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Marine Weather Services

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PREFACE

There is an increasing recognition and understanding of the reliance of human kind on the vital life supporting services provided by the Ocean. At the same time Oceans are a breeding ground for various natural hazards like tropical cyclones (TCs), monsoon depressions & lows, thunder squalls and high winds. Thus, for the safety of life at sea and to ensure sustainable economy, there is a need for well monitored and predicted Ocean. There is thus growing need to improve the infrastructure in terms of Oceanic observations, development of climatology, archival of data, development of prediction models and finally the Early Warning System (EWS) in order to better monitor and predict Ocean.

The India Meteorological Department (IMD) is mandated to provide weather warnings and advisories to ensure safety of life and property at sea, promote international commerce through improved efficiency of marine operations supported by marine weather services. IMD envisions that no ocean hazard should go undetected and unpredicted and improve forecast accuracy by 10% for all oceanic parameters by 2030. IMD aims to deliver accurate, timely, and actionable marine weather forecasts and warnings to safeguard lives, promote sustainable maritime operations, and support the Blue Economy initiatives in the Indian Ocean.

It is needless to mention that investments for technological upgradation and capacity building are essential to have a reasonable predicted Ocean with multi hazard early warning system in all spatial and temporal scales. This document presents the vision, mission, strategy and expected outcome of the various initiatives to achieve improvement in marine weather services in North Indian Ocean. It aims to elevate stakeholder's trust and further reliance on IMD's Marine Weather Services with introduction of customized advisories as per user's requirements. IMD envisions to emerge as a benchmark for other regional marine weather services globally.

Mrutyunjay Mohapatra
Director General of Meteorology

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1. Introduction:

There is an increasing recognition and understanding of the reliance of human kind on the vital life supporting services provided by the Ocean. From a very ancient era, we in India understand well about the role of the Ocean and its potential influence on the socio-economic activities of mankind. The evolution of the wealth from the deep ocean through Sagar Manthan as described in the Indian epic is a testimony of the ancient knowledge on the role of ocean in improving socio-economic conditions of society. Therefore, sustainable Ocean Economy plays a dominant role in the society.

At the same time, the Ocean is a source of natural hazards like tropical cyclones (TCs), monsoon depressions & lows, thunder squalls and high winds. Hence, to ensure sustainable economy, there is a need for well monitored and predicted Ocean. Also, to ensure resilience in society, the knowledge and innovation for Multi Hazard Early Warning System (MHEWS) against the Oceanic hazards will not only ensure a resilient society, but also a healthy and resilient Ocean. While considering these two aspects namely (i) monitored and predicted Ocean and (ii) knowledge and innovation for MHEWS against Oceanic hazards, the humankind has always thought of improving the infrastructure in terms of Oceanic observations, development of climatology, archival of data, development of prediction, models and finally the Early Warning System (EWS).

In the earth system, though Ocean is a major component, it is not the only component. It interacts with other spheres of the earth including Lithosphere, Atmosphere, Biosphere and Cryosphere. These interactions within Ocean and within Earth system influence the variations in the characteristics of Oceans in daily basis and also, it's evolution in the multi-hazard arising out of this interaction.

Considering India and South Asia which are surrounded by Bay of Bengal to the East, Arabian Sea to the West, North Indian Ocean to the South and Great Himalayas to the North, the interactions among the Ocean, atmosphere and land in the region decide the weather and climate and their variation on daily, monthly, seasonal, annual, inter-annual and inter-decadal time scales.

Therefore, on the eve of International Decade of Oceans, National Decade of Oceans gives an opportunity to review the current status, past achievements, geographical areas, vision for next decade, strategy to be adopted and the expected outcome. The above aspects are presented in following sections in line with the national programmes like Blue Economy and Deep Ocean Mission taken up by the Ministry of Earth Sciences (MoES) as the nodal agency. There is enough opportunity to expand, enhance and understand the observational and modelling infrastructure for the better monitored and predicted Ocean.

The NIO has huge potential for harvesting natural resources for socio-economic development of the country. It includes marine resources like the (i) fish, (ii) sea food, (iii) oil & gas, (iv)

metals, (v) drinking water, (vi) tidal energy, (vii) ocean thermal energy and many others. Hence a sustainable Ocean economy can be ensured by better monitoring and prediction of Ocean Weather.

2. Role of ocean on weather systems:

Apart from the multi hazards like cyclonic disturbances (CDs), high waves and depression & lows, there are also large scale processes in the Earth-Ocean-Atmosphere system which influence the weather & climate and the hazards. To top it all, it is the monsoon which is considered as the life of Indian economy, which is called as Giant Sea Breeze, depends largely on oceanic behaviour. The monsoon is daily monitored mainly through 6 components for the prediction and early warning of severe weather. It includes monsoon trough (MT), heat low, Mascarene High (MH), Tibetan High (TH), Somali Low Level Jet Stream (SLLJS) and Tropical Easterly Jet (TEJ). Out of these 6 components MH, TEJ & SLLJS are directly influenced by ocean and others are influenced indirectly. The transient disturbances which develop during the monsoon season are mainly the CDs which develop over the Bay of Bengal (BoB) and move west-northwestwards along the MT. About 5 TCs develop over the BoB and the Arabian Sea (AS) in the pre monsoon (April-June) and post monsoon season (October-December) seasons. On an average about 13 low pressure systems including 5 monsoon depressions develop over the NIO during monsoon season.

