short to medium range impact based forecasting of heavy rainfall in India, *Mausam.*

Mukhopadhyay, P., Taraphdar, S. and Goswami, B. N., 2011, "Influence of moist processes on track and intensity forecast of cyclones over the North Indian Ocean", *J. Geophys. Res*., **116**, D05116, 1-21.

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.

NDMA, 2008, Guidelines on Cyclones published by National Disaster Management Authority, India.

Neumann, C. J. and Mandal, G. S., 1978, "Statistical prediction of tropical storm motion over the Bay of Bengal and Arabian Sea", *Indian J. Meteorol. Hydrol. Geophys*., **29**, 487–500.

Neumann, C. J. and. Lawrence, M. B, 1975, "An operational experiment in the statistical-dynamical prediction of tropical cyclone motions", *Mon. Wea. Rev*., **103**, 665-673.

Normand, C. W. B., 1925, "Storm tracks in the Bay of Bengal", India Meteorological Department.

Normand, C.W. B., 1926, "Storm tracks in the Arabian Sea", India Meteorological Department.

Osuri, K. K., Mohanty, U. C., Routray, A. and Mohapatra, M., 2012b, "Impact of Satellite Derived Wind Data Assimilation on track, intensity and structure of tropical cyclones over North Indian Ocean", *Int. J. Remote Sens*., **33**, 5, 1627-1652.

Osuri, K. K., Mohanty, U. C., Routray, A. and Niyogi, D., 2015, "Improved prediction of Bay of Bengal tropical cyclones through assimilation of Doppler weather radar observations", *Monthly Weather Review*, **143**, 11, 4533-4560.

Osuri, K. K., Mohanty, U. C., Routray, A., Kulkarni, M. A. and Mohapatra, M., 2012a, "Sensitivity of physical parameterization schemes of WRF model for the simulation of Indian seas tropical cyclones", *Nat. Hazards*, **63**, 3, 1337-1359.

Pattanaik, D. R and Mohapatra, M., 2021, "Evolution of IMD's operational extended range forecast system of tropical cyclogenesis over North Indian Ocean during 2010-2020", *MAUSAM*, **72**, 1, 35–56.

Pattanaik, D. R., M. Mohapatra, B. Mukhopadhyay, Ajit Tyagi, 2013, "A preliminary study about the prospects of extended range forecast of tropical cyclogenesis over the north Indian Ocean during 2010 post-monsoon season", *Mausam*, **64**, 1, 171-188.

Pike, C. A., and C. J. Neumann, 1987, "The variation of track forecast difficulty among tropical cyclone basins", *Wea. Forecasting*, **2**, 237-241.

Prasad, K., 1997, "Prediction of tropical cyclones by numerical models", *MAUSAM*, **48**, 2, 225-238.

Prasad, K., Kalsi, S. R., Rama Rao, Y. V., Roy Bhowmik, S. K. and Joardar, D., 2000, "Evaluation of operational cyclone track forecasts by IMD limited area NWP model during 1998", *Mausam*, **51**, 91-95.

Raghavan, S., 1997, "Radar observations of tropical cyclones over the Indian seas", *Mausam*, **48**, 169-188.

Raju, P. V. S., Jayaraman, P. and Mohanty, U. C., 2011, "Sensitivity of physical parameterizations on prediction of tropical cyclone Nargis over the Bay of Bengal using WRF model", *Meteo. Atm. Phy*., **113**, 125-137.

Rao, Bhaskar, D. V. and Hari Prasad, D., 2006, "Numerical prediction of the Orissa super cyclone: Sensitivity to the parameterization of convection, boundary layer and explicit moisture processes", *Mausam*, **57**, 1, 61-78.

Rao, Bhaskar, D. V., Hari Prasad, D. and Srinivas, D., 2009, "Impact of horizontal resolution and the advantages of the nested domains approach in the prediction of tropical cyclone intensification and movement", *Journal of Geophysical Research: Atmospheres*, D (114).

