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VISION 2047

for

Cyclone Warning Services

and

Action Plan

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PREFACE

India Meteorological Department (IMD) is committed to deliver world-class cyclone warning services through holistic development of its early warning components. Along with the existing challenges posed by the inherent scientific intricacies involved in the tropical cyclone forecasting, the climate change scenario in the years to come is compounding the problem more and more over South Asian region at the rim of North Indian Ocean (NIO) due to its complex geographic, demographic and socio-economic nature. The arena of impact based forecast and risk based warning for a multi-hazard disaster like tropical cyclone holds utmost importance and seer focus from the scientific community in today's time.

A necessary roadmap and projection of scientific development in coming years is an essential and crucial to keep pace with the expected changes in climate, socio-economic behavior and the future needs & challenges. The clear view about the outcomes with the proper functioning of various components in the development process utilizing many state-of-art future technologies is therefore very essential. In addition, the advancement process would be flexible enough for need-based maneuvering or accepting new pathways in the unexplored scientific domain. The vision for upcoming advancements in the tropical cyclone forecast and warning services to create a climate and disaster resilient society over the South Asia region in future is a noble objective. This document presents the vision, mission, strategy and expected outcome of the various initiatives to achieve improvement in cyclone warning services in North Indian Ocean.

The continuous development of vision and strategy in this regard since 2010 is praiseworthy. The vision and strategy document presented here brings in new objectives and strategies while updating the previous versions of 2010 and 2015. There has been paradigm shift in cyclone warning services of the IMD leading to global accolades & appreciations and significant reduction in death toll over the region due to any cyclone. IMD envisions to improve the impact based forecast accuracy of all parameter by 10% for lead period upto 5 days by 2030. It would enable the public and disaster managers to **further minimize loss of lives and reduce loss of property** due to any cyclone over the region.

Mrutyunjay Mohapatra

February 2024 **Director General of Meteorology**

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Vision 2047 for Cyclone Warning Services and Action Plan

1. Introduction:

India experiences various types of natural hazards including tropical cyclones (TCs), floods, droughts, earthquakes, landslides, heat waves, cold waves, thundersqualls and tornadoes. Most of these hazards (about 80%) are hydro-meteorological in nature. Among the various hydrometeorological hazards, the TCs over the North Indian Ocean (NIO) pose a potential threat to coastal population as well as marine community of the region. Historically, in terms of loss to human life, the Bay of Bengal (BoB) TCs accounted for deaths exceeding thousands and caused huge loss to property. Till the beginning of 2000, 75% of the TCs which caused death of 5000 or more in the world were over north Indian Ocean (NIO) especially over the Bay of Bengal (BoB). BoB has a notorious history of 300,000 deaths in Bangladesh in 1970 due to "Bhola" cyclone and about 10000 deaths due to super cyclone which hit Odisha coast in Paradeep in 1999. considering the facts above, worldwide people tried to minimize the loss of life and properties through various methods. The risk management of the cyclones depends on several factors including (i) hazard & vulnerability analysis, (ii) preparedness & planning, (iii) early warning, (iv) prevention and mitigation. Out of these, early warning is the most crucial for all type of response actions before, during and after the cyclone. The early warning component includes (i) skill in monitoring and prediction, (ii) effective warning products generation and dissemination, (iii) coordination with disaster response units and (iv) public awareness & perception about the credibility of early warning of cyclone issued by India Meteorological Department (IMD). It is thus important to continuously upgrade all the components of early warning based on latest technology for effective management of TCs.

While the first cyclone warning was commenced as the port warning for Kolkata Port in 1865, it gradually extended to cover the entire country. The early warning system has undergone various improvements over the years with the introduction of various tools, technology and scientific methods.