In addition, there are various largescale processes related to Ocean which govern or influence the weather systems in India. These largescale processes also influence the inter-annual & intra-seasonal variation of monsoon rainfall and also genesis, track, intensity of TCs. The major largescale processes influencing the weather systems are presented below;

i. EL Nino and Southern Oscillations (ENSO)
ii. Madden Julian Oscillation (MJO)
iii. Indian Ocean Dipole (IOD)
iv. Convectively coupled Equatorial waves including Equatorial Rossby Waves (ERW) and Kelvin Waves (KW)

Polar ocean also influences the monsoon and the circulation features over the Indian Region. India also plays an important role in Polar Meteorology with its station in Maitree (Antarctica) and Himadri (North Pole).

3. Current status:

IMD maintains round the clock watch over the North Indian Ocean (NIO). The analysis and prediction of the weather over sea involves blending of meteorological observations, conceptual, dynamic and statistical models, technology, digitised decision support system and forecaster's expertise to analyse, predict and prepare advisories and warnings in an actionable format. In this section the mode of data collection & dissemination, sources of observations, numerical models for prediction and user specific services by IMD have been discussed.

3.1. Meteorological Observations:

The current status of atmosphere 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), 39 Doppler weather radar (DWR), ships under voluntary observing fleet (50) and meteorological buoys (20) for monitoring the weather over sea. There is an objective decision support system to continuously compare, comprehend and analyse all the observations from various sources and to identify various systems like cyclonic circulations, low pressure areas, depressions, cyclones, and weather parameters like wind, weather, wave, visibility, swells etc.

The meteorological data for oceanic areas and landmass are collected in real time utilising various modes of communication every hourly/3 hourly. It includes email, GTS, FTP etc. The data are transmitted for the observational platform through GTS and other means to the forecasting centres at National & Regional level. Radar and satellite data and products are also collected and analysed in above platform every 10 minutes/ 15 minutes respectively. The data analysis is done on a digital platform utilising graphical user interface (GIS).

3.2. **Numerical Weather Prediction Modelling:**

IMD utilises an array of models that are deterministic and ensemble based, global & regional, cyclone specific models and models available from global agencies under bilateral arrangement. IMD and INCOIS also run storm surge models. Indian National Centre for Ocean Information Services (INCOIS) runs global and regional ocean forecast models to provide forecast of waves & swells and astronomical tides.

Currently, the surface observations are available at a distance of about 50 km supported by geostationary satellites (INSAT 3 D & 3D (R)) with resolution of 1 km in visible band, 4 km in infra-red band and 8 km in water vapour channel and Doppler weather radars with a spatial resolution of 350 m. The models interpolate these observations to create the initial conditions of atmosphere and ocean at a given resolution (e.g. 12X12 km for IMD GFS model). Based on these initial conditions, models are run to generate the forecast upto a few hours to a few days.

The atmospheric models include global models with a resolution of 12 km each & forecast lead period of 10-15 days (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 include (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 model 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 based on linear regression approach, rapid

intensification/weakening model and (xi) indigenously developed multi model ensemble (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 various short to medium range forecast instead of one single model, multi model guidance is utilised. Further, extra weightage is given to historically best model, the model which is performing the best under current state of atmosphere. This multi model guidance is further modulated utilising current observations and experience & expertise of forecasters maintaining the consistency in forecast.

For climate prediction, MoES utilises a Monsoon Miss Climate Forecast System (MMCFS) which is an ocean atmosphere coupled model with resolution of 38 km. IMD uses MME based on various best performing Ocean atmosphere coupled climate forecast models in the world to produce forecast for each month and season of rainfall, temperature and large scale processes like El Nino/La Nina, IOD. IMD also runs an atmosphere – ocean coupled extended range forecast model to provide forecast on temperature, rainfall and large scale processes like Madden Julian Oscillation etc.

All these models are run with assimilation of Ocean and atmospheric data. Hence a predicted ocean depends on performance of these models which further depend upon Ocean data collection.

3.3. **Decision Support System:**

IMD has an indigenously developed decision support system of IMD in GIS platform capable of comparing, comprehending and analysing all observations and model forecast products in a single platform. Once the observations are analysed and forecast prepared, final decision is arrived at through the discussion among forecasters countrywide through video conferencing. Thereafter, final forecast is generated in an actionable format. Thus, consensus forecast is generated which is mainly based on objective consensus derived from an array of numerical models utilising DSS which is modulated by the subjective consensus derived from exchange of knowledge, experience and expertise of forecasters through a video conferencing system.