Routray, Ashish, U. C. Mohanty, K. K. Osuri, S. C. Kar and D. Niyogi, 2016, "Impact of Satellite Radiance Data on Simulations of Bay of Bengal Tropical Cyclones Using the WRF-3DVAR Modeling System," in IEEE Transactions on Geoscience and Remote Sensing, **54**, 4, 2285-2303, doi: 10.1109/TGRS.2015.2498971.

RSMC New Delhi, 1991-2024, Report on Cyclonic Disturbances over North Indian Ocean during 1990-2024 published by RSMC New Delhi, IMD (rsmcnewdelhi.imd.gov.in).

Sanders, F. and Burpee, R. W., 1968, "Experiments in barotropic track forecasting", *J. Appl. Meteor*., **7**, 313-323.

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.

Shukla, J. and Saha, K. R., 1970, "Application of non-divergent barotropic model to predict flow patterns in the Indian region", *J. Met. Soc*. Japan, **48**, 405-410.

Sikka, D. R., 1975, "Forecasting the movement of tropical cyclones in the Indian seas by non-divergent barotropic model Indian", *Indian J. Met. Geophys*., **26**, 323-325.

Singh S. S. and Sugi, M., 1986, "Prediction of monsoon depression with a regional primitive equation model", *Mausam*, **37**, 17-26.

Singh, Randhir, Kishtawal, C. M., Pal, P. K. and Joshi, P. C., 2012a, "Improved tropical cyclone forecasts over north Indian Ocean with direct assimilation of AMSU-A radiances", *Meteor. Atmos. Phys*., **115**, 1-2, 15-34.

Singh, Randhir, Pal, P. K., Kishtawal, C. M. and Joshi, P. C., 2008, "The impact of variational assimilation of SSM/I and QuikSCAT Satellite observations on the Numerical Simulation of Indian Ocean Tropical Cyclones (2008)", Wea. Forecasting, **23**, 460-476.

Singh, Randhir, Prashant, K. and Pal, P. K., 2012b, "Assimilation of Oceansat-2 Scatterometer-Derived Surface Winds in the Weather Research and Forecasting Model", *IEEE Trans. Geosci. Remote Sens*., **50**, 4, 1015-1020.

Soyono, S. and Yamasaki, M., 1966, "Stability of symmetrical motion driven by latent heat release by cumulus convection and surface friction", *J. Met. Soc. Japan*, **44**, 353-375.

Srinivas, C. V., Venkatesan, R., Bhaskar Rao, D. V. and Hariprasad D., 2007, "Numerical simulation of Andhra severe cyclone (2003): model sensitivity to boundary layer and convection parameterization", *Pure Appl. Geophys*., **164**, 1-23.

Srinivas, C. V., Yesubabu, V., Hari Prasad, K. B. R. R., Venkatraman, B. and Ramakrishna, S. S. V. S., 2012, "Numerical simulation of cyclonic storms FANOOS, NARGIS with assimilation of conventional and satellite observations using 3-DVAR", *Nat. Hazards*, **63**, 2, 867-889.

Srinivas, C. V., Yesubabu, V., Venkatesan, R. and Ramakrishna, S. S. V. S., 2010, "Impact of assimilation of conventional and satellite meteorological observations on the numerical simulation of a Bay of Bengal Tropical Cyclone of November 2008 near Tamilnadu using WRF model", *Mete. Atmos. Phys*.,**110**, 19-44.

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.

Trivedi, D. K., Mukhopadhyay, P. and Vaidya, S. S., 2006, "Impact of physical parameterization schemes on the numerical simulation of Orissa super cyclone (1999)", *Mausam*, **57**, 1, 97-110.

Vanderman, L. W., 1962, "An improved NWP model for forecasting the path of tropical cyclones", *Mon. Wea. Rev*., **90**, 19-22.

WMO, 2009-2024, Tropical Cyclone Operation Plan (TCP-21) published by WMO.