In the recent decade the death toll has been reduced significantly, being limited to less than 100 due to any TC, not only in India but also in all the countries bordering BoB and the Arabian Sea (AS). This paradigm shift in cyclone warning services of IMD has occurred mainly due to improvements in all components viz. observations, modelling, warning products generation & dissemination, response actions, well defined synergised standard operation procedure (SSOP), institutional mechanism, legal provision for policy guidelines like DM ACT 2005, DM Plan and NDMA guidelines for Cyclone Management.

Prior to this, first Vision document was prepared by Ministry of Earth Sciences (MoES) for 2020 with the base year 2010 (MoES, 2010). It was envisioned to improve the TC forecasting accuracy by 20% by 2015 and 40% by 2020. The second Vision on cyclone and storm surge was written by MoES in 2015 as Vision 2030 (MoES, 2015). It was then envisioned to improve the TC forecast accuracy by about

20% by 2030. Further the landfall point error was planned to be reduced to 30 km, 60 km and 90 km for 24, 48 and 72 hours forecast lead period respectively.

The Vision and Mission of IMD for short, medium and long range for the years 2025 (next 2 years), 2030 (subsequent 5 years), 2040 (subsequent 10 years) and 2047 (next 7 years) respectively are presented in this document.

This document discusses, the current status of cyclone warning system in the country under section 2, the gap area & challenges under section 3 and vision and mission statement under section 4. The strategy for implementation is present in section 5. Expected outcomes and conclusion are presented in section 6 and 7 respectively.

2. Current Status

In this section, the current status of observations, monitoring, forecasting, warning services and operational forecast errors are presented below.

IMD maintains round the clock watch over the North Indian Ocean (NIO). The analysis and prediction of TCs involve blending of meteorological observations, conceptual, dynamic and statistical models, technology, digitised decision support system and forecaster's expertise to prepare advisories and warnings in an actionable format. The current status of a cyclonic disturbance (CD) is determined utilising observations from all available sources which are space based, upper air based and land based. Currently, IMD utilizes satellite observations from various national & international satellites (INSAT 3D, 3D(R), Meteosat 7, ASCAT, SCATSAT, ASCAT, OceanSat-3), upper air observations (from Radars (39), RS/RW (56) & Pilot Balloon stations (62)), surface observations (560), automatic weather stations (1008), automatic rain gauges (1382), high wind speed recorders (37), ships under voluntary observing fleet (50) and meteorological buoys (20) for monitoring the TCs and associated adverse weather. These observations are analysed in a digital platform to find out the developing CD from the stage of upper air cyclonic circulation. Once, a low pressure area forms, standard operation procedure is followed to find out its location, movement, intensity in terms of pressure drop at centre, estimated central pressure, pressure of outermost closed isobar, radius of outermost closed isobar, associated maximum sustained wind speed, radius of maximum wind and depth of convection. IMD criteria (IMD, 2013 and 2023) is utilised for classification of various categories of cyclonic disturbances.

Table 1: Classification of cyclonic disturbances over the NIO (since 2015)

Low Pressure System	Maximum sustained wind speed (kts/kmph)
Low pressure area (L)	< 17 knots/ 31 kmph
Depression (D)	17-27 knots/ 31-49 kmph
Deep Depression (DD)	28-33 knots/ 50-61 kmph
Cyclonic Storm (CS)	34-47 knots/ 62-88 kmph
Severe Cyclonic Storm (SCS)	48-63 knots/ 89-117 kmph
Very Severe Cyclonic Storm (VSCS)	64-89 knots/ 118-166 kmph
Extremely Severe Cyclonic Storm (ESCS)	90-119 knots/ 167-221 kmph
Super Cyclonic Storm (SuCS)	≥120 knots/ 222 kmph

Once the system intensifies into a depression and cyclone, it's structural characteristics are also analysed to find out the vital parameters in terms radial extension of winds reaching 28kts, 34kts, 50kts and 64 kts in four geographical quadrants around the centre of the storm and depth of convection.

