सत्यमेव जयते

150 Years of Service to the Nation
राष्ट्र सेवा के 150 वर्ष

India Meteorological Department
Ministry of Earth Sciences
Government of India

VISION-2047

2025

Har-Har Mausam, Har-Ghar Mausam

डॉ. मृत्युंजय महापात्र
मौसम विज्ञान विभाग के महानिदेशक,
विश्व मौसम विज्ञान संगठन में भारत के स्थाई प्रतिनिधि
विश्व मौसम विज्ञान संगठन के तीसरे उपाध्यक्ष

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Preface

India Meteorological Department (IMD), Ministry of Earth Sciences continuously enhances and upgrades its capabilities to provide Weather & Climate services based on contemporary Science & technology. In the past, India Meteorological Department prepared the Vision Document 2020 in the year 2010 which was further upgraded in 2015 for the Vision 2030. IMD has shown significant achievements against the Vision 2030 by 2024. Due to such rapid progress during the last ten years, it has become essential to prepare the Vision 2047 when India completes 100 years of its independence based on the current status of science and services. Here, IMD presents a Vision 2047 on weather & climate science and services.

The Vision 2047 brings out the current status of various components of Weather & Climate monitoring and forecasting systems and the achievements during the past ten years. It also brings out the gap areas with respect to the Weather & Climate monitoring and forecasting systems in the country. The Vision 2047 while considering the gaps also considers the future developments of the Science & Technology. Accordingly, the Vision document brings out the targets for next two years, next ten years i.e., by 2035 and next 22 years, i.e. by 2047. The Mission and Strategy to achieve the Vision 2047 are also presented in this document. This document will be very helpful to plan and implement the various policies and programs of India Meteorological Department and Ministry of Earth Sciences in line with the mainstream Vision of Government of India. This Vision document will also help in fine-tuning various components of Multi Hazard early Warning System and the sectoral applications.

Broadly speaking, the Vision 2047 aims at 100% detection of all types of severe weather at the village and house-hold level with augmentation of Meteorological observational systems upto village level supported by the remote sensing systems like Satellites and Radars. The Vision 2047 aims to improve the weather forecasting accuracy such that there is almost zero error in the forecast upto 3 days, 90% forecast accuracy upto 5 days, 80% forecast accuracy upto 7 days and 70% forecast accuracy upto 10 days in terms of each and every severe weather at the block and panchayat level by 2047.

The expected outcome of this Vision 2047 is to minimize the loss of life to zero for all types of severe weather events by enabling the disaster managers, stakeholders and the general public to take early action following the early warning. It also aims to minimize the loss of property and damages by maximizing the impact based forecast and risk based warnings which will be developed in a dynamic scenario utilizing Geo-spatial technology and all the components of Hazard & Impact modeling as well as data driven models and acquisition of all types of relevant data including socio-economic, Geospatial, Meteorological and Secondary & tertiary hazards data.

The Vision 2047 document will help in mainstreaming weather & climate information so as to make Bharat a weather ready and climate smart nation and mainstream the weather & climate information with all national objectives so as to improve our socio-economic conditions. India will surely emerge as a global leader in the science of Meteorology and the services to people by the realization of Vision 2047.

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Message

It gives me immense pleasure to learn that the India Meteorological Department (IMD) has prepared the Vision-2047, a forward-looking framework that envisions the integration of modern technologies like AI and ML to revolutionize weather forecasting. This document outlines a comprehensive strategy for the implementation of Vision-2047 in the coming years.

Vision 2047 focuses on integrating cutting-edge technologies, enhancing data collection and prediction models, fostering international collaborations, and building adaptive infrastructure to address the challenges posed by climate change. These technological advancements will enable IMD to deliver highly accurate and reliable weather forecasts and timely early warnings in an earth system science framework including oceanic, terrestrial, atmospheric and space systems.

I congratulate IMD for bringing out this document with a comprehensive plan and strategies as we move forward with Vision 2047. The IMD is committed to ensure that India not only adapts to the challenges posed by changing weather patterns but also thrives in a world marked by ever-evolving climate conditions. I am sure that upon implementation of this vision, Bharat will become more resilient to weather & climate hazards and will be global icon in the field of meteorology and its services to the society. The Vision-2047 will lay foundation for transition from weather forecasting to weather modification and finally the weather management by 2047.

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Chapter 1 Observational Network

1.1 SURFACE OBSERVATIONAL NETWORK

1.1.1 Current Status and major achievements during the past 10 years

IMD maintains a dense network of Surface Observational Network at all over the country. The Surface Observational Network is an extensive system of weather stations across India that plays a crucial role in collecting real-time meteorological data. These Surface observational stations strategically located across the country, including urban, rural, and remote areas. These stations measure a variety of parameters, including temperature, humidity, rainfall, wind speed and direction, atmospheric pressure, and solar radiation. List of stations are given in Table 1. The data collected is vital for weather forecasting, climate studies, disaster management, agriculture, and research. The IMD Surface Observational Network is continuously upgraded with modern instruments and technologies to ensure accurate and timely data collection, contributing significantly to India's weather prediction and climate monitoring systems.

Table 1. Surface Observation Network

Sl.No.	Type of the network	Number of Stations
1.	Surface Manual Observatory	547
2.	AGRO Manual observatory	223
3.	District Rainfall monitoring stations in 703 districts.	6095
4.	AWS network	1008
5.	AGRO AWS network	200
6.	ARG network	1382
7.	Aviation Meteorological Stations	112
8.	ASG (Automatic Snowgauge Stations)	4
9.	High Wind Speed Recorder	37
10.	Solar Radiation Station Network	46
11.	Surfce Ozone Sonde Network	