3.4. **Services:**

As per IMO guidelines, IMD acts as Flag State, Coastal State and Port State. As part of it's international and national responsibilities, IMD maintains continuous watch over the sea areas under its area of responsibilities and issues user specific forecast to marine community for following parameters:

i) Wind speed and direction
ii) Weather
iii) Significant wave height
iv) Visibility
v) Swells

vi) Cyclonic disturbance including low pressure areas, depressions and cyclones
vii) Storm surge guidance

International responsibility:

The International Convention for the Safety of Life at Sea (SOLAS), obligates states to provide necessary meteorological warnings and forecasts in the specified area. Further, members of World Meteorological Organisation (WMO) are obligated to implement Marine Meteorological Services (MMS) in their specified region to ensure international coordination of meteorological services. Meteorological forecasts and warnings are issued as part of Maritime Safety Information (MSI) under the auspices of the International Maritime Organisation (IMO) and World Meteorological Organisation (WMO) as World-Wide Met-Ocean Information and Warnings Service (WWMIWS) under the Global Maritime Distress and Safety Systems (GMDSS). The bifurcation of various areas under Met Area for issue of bulletins under GMDSS is presented in **Fig.1a**.

As part of it's international obligation, **India Meteorological Organisation (IMD) is one among 16 services** in the world for issuing Sea Area bulletins for broadcast through GMDSS for MET AREA VIII (N). The METAREA VIII (N) is the area of the Indian Ocean enclosed by lines from the Indo-Pakistan frontier in 23°45'N 68°E to 12°N 63°E, thence to Cape Gardafui; the east African coast south to the equator, thence to 95°E, to 6°N, thence northeastwards to the Myanmar/ Thailand frontier in 10°N 98°30'E (**Fig.1b**).

IMD is one among the six **Regional Specialised Meteorological Centres** to provide cyclone warnings and advisories to 13 WMO/ESCAP Panel member countries including Thailand, Myanmar, Bangladesh, India, SriLanka, Maldives, Pakistan, Iran, Saudi Arabia, United Arab Emirates, Qatar, Sultanate of Oman and Yemen. The area of responsibility covers all area to the north of 10^0S between longitude 40^0-100^0 E (**Fig. 1c**).

IMD and INCOIS also jointly provide the bulletins for Marine Emergency Response and Search And Rescue (MER-SAR) to WMO and 13 WMO/ESCAP Panel member countries fto support search & rescue operations and marine emergency response over the region. The area of responsibility covers all area to the north of 10^0S between longitude 40^0-100^0 E (**Fig. 1c**)..

National Responsibilities:

IMD is the national hydro-meteorological organisation and is responsible for monitoring, & forecasting of all types of hydro-meteorological hazards and issuing advisories to various stakeholders. The Office of Director General of Meteorology at New Delhi is the command in chief to carry out these responsibilities. The *National Weather Forecasting Centre* (NWFC) at IMD New Delhi cordinates IMD's forecasting activities for the entire country and the Weather Central, IMD, Pune functions as the standby Centre for NWFC. The *Regional Meteorological Centres* (RMCs) carry out weather monitoring and forecasting for their respective regions, the *Meteorological Centres* (MCs) at the state capitals do the same for their respective states.

Further, the cyclone and Marine related operational activities are carried out, monitored and coordinated by *Cyclone Warning Division* (CWD) and Marine Weather Services Division (MSD) at the IMD headquarter respectively. The CWD and MSD at national level carryout their responsibilities with support from 3 Area Cyclone Warning Centres (ACWCs) at Chennai, Mumbai & Kolkata, 4 Cyclone Warning Centres (CWCs) at Bhubaneswar, Visakhapatnam, Ahmedabad and Thiruvananthapuram and various Port Met Offices collocated with ACWCs and CWCS for Marine Weather Services and Cyclone Warning Services of the coastal states as well as Sea Area, as per their area of responsibility.

In addition to above operational responsibilities, IMD also contributes towards

Calibration of instruments: Port Meteorological Offices (PMO) at Kolkata, Visakhapatnam, Chennai, Kochi, Goa and Mumbai provide instrumentation support to IVOF including regular check/ inspection of Meteorological and marine equipment.

Collection, quality control and archive of Marine Meteorological data: Marine Climatological Section, Pune is responsible for the collection, quality control and archive of Marine Meteorological data. It evaluates performance of individual ships, who have transmitted and submitted their ship log books in time and also transmitted real time data during depression/ cyclonic storms.

Capacity building: Meteorological Training Institute, Pune contributes to training requirements as per the WMO guidelines. Training in Marine weather observation and forecasting.