As the cyclones normally develop over warm oceanic areas, monitoring of cyclonic disturbances is based on the satellite based guidance at the genesis stage alongwith ship or buoy observations, if available. The manual Dvorak technique is utilised to find out the centre and intensity of CDs alongwith objective Advanced Dvorak technique and AI/ML based Dvorak Technique available from various international sources. Once the system comes under radar range (upto 500 km off coast), the radar based observations are given more weightage to determine the location and intensity. Once the system comes near to the coast, more weightage is given to coastal observations. Various steps for determination of centre and intensity of TC are discussed by Sharma and Mohapatra(2017).

IMD utilizes an array of models including global, regional and cyclone specific models for forecasting TC track, intensity and associated adverse weather like heavy rainfall, gale wind and storm surge. These models are deterministic and ensemble based from various constituents of Ministry of Earth Sciences (MoES) and also from various international agencies under bilateral arrangement. The atmospheric models namely (i) IMD Global Forecast System (GFS) model, (ii) National Centre for Medium Range Weather Forecasting Centre (NCMRWF) Unified Model (NCUM), (iii) National Centre for Environment Prediction (NCEP) GFS, (iv) European Centre for Medium Range Weather Forecasting (ECMWF), (v) IMD Global Ensemble Forecasting System (GEFS), (vi) NCMRWF Ensemble Prediction System (NEPS), regional models including (vii) HURRICANE Weather Research & Forecast (HWRF) model with a resolution of 2 km & lead period of 5 days during cyclone period, (viii) IMD Weather Research Forecast System (IMD WRF) with a resolution of 3 km & lead period of 3 days, (ix) NCUM Regional with a resolution of 4km & lead period 5 days, (x) various s**tatistical dynamical model for cyclone genesis and intensity prediction developed by IMD including** genesis potential parameter (GPP), 12 hourly intensity prediction for forecasts up to 120 hours, statistical multi model multi model ensemble (MME) based on linear regression approach, rapid intensification/weakening model and (xi) indigenously developed MME based on TC tracker. In addition, for ocean state prediction, wave model, storm surge and coastal inundation model from Indian National Centre for Ocean Information Services (INCOIS), storm surge model from IIT Delhi and Ghosh nomograms for storm surge forecast are utilised.

For generating the forecast instead of one single model, the MME is utilised. Further, extra weightage is given to historically best model and the model which is performing the best under current state of atmosphere. This MME further modulated utilising current observations and experience & expertise of forecasters maintaining the consistency in forecast.

Further, a Standard Operation Procedure is followed for monitoring, prediction and dissemination of cyclone warnings and advisories for effective monitoring and prediction of of cyclone warnings over the NIO (IMD, 2013, IMD, 2021, Sharma and Mohapatra, 2017).

IMD has a seamless flow of warnings starting from extended range outlook which is issued every Thursday with probabilistic forecast of cyclogenesis for next 2 weeks indicating area of genesis and period of genesis. This is followed by daily tropical weather outlook with forecast of cyclogenesis over the BoB and the AS for next 7 days indicating probable area and day of genesis. The regular monitoring continues and once a cyclonic circulation develops/emerges into the area of responsibility, the information is shared in daily tropical weather outlook and regular national bulletins for national level disaster managers and general public. On formation of low pressure area, a special message which is called as pre-genesis forecast is issued. It includes forecast track alongwith cone of uncertainty and wind distribution around the centre of storm for next 72 hours in case it is expected to be a TC. IMD is the first agency across globe that has commenced pre-genesis forecast in terms of track & intensity forecast in graphical format alongwith cone of uncertainty and wind distribution around the centre of storm for next 72 hours at the stage of low pressure area since 2022. On formation of depression, regular bulletins are issued 5 times a day with information about the location, movement & intensity of the CD alongwith quantitative track and intensity forecast for next 72 hours in textual form and also in graphical form alongwith cone of uncertainty & wind distribution around the centre of storm since 2021. On formation of deep depression, the lead period of forecast increases to next 120 hours. Once, cyclonic storm develops, frequency of bulletins increases becoming 3 hourly with lead period of forecast upto next 120 hours.