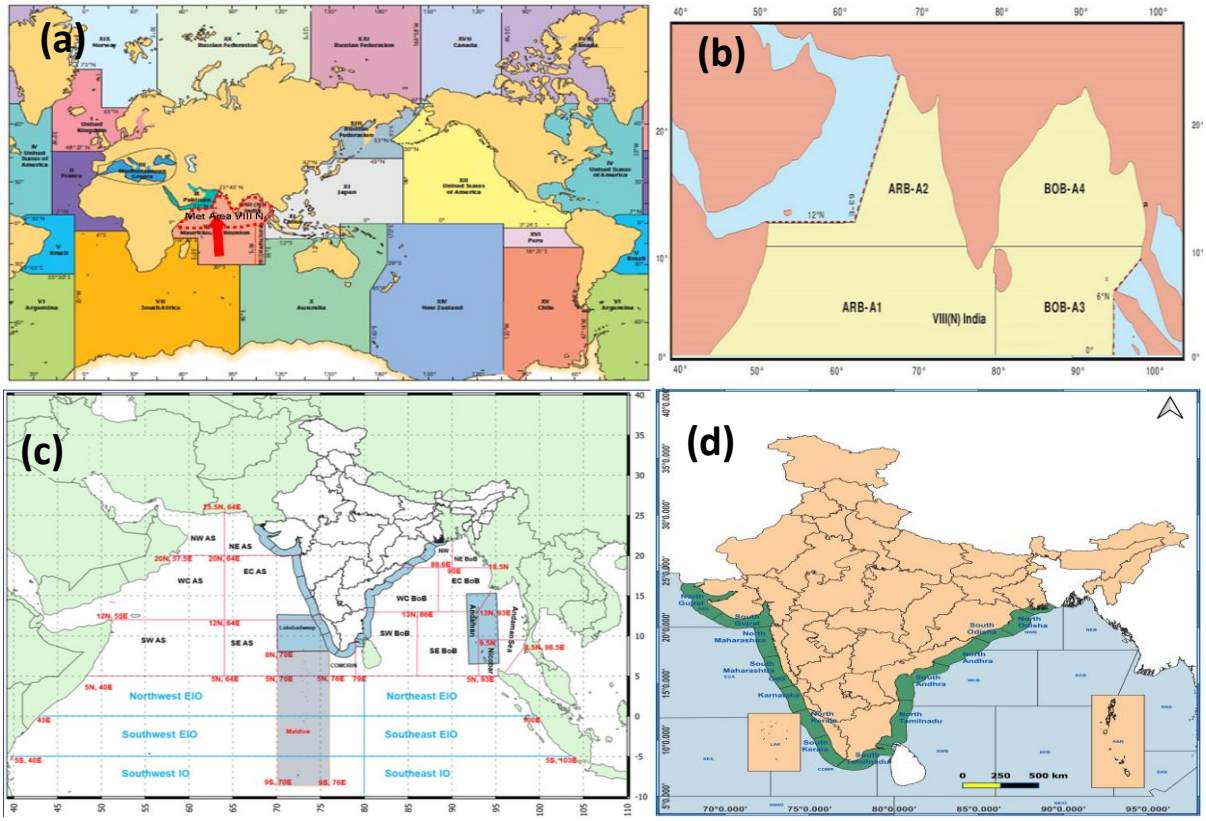

Fig.1 (a): Met Area Limits globally for GMDSS bulletin, (b) Met Area VIII (N) subdivisions, (c) Area of responsibility for cyclone warnings and MER-SAR, (d) Area of responsibility for coastal area bulletins

These weather information are shared through customised forecasting Services by respective sub-offices of IMD as mentioned below:

i) Bulletins to International Shipping community under Global Maritime Distress Safety System (GMDSS)
ii) Bulletins for Marine Emergency Response and Search & Rescue Operations
iii) Cyclone Warnings
iv) Sea area bulletin for ships plying beyond 75 km in Bay of Bengal and Arabian Sea
v) Coastal weather Bulletins for ships plying within 75 km from the coast in Bay of Bengal and Arabian Sea
vi) Bulletins for Indian Navy
vii) Port warnings
viii) Fishermen Warnings
ix) Warnings for Fisheries Officials
x) Warnings for Offshore & onshore industries

The details of bulletins, frequency, content, format, mode of dissemination and information contained in various bulletins are presented in the Fig. 2.