IMD has 4 stage warning system for communicating cyclone warnings to the disaster management agencies. At the initial stage a special “Informatory Message” is issued on formation of low pressure area stage when it has the potential to intensify into a cyclonic storm based on 0830 hours IST or at any synoptic hour depending upon time of formation of low pressure system to all the disaster managers and press. A “pre-cyclone watch” bulletin is issued soon after the formation of a depression informing senior central government officials including chief secretary of coastal maritime states about likely development of a cyclonic storm, its movements, coastal belt of India likely to experience adverse weather. This bulletin is issued at least 72 hours in advance of commencement of adverse weather. It can be issued even earlier, depending upon the confidence level in forecast. At the second stage, a "cyclone alert" is issued at least 48 hours in advance of the expected commencement of adverse weather in association with the cyclonic storm over the coastal area. The third stage of the warning, known as "cyclone warning" is issued at least 24 hours in advance of commencement of severe weather over the coastal area. The last stage of warning covering the post-landfall scenario is included in the cyclone warnings issued 12 hours before the expected time of landfall and is continued till the cyclonic wind force is maintained in the core area of the cyclonic storm over land. However, this is not applicable in case of cyclonic disturbances developing near the coast and in case of rapidly intensifying systems. In such cases, the cyclone warning can be issued directly without issuing cyclone alert and watch bulletins and similarly cyclone watch can be issued directly without issuing pre-cyclone watch. Further these 4 stage warnings can be issued in case of non-landfalling cyclones also, moving close to coast and likely to bring adverse weather associated with cyclonic storm and above intensity category over the affected areas.

In terms of forecast accuracy, IMD is at par with leading international centre i.e. the National Hurricane Centre, USA and even better than Japan Meteorological Agency for all lead periods and for track, landfall and intensity prediction. The average track forecast errors during 2019-23 have been 72 km, 112 km and 156 km respectively for 24, 48 and 72 hrs against the average errors of 86, 132 and 178 km during 2014-18. The errors in track prediction registered an overall improvement of 20% upto 96 hours lead period during 2019-23 as compared to 2014-18. The annual average errors in intensity forecast during 2019-23 have been 7.1 knots, 9.3 knots and 13.8 knots respectively for 24, 48 and 72 hrs lead period of forecast against the average errors of 9.6, 14.1 and 14.3 knots during 2014-18. The errors in intensity prediction registered an overall improvement of 20-30% upto 60 hours lead period during 2019-23 as compared to that of 2014-18. The annual average landfall point forecast errors during 2019-23 have been 18 km, 42 km & 73 km for 24, 48 & 72 hrs lead period against the average errors of 47 km, 70 & 104 km during 2014-18. The errors in landfall point prediction registered an overall improvement of 30-60% upto 72 hours lead period during 2019-23 as compared to that of 2014-18. The landfall time forecast errors during 2019-23 have been 2.8, 4.6 & 9.5 hrs for 24, 48 & 72 hrs lead period against the average errors of 2.9, 5.1 & 5.8 hrs respectively during 2014-18. The errors in landfall time prediction registered an overall improvement of 10% upto 48 hours lead period during 2019-23 as compared to that of 2014-18.

3. Challenges and gap areas

Even though there have 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. Gaps in observations primarily include lack of direct observations from the cyclone field as over the NIO, as we do not have dropsonde, aircraft/UAV reconnaissance, limited scatterometer, no ground based mobile observing platforms. There is lack of complete coverage of NIO with sea surface wind observations atleast once a day. There is need to augment the ground observing systems with mobile observing platforms (mobile wind profilers) around the expected area of landfall; and also install temporary observing equipments in the coastal areas near the expected landfall point (meso-network) at the premises of individuals & private agencies interested in weather monitoring and remove the equipments after the event. In the absence of direct observations in the cyclone field, characteristics like wind & temperature distribution along the vertical and horizontal structure of eye and eye wall etc. over the NIO are still highly subjective. There is need to augment at least one in every 2^0X 2^0 grid over the BoB and AS. There is need to augment surface, upper air and radar observations in the Bay and AS Islands with AWS/ARG and 5 doppler weather radars (DWRs) each in Bay and Lakshadweep Islands.