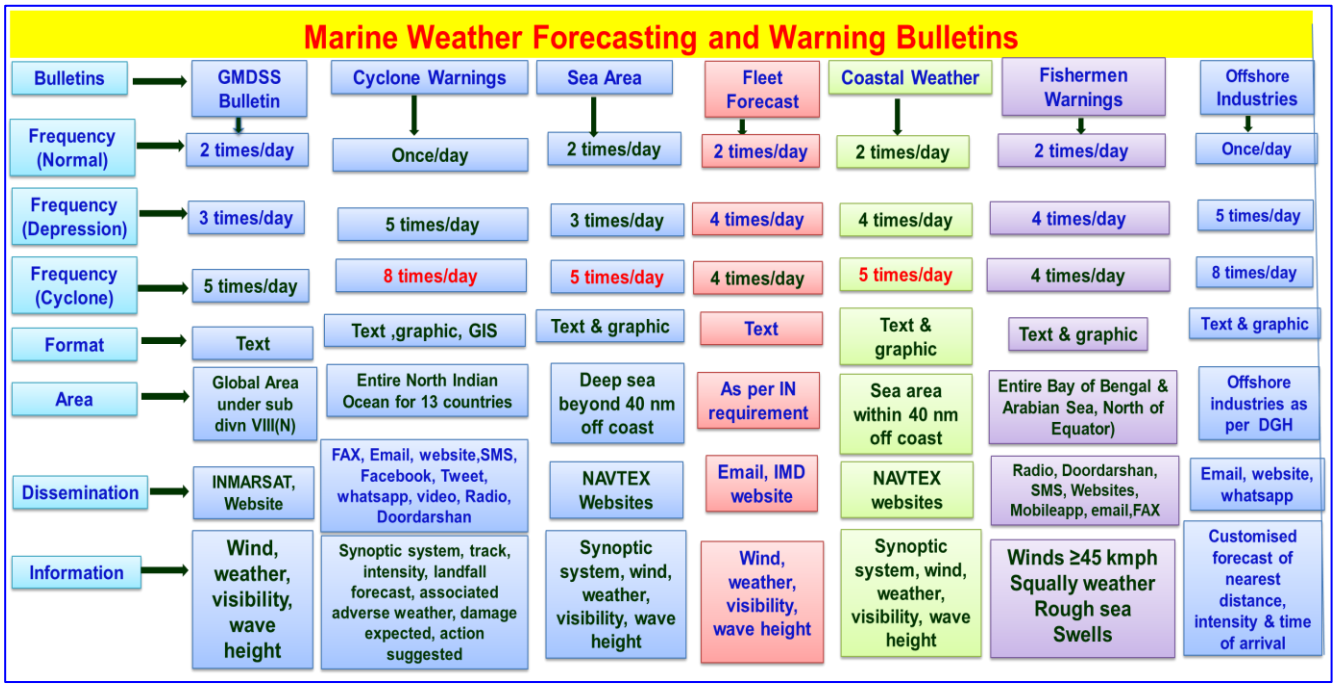

Fig. 2: Flow Diagram of various types of bulletins issued by IMD

Following are the user agencies for marine weather services of IMD:

i) Merchant mariners

ii) Navy
iii) Port authorities
iv) Harbour managers
v) Offshore asset managers
vi) Shipping
Oil and gas explorers
viii) 13 PTC member countries bordering the Bay of Bengal and the Arabian Sea

3.5. **Details of the bulletins issued by IMD for marine community:**

a) **GMDSS Bulletin**

IMD is transmitting daily two GMDSS bulletins for Met. Area VIII(N), at 0900 UTC and at 1800 UTC valid for next 24 and 48 hours under undisturbed weather. During Cyclone period additional bulletins (4) are also issued based on 00, 03, 06, 12 & 18 UTC for GMDSS broadcast depending on the requirement. This bulletin has two parts. Part 1 discusses the significant system and Part 2 discusses wind, weather, visibility, state of sea, port warnings for 24 hours and 48 hours validity period for different sea area under Met Area VIII (N).

This bulletin is prepared by Marine Weather Services Division of NWFC, New Delhi and transmitted to Tele-communication Division (Regional Telecommunication Hub (RTH), New Delhi) for further transmission by e-mail to the Local Earth Station (LES) of VSNL in Ghaziabad. They in turn transmit the message to INMARSAT. This bulletin is also sent to Naval Headquarter and Navy Western Command by email from Marine Service Division at HQ and uploaded on various websites of IMD including www.rsmcnewdelhi.imd.gov.in, www.mausam.imd.gov.in

b) Sea Area bulletin:

The sea area weather forecast also known as 'sea area bulletins' for BoB are issued by ACWC Kolkata and broadcast by the NAVTEX stations at Kolkata (VWC) and Chennai (VWM) and those for AS are issued by ACWC Mumbai and broadcast by the Navtex stations at Mumbai (VWB). This bulletin is issued twice daily based on 0300 and 1200 UTC observations at 0900 & 1800 UTC. In case of depressions/cyclones, the frequency increases and this bulletin is issued 5 times based on 0000, 0300, 0600, 1200, 1800 UTC. This bulletin is also uploaded on various websites of IMD namely www.rsmcnewdelhi.imd.gov.in and www.mausam.imd.gov.in . The area covered by these bulletins is the area of responsibility assigned to India by the World Meteorological Organization (WMO). The bulletin primarily has six parts. **Area of responsibility is presented in Fig.1 (a & b).**

c) Cyclone Warnings:

IMD acts as RSMC New Delhi and provides advisories for cyclonic disturbances over the NIO region to 13 member countries including Thailand, Myanmar, Bangladesh, India, Sri Lanka, Maldives, Pakistan, Iran, Qatar, United Arab Emirates, Saudi Arabia, Sutanate of Oman and Yemen. 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 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 is issued. It also includes forecast track alongwith cone of uncertainty and wind distribution around the centre of storm for next 72 hours. 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. On the day of landfall hourly advisories are issued. Area of responsibility is presented in Fig. 1(c).

d) Coastal weather bulletins:

These are broadcast by NAVTEX, and are meant for ships plying in coastal waters (within 40 nm from the shoreline). These are for the benefit of vessels sailing close to the coast and are issued twice daily based on 0300 UTC and 1200 UTC at 0900 & 1800 UTC respectively by the ACWCs - Kolkata, Chennai, Mumbai and CWCs - Visakhapatnam, Bhubaneshwar, Thiruvananthapuram and Ahmedabad covering the areas under their responsibility in normal situation. In case of depression over the sea, it will be issued 3 times a day with additional bulletin based on 1800 UTC. In case of cyclone lying over sea, it is issued based on 0000, 0300, 0600, 1200, 1800 UTC. These bulletins are broadcast by 11 NAVTEX stations– 6 on the west coast, 4 on the east coast and 1 in Andaman and Nicobar Islands in plain language through the Control Centre at Mumbai. This bulletin is also uploaded on various websites of IMD including www.rsmcnewdelhi.imd.gov.in and www.mausam.imd.gov.in . Area of responsibility is presented in **Fig.1d.**

e) Fleet Forecast Bulletin: Fleet forecast bulletins are issued exclusively for broadcast to Indian Naval ships. They are issued twice daily. Fixed times of origin are given to the Fleet Forecast messages – 0800 UTC in the case of day bulletin and 1700 UTC in the case of the night bulletin. The forecast covers surface wind, visibility, weather, state of sea and an *outlook* for the next 12 hours. The special bulletins are issued thrice a day with addition of bulletin based on 1800 UTC during the depressions and cyclones lying over the north Indian Ocean. The area of responsibility extends in latitude between 35^0S & 30^0N and in longitude between 30^0E & 115^0E. This bulletin is sent to Naval Headquarter, Navy Western & Eastern Command by email from Marine Service Division at HQ.

f) Port Warnings:

The IMD (through the ACWCs/CWCs) maintains a port warning service by which the port offices are warned by telefax/emails about disturbed weather likely to affect their ports.

Port warnings are also uploaded on various websites of IMD. The port warning bulletin issued by IMD contains information about the current location & intensity and forecast about movement, intensification & landfall of the system. It also contains information about the warning signal to be hoisted on the port. Port warning is issued for 120 Ports along the Indian coast.

On receipt of the warning bulletin from the ACWC/CWC, the port offices hoist appropriate visual signals prominently on signal masts so that they are visible from a distance. Mariners and other sea-faring people, including fishermen who may not be literate, are generally aware of the meaning of these signals and the port authorities are always ready to explain them whenever necessary. At some ports, the meanings of the signals are displayed in English as well as in the local languages prominently on a notice board. While the IMD is responsible for issuing the warnings, the port authorities arrange the display of signals. In addition to hoisting the signals, the port offices in most cases, make arrangements for disseminating the warnings received by them, to country craft and sailing vessels in the harbours.

Port warnings are issued twice a day based on 0300 and 1200 UTC in case of distant disturbances, 3 times a day based on 0300, 1200 and 1800 UTC in case of squally weather likely over port and based on 0000, 0300, 0600, 1200 and 1800 UTC in case of cyclone warning for the port.

g) Fishermen Warnings:

Marine Service Division at HQ issues Fishermen Warnings in graphical and text format for next 5 days for entire North Indian Ocean once/day. In addition, it also provides probability of exceedance of maximum sustained wind speed exceeding 25 knots and 35 knots. Warnings for fishing interests are also issued by the ACWCs/CWCs for their respective area of responsibility. Area of responsibility covers entire North Indian Ocean**.**

These advisories are issued 4 times/day during normal weather, 5 times/day durng depression and every 3 hourly during cyclone period by the ACWCs and CWCs for their respective area of responsibility.

Criteria for fishermen warnings: Whenever any one of the following is expected:

(i) the wind speed is expected to exceed 45 kmph (i.e. for squally weather, gales and strong monsoon and off shore winds),

(ii) state of sea is likely to be very rough or above,

(iii) swells are expected

(iv) squally weather (fairly wide spread to widespread rainfall and maximum sustained wind speed of 20 knots or more) is expected.

These warnings are transmitted by telephone/FAX/email to the AIR/Doordarshan stations in the maritime states. These warnings are updated by IMD and broadcast as a routine four times a day (morning, mid-day, evening and night) from the AIR stations in the local language. During a cyclonic storm, such warnings are covered in the cyclone bulletins

sent to the AIR/Doordarshan stations at hourly or 3 hourly intervals for frequent broadcast. The fishermen can listen to these broadcasts through portable radio receiving sets. These warnings area also uploaded on website in graphical form and appended with the bulletin. These bulletins are also transmitted to fishing officials through SMS/Whats App/Mobile App and registered fishermen through SMS/Mobile App.

h) Warnings for Fisheries Officials:

In line with warnings for fishermen, warnings for fisheries officials are also issued. However, the warnings for Fisheries official contain technical information also. The warnings for fishermen are issued in plain language.

i) Advisories for onshore & offshore industries:

Under normal weather conditions, IMD provide (i) daily tropical weather outlook with discussion about the convection over the Bay of Bengal and the Arabian Sea and probabilistic forecast of cyclogenesis (formation of depression) for next 7 days and (ii) extended range outlook for next two weeks every Thursday with discussion about the environmental features, model guidance and probabilistic forecast of cyclogenesis. On formation of depression/cyclone, IMD provides customised location specific color-coded forecast (impact based) for offshore industries in case of cyclonic storms over the Bay of Bengal and the Arabian Sea. These bulletins are issued every 6/3 hourly, in case of depression/ cyclonic storms over the region. These are shared by email to the registered group of offshore & onshore operators, Directorate General of Hydrocarbons, Indian Coast Guard & Indian Navy.

j) Bulletins for Marine Emergency Response (MER) and Search And Rescue (SAR)

INCOIS and IMD jointly act as Regional Specialised Meteorological Centre for Marine Emergency Response and Search And Rescue (RSMC: MER-SAR) and issue bulletins and advisories for the member countries bordering Bay of Bengal and Arabian Sea on receipt of request from member states in the region. It contains information about the ocean and atmospheric conditions. INCOIS provides probable area for search in QGIS & GIS platform, sea surface current, sea surface temperature, wind speed, significant wave height and wave period. IMD provides multi-model ensemble based information about the atmospheric conditions required for safe helicopter and marine operations including mean maximum wind speed, rainfall distribution, rainfall intensity, relative humidity, cloud cover, significant wave height and visibility. These bulletins are updated every 6 hourly and have a validity of 48 hours and contain textual, graphical and GIS based guidance. These are sent by email to the concerned member state.

k) Bulletins issued by INOSHAC Pune:

INOSHAC Pune carries out analysis of surface and upper air charts covering *viz.* South Indian Ocean and West Pacific Ocean and prepares surface and upper air data (850,700,500,300,200hpa). INOSHAC prepares extended weather charts daily, calculate Mascarene High and Australian high daily during southwest (SW) monsoon, analysis of daily & weekly ship composite charts based on day to day 00, 06, 12 & 18 UTC ship observations and the low pressure systems in West Pacific and Indian Ocean. These reports and bulletins are uploaded on IMD Delhi and IMD Pune websites daily and sent by Email to concerned agencies.

4. **Gap areas:**

Even though there has been tremendous progress in recent years with respect to marine weather forecast, still there are gaps in observations, understanding the core features, modelling, warning products generation & dissemination and last mile connectivity. Following are the gap areas and challenges in monitoring and prediction of marine weather hazards:

Gaps in observations primarily include lack of direct observations in case of marine weather hazards including TCs, as we have limited ships, buoys and scatterometer observations. There is lack of complete coverage of NIO with sea surface wind observations at least once a day. The weather monitoring over the region is still very subjective. There is need to augment observations with at least one buoy in every 2^0X 2^0 grid over the BoB and AS. There is need to augment surface, upper air and radar observations also in the Bay and AS Islands with AWS/ARG in each island, 5 doppler weather radars (DWRs) and an RS/RW station each in Bay and Lakshadweep Islands.

There are also gaps in comprehensive real-time data that captures the vast biodiversity and complexity of the Indian Ocean.

In order to better understand marine weather hazards including TCs, more research is required. There is need to carry out more diagnostic studies on past marine hazards 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, movement, vertical wind shear, diurnal cycle & convective bursts. Hence Research Test Bed on marine weather hazards should be established with all observations and computing infrastructure facility in a coastal state at Bay of Bengal/Lakshadweep Islands.

Even though, IMD has one of the best forecasting system, with computing power of 8 Peta Flop and assimilation of 300 GB data into numerical models every day, still forecasting marine hazards including TC track & intensity in some cases is a challenge. The cases of rapid intensification/rapid weakening of TCs, 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.

Still probabilistic forecast products have not been introduced for marine weather hazards. There is need to introduce probabilistic information like probability of exceedance of various thresholds of severe weather like rainfall, wind, wave, visibility, thunder squall, storm surge, etc. There is need to introduce dynamic probabilistic cone of uncertainty in track and probabilistic forecast of intensity of TCs & strong monsoon condition. 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 along & off the coast as onshore & offshore industries. The extended range forecast accuracy is reasonable for week1 and needs to be improved in terms of accuracy and lead period upto 4 weeks. There is no seasonal forecast of TCs which is also a gap area compared to other ocean basins.

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

Also there is need to develop decision support system for impact based forecast & risk based warning for all marine weather hazards.

The efficacy of forecast and mitigation measures strongly depend upon the warning dissemination system, last mile connectivity and public perception in warnings issued by the nodal agency. 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, video messages, broadcasting through All India Radio, Television and private Channels, common alert protocol (CAP), global multi-hazard alert system (GMAS) NAVIC etc.. Further redundancy is maintained in communication. However, still there are gaps in reaching out to last mile especially for marine weather hazards. There is thus need for community involvement towards preparing, protecting, mitigating, responding and recovering actions through last mile connectivity over the sea areas.

Increased unpredictability in marine weather due to climate change effects needs further understanding in terms of detecting attributes and prediction as well as adoptive & mitigative actions

There is limited integration of Blue Economy principles in current marine weather services and maritime activities. The integration will not only avoid loss of economy but also it will improve the sustainability & resilience.

Slow uptake of sustainable practices among regional maritime stakeholders due to lack of awareness or resources is another gap area. There is need for enhanced awareness campaign for mariners & other.

5. **Vision:**

- ❖ No ocean hazard should go undetected and unpredicted
- ❖ Forecast accuracy to improve by 20% for all oceanic parameters by 2030.
- ❖ India to emerge as a premier marine weather service provider in the Indian Ocean, leading in sustainable maritime guidance and contributing significantly to the Blue Economy while addressing the challenges of climate change.
- ❖ Deliver accurate, timely, and actionable marine weather forecasts and warnings to safeguard lives, promote sustainable maritime operations, and support the Blue Economy initiatives in the Indian Ocean.