In order to better understand TC processes more research is required. There is need to carry out more diagnostic studies on past cyclones to understand the influences of land interactions & synoptic scale eddy interactions, develop conceptual models specific to NIO basin and also need to undertake more studies on asymmetry in precipitation structures under the influence of topography, cyclone movement, vertical wind shear, diurnal cycle & convective bursts. While the TC environment is largely understood, the TC inner core structure is least understood. Hence Research Test Bed on cyclone should be established with all observations and computing infrastructure facility in a coastal state.

Even though, IMD has one of the best forecasting mechanism, with computing power of 8 Peta Flop and assimilation of 300 GB data into numerical models every day, still forecasting track & intensity in some cases a challenge. The cases of rapid intensification/rapid weakening, predicting point & time of recurvature and area of recurvature is still a challenge. The track forecast error is more difficult when there is rapid change in track near landfall. Such difficult situations include the (i) recurving TCs, and (ii) rapid/slow movement of TCs during landfall). It is found that the error is higher by about 5 to 20% for 12 hr to 72 hr lead period of forecasts in case of TCs with rapid track changes as compared to the mean track forecast errors based on the data of 2003-13 (Heming et al., 2018). Still probabilistic forecast products have not been introduced. There is need to introduce probabilistic information of landfall, heavy rainfall, winds and storm surge. Currently a static cone of uncertainty is overlaid on the forecast track based on past 5 years average errors. There is need to introduce probabilistic cone of uncertainty. Further, intensity prediction is still a challenge. There is need to enhance research towards improved understanding of the conditions, precursors, and processes leading to TC intensity change throughout the entire TC lifecycle (pre-formation to decay). 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. The landfall characteristics are strongly influenced by the prevalent atmospheric & sea conditions, topography, bathymetry and the physiography of the region. Thus, there is need to improve adverse weather forecast accuracy for landfalling cyclones including track, intensity, landfall and associated adverse weather including heavy rainfall, strong winds and storm surge. There is also need to improve the accuracy of location specific quantitative precipitation forecast for extreme rainfall events & gale wind speed warnings. The extended range forecast accuracy is reasonable for week1 and needs to be improved in terms of accuracy and lead period. There is no seasonal forecast of TCs which is also a gap area compared to other basis.

Though IMD has introduce dynamic impact based forecast based on Web DCRA (Web based Dynamic Composite Risk Atlas) with hazard, impact modelling for wind, rainfall, storm surge, it needs further improvement with increase in resolution of geospatial database, populating the data on socioeconomic condition at village level, high resolution modeling of hazards like wind, rainfall, wave, storm surge, etc.

The efficacy of forecast and mitigation measures strongly depend upon the warning dissemination system, last mile connectivity and public perception in cyclone warnings issued by IMD. Nowadays, all means of information, communication &

technology are utilised to reach out to last mile. These means include transmission of warnings through FAX, email, websites, social networking channels (face book, whatsapp, twitter), SMS, mobile apps, application programming interface for cyclones (APIs), video messages, broadcasting through All India Radio, Television and private Channels, common alert protocol (CAP), global multi-hazard alert system (GMAS) etc.. Further redundancy is maintained in communication. IMD alongwith it's 3 Area Cyclone warning Centre, 4 Cyclone Warning Centres, 36 Meteorological Offices, 6 Regional Meteorological Centres manages the cyclone warning services. In addition, the National Disaster management Agency, National Disaster Response, Ministry of Home Affairs also contribute towards warning dissemination and mitigation measures. However, still there are gaps in reaching out to last mile. Common man may not have smart phones, access to internet, websites etc. There is thus need for community involvement towards preparing, protecting, mitigating, responding and recovering actions.

Unlike other basins, NIO region has two cyclones seasons viz. Pre-monsoon (April-June) and Post-monsoon season (October-December). Out of the total of 85 TCs developing across globe only 5 develop over the NIO region with 4 over the BoB and 1 over the AS. Thus, considering large variability and less number of cyclones annually, the predictability of seasonal and sub-seasonal forecast still lacks predictability.

4. Vision

The India Meteorological Department is committed to deliver world-class cyclone warning services through holistic development of all four pillars of early warning services, including (i) observations, (ii) modelling, (iii) forecasting (iv) early warning products generation and dissemination. The target for 2047 includes improvement in quality, accuracy & efficiency in service delivery of all the above along with improvement in forecast accuracy. Specifically, it is aimed at the following:

- No low pressure system should go undetected and unpredicted at least 20 days in advance.
- Sustainable development of cyclone warning services of IMD to achieve zero death toll and zero loss to property through accurate impact based forecast and risk based warnings for cyclones track, intensity, landfall and associated adverse weather. It would enable the Government to minimize death and damage due to TCs and thus build a disaster resilient society through accessible and actionable cyclone warnings at each household.
- IMD to be a major contributor to Govt. exchequer by saving expenditure towards disaster management and rehabilitation activities and contributing to the prosperity of the nation through sector specific, accurate and actionable advisories
- Development of a cyclone warning system which can combat the impact of climate change through accurate forecast, at desired spatio-temporal scales and for implementation of various adaptation & mitigation measures
- IMD to emerge as a global leader in providing cyclone warning and capacity building services to the world community

➢ Targeted forecast accuracy for the years 2025, 2030, 2040 and 2047 is presented in Table 1.

Table1: Targeted forecast accuracy and achievements for 2025, 2030, 2040 and 2047

Parameter	Status in 2019-2023		Goal for 2025	Goal for 2030	Goal for 2040	Goal for 2047
Medium range forecast of Genesis (Area and time)	Forecast of depression 7 days ahead		Forecast of low 7 days ahead	Forecast of Low 10 days ahead, depression 7 days ahead and cyclone 5 days ahead.	Forecast of Low 15 days ahead, depression 12 days ahead and cyclone 7 days ahead	Forecast of Low 20 days ahead, depression 15 days ahead and cyclone 10 days ahead
Extended range genesis forecast	Low: Nil		Low: upto 2 weeks	Low: upto 3 weeks	Low: upto 4 weeks	Low: upto 5 weeks
	Depression: upto 2 weeks		Depression: upto 3 weeks	Depression: upto 4 weeks	Depression: upto 6 weeks	Depression: upto 8 weeks
	Cyclone: Subjective prediction at the stage of cyclonic circulation/low		Cyclone: upto 1 week	Cyclone: upto 3 week	Cyclone: upto 5 weeks	Cyclone: upto 8 weeks
	Accuracy for week 1	Low: 80%	Low: 82%	Low: 87%	Low: 95%	Low: 100%
		Dep.: 70%	Dep.: 72%	Dep.: 77%	Dep.: 85%	Dep.: 100%
		Cyclone: 60%	Cyclone: 62%	Cyclone: 67%	Cyclone: 80%	Cyclone: 95%
	Accuracy for week 2	Low: 70%	Low: 72%	Low: 72%	Low: 90%	Low: 95%
		Dep.: 60%	Dep.: 62%	Dep.: 67%	Dep.: 80%	Dep.: 90%
		Cyclone: 50%	Cyclone: 52%	Cyclone: 57%	Cyclone: 75%	Cyclone: 80%