6. **Strategy:**

It is needless to mention that investments for technological upgradation and capacity building are essential to have a reasonable predicted Ocean with multi hazard early warning system in all spatial and temporal scales. To achieve improvements in forecast accuracy by 20% in respect of various marine weather parameters all components of early warning system need to be addressed holistically as per details below:

Observations:

- Enhancement in observational network with more number of radars to cover particularly the west coast, Islands, more high wind speed recorders and ship & buoy observations AWS, wind profiler & RS/RW, multiple scatterometer is essential. The satellite based hyper spectral microwave radiometer is essential so as to have 3-D temperature, humidity and wind profile every 50 km over BoB & AS every three hours. The amount of observational data should increase at least by 50% by 2030. Continuous observations from the enhanced platforms alongwith the past observational and impact data available from various stakeholders would help in validation of models, bias corrections to improve forecast accuracy, hazard and impact modeling and hence the real time risk assessment.
- Encouragement of partnerships with neighbouring countries for data sharing.
- 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 marine and coastal environment to improve initial conditions captured by the models. When possible, make these observations available in real time.

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

Modelling and Technological Advancements:

- Special focus should be given to TC associated hazards in particular the cases of 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.
- Introduction of probabilistic forecast at high resolution over the marine area for all weather parameters about the location, intensity & impact.
- Encourage the development of skilful seasonal and sub-seasonal (2 to 6 weeks) 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 marine severe weather events including TCs, thundersquall, waves & severe hazard and impact modelling and risk assessment to support Early Warning & Early Action initiative of United Nations.
- Introduction of AI/ML approach in prediction system
- Development of automated marine severe weather including TCs prediction system by using numerical, statistical and AI/ML approach to help forecasters.
- Launch mobile and web platforms offering real-time weather alerts and Blue Economy guidelines for maritime stakeholders.

Research and Development:

- Develop a centralized research and data centre focused on understanding the impacts of climate change on the Indian Ocean's marine weather patterns.
- Enhance regional partnerships to share research, and best practices focusing on sustainable marine activities.
- Invest in advanced research to develop innovative technologies and methodologies that enhance the region's resilience to climate change impacts, including rising sea levels, increasing extreme weather, and changing marine biodiversity.
- The research to be enhance through Research Test Bed to improve understanding of the marine severe weather events including TCs.
- Invest in R&D for AI and GIS-driven weather prediction models.
- Embrace emerging technologies like AI, satellite imaging, and autonomous marine vehicles to improve data collection, analysis, and dissemination. This tech-driven approach will significantly enhance forecasting accuracy, resource management, and marine research.
- Mitigation study based on future projections in terms of marine severe weather including TCs, inundation, amount of rainfall, high waves, storm surge, thundersqualls etc.
- To review the risk assessment and map the risks in a timely manner, climate policies may

be designed in view of the revised multi-hazard risk assessment to reduce loss of life, properties and marine weather risks. Focus should be given on measures to reduce the socio-economic impacts.

Stakeholders Engagement:

- Ensure that all maritime stakeholders, from large-scale commercial entities to local fishermen, are actively involved in decision-making processes. This inclusive approach will promote the widespread adoption of sustainable practices across the board.
- Conduct workshops and training sessions for fishermen and other stakeholders.
- Amplify public awareness campaigns on climate change, its impact on marine weather, and the importance of sustainable maritime practices.
- Collaborate with governments, NGOs, and maritime stakeholders to introduce and promote sustainable maritime practices that both benefit the Blue Economy and mitigate climate change impacts.
- Enhancing cooperation and collaboration among meteorologists, researchers, disaster managers, social scientists & workers for effective management of marine disasters.

A framework should be established to fully integrate Blue Economy principles into marine weather services, aiding stakeholders in sustainable decision-making.

A comprehensive ocean management system should be developed that integrates marine weather services, sustainable resource extraction, and biodiversity conservation. The goal will be to achieve a balanced coexistence between economic activities and ecosystem health in the Indian Ocean.

India should strive to set global standards in sustainable marine weather services and ocean management. By pioneering best practices in the Indian Ocean, inspire other oceanic regions to adopt similar sustainable frameworks.

7. **Outcome:**

- ❖ Improvement in forecast accuracy of all marine weather parameters by 20% by 2030.
- ❖ Reduction in maritime accidents and losses in the Indian Ocean due to adverse weather conditions.
- ❖ To enable public and disaster managers to realize zero death
- ❖ Development of a society, which is not afraid of marine severe weather including TCs and is well familiar with actions prior to, during and post hazard, thereby enabling a disaster resilient society, not only in the country but also in the BoB and AS region.
- ❖ Elevated trust and reliance on the marine weather service by all maritime stakeholders.
- ❖ Introduction of new services to promote tourism, extension of customized forecast for various offshore/onshore industries and route forecast to ships etc.
- ❖ The Indian Ocean Marine Weather Service will be benchmark for other regional marine

weather services globally.

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