Accuracy in genesis forecast 5 days ahead	Low: 80% Depression: 70% Cyclone: 60%	Low: 82% Depression: 72% Cyclone: 62%	Low: 87% Depression: 77% Cyclone: 67%	Low: 95% Depression: 85% Cyclone: 80%	Low: 100% Depression: 100% Cyclone: 95%
Detection error	Satellite: 55km	Satellite: 50km	Satellite: 40km	Satellite: 30km	Satellite: 20km
	Radar:30km	Radar:30km	Radar:25km	Radar:20km	Radar:10km
	Synoptic Obs.: 1 in 100 km	Synoptic Obs.: 1 in 75 km	Synoptic Obs.: 1 in 50 km	Synoptic Obs.: 1 in 25 km	Synoptic Obs.: 1 in 10 km
	Marine Obs.: 1 in 1000 km	Marine Obs.: 1 in 1000 km	Marine Obs.: 1 in 800 km	Marine Obs.: 1 in 500 km	Marine Obs.: 1 in 300 km
Lead period for track & intensity forecast	5 days	5 days	6 days	7 days	10 days
Track forecast errors (km)	24: 70	24: 50	24: 20	24: 0	24: 0
	48:110	48: 100	48:70	48: 20	48:0
	72: 160	72: 140	72: 110	72: 50	72: 10
	96: 200	96: 180	96: 140	96: 70	96: 20
	120: 300	120: 250	120: 150	120: 100	120: 30
Intensity forecast errors (knots)	24: 7.5 knots	24: 7.5 knots	24: 3.5 knots	24: 0 knots	24: 0 knots
	48:10.5 knots	48:10.0 knots	48:7.8 knots	48: 4 knots	48:0 knots
	72:12.5 knots	72:11.0 knots	72: 9.0 knots	72:.5 knots	72:3.0 knots
	96:16.5 knots	96:14.0 knots	96:12.0 knots	96:7.0 knots	96:5.0 knots
	120:17.5 knots	120:15.0 knots	120:15.0 knots	120:10.0 knots	120:10.0 knots
Landfall point forecast errors (km)	24: 20 km	24: 10 km	24: 0 km	24: 0 km	24: 0 km
	48: 50 km	48: 40 km	48: 20 km	48: 0 km	48: 0 km
	72: 60 km	72: 50 km	72: 30 km	72: 10 km	72: 0 km
	96: 70 km	96: 65 km	96: 45 km	96: 15 km	96: 5 km

	120: 100 km	120: 95 km	120: 75 km	120: 35 km	120: 10 km
Landfall time forecast errors (hrs)	24: 2.5 hrs	24: 1.5 hrs	24: 0 hrs	24: 0 hrs	24: 0 hrs
	48: 5.5 hrs	48: 4.5 hrs	48: 3.0 hrs	48: 1.5 hrs	48: 0 hrs
	72: 10.0 hrs	72: 8.0 hrs	72: 5.0 hrs	72: 2.0 hrs	72: 0 hrs
	96: 10.5 hrs	96: 10.0 hrs	96: 7.0 hrs	96: 4.0 hrs	96: 1.0 hrs
	120: 12.0 hrs	120: 11.0 hrs	120: 9.0 hrs	120: 6.0 hrs	120: 3.0 hrs
Heavy rainfall forecast accuracy improvement	24hrs: 80% at district level	24hrs: 82% district level	24hrs: 85% block level	24hrs: 90% Panchayat level	24hrs: 100% village level
	48hrs: 70%	48: 72%	48: 77%	48: 85%	48: 95%
	72hrs: 65%	72: 67%	72: 72%	72: 80%	72: 90%
	96hrs: 60%	96: 62%	96: 67%	96: 75%	96: 85%
	120hrs:55%	120:58%	120:62%	120:70%	120:80%
Storm surge forecast accuracy improvement	24hrs: 80% district level	24hrs: 82% district level	24hrs: 87% Panchayat level	24hrs: 93% Village level	24hrs: 100% Household level
	48hrs: 75%	48hrs: 77%	48hrs: 82%	48hrs: 90%	48hrs: 100%
	72hrs: 70%	72hrs: 72%	72hrs: 75%	72hrs: 85%	72hrs: 95%
	96hrs: Not issued	96hrs: Not issued	96hrs: 65%	96hrs: 80%	96hrs: 90%
	120hrs: Not issued	120hrs:Not issued	120hrs: 60%	120hrs: 75%	120hrs: 85%
Hazard, vulnerability & risk	Wind: District level	Block level	Panchayat level	Village level	House hold level
Spatial coverage & quantification of risk	Heavy rainfall/storm surge associated Flood: District level	Block level	Panchayat level	Village level	House hold level

5. Strategy:

It is needless to mention that investments for technological upgradation and capacity building are essential to improve forecast accuracy. In order to achieve the target discussed in Section 4, all components of early warning services in the value chain need to be addressed simultaneously as discussed below:

- ❖ 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 in each phase by 20% by 2030, 40% by 2040 and 50% by 2047, 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.
- ❖ Explore the 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.
- ❖ Enhancement of observations for landfalling cyclones through engagement of doppler on wheels, Mobile Mesonet Probe Systems, Mobile Integrated Profiling System, Mobile instrumented tower etc.
- ❖ Introduction of probabilistic information of landfall, heavy rainfall, winds and storm surge at village level.
- ❖ The research to be enhance 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 (pre-formation to decay).
- ❖ 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.
- ❖ 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.
- ❖ Implementation of Machine learning approach for reliable probabilistic forecasting of tropical cyclone intensity, track and associated adverse weather, hazard and impact modelling and risk assessment to support Early Warning & Early Action initiative of United Nations.
- ❖ Introduction of AI/ML approach in TC prediction system enhancement of ocean observation systems like Buoys, additional data collection platforms(ADCPs), Drifters, tide gauges, ship observations etc.
- ❖ Studies regarding future climatic projections of TC of North Indian Ocean in collaboration with various research institutes nationally and internationally
- ❖ Development of automated Tropical cyclone prediction system by using

numerical, statistical and AI/ML approach to help forecasters.

- ❖ Mitigation study based on future TC projections in terms of cyclone intensity, inundation, amount of rainfall
- ❖ 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.
- ❖ To review the risk assessment and map the risks in a timely manner, IMD may design climate policies 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.
- ❖ Enhancing cooperation and collaboration among meteorologists, researchers, disaster managers, social scientists & workers for effective management of disasters associated with tropical cyclones.
- ❖ 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.

- ❖ 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.
- ❖ **Establishment of National Centre for Tropical Cyclones in India:** 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 Shanghai Typhoon Institute of China and Hurricane Research Division of USA.

6. Outcome:

- ➢ Improvement in forecast accuracy of genesis, track intensity, landfall point and time and associated adverse weather including heavy rainfall, wind and storm surge leading to zero error (100%) upto 3 days lead period and more than 90% for 5 days lead period.
- ➢ To enable public and disaster managers to realize zero death and drastic reduction in loss of property due to any cyclone over the region.
- ➢ Development of a society, which is not afraid of tropical cyclones and is well familiar with actions prior to, during and post every cyclone, thereby enabling a disaster resilient society, not only in the country but also in the BoB and AS region.
- ➢ India to emerge as a global leader in monitoring & prediction of TCs and capacity building initiatives in this regard and provide TC forecast for entire globe.

7. References

MoES, 2011, Vision for 2015, Published by Ministry of Earth Sciences

MoES, 2015, Vision for 2030, Published by Ministry of Earth Sciences

IMD, 2013, “Cyclone Warning Services: Standard Operation Procedure”, Published by Cyclone Warning Division, IMD, New Delhi

IMD, 2023, “Cyclone Warning Services: Standard Operation Procedure”, Published by Cyclone Warning Division, IMD, New Delhi

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, 367-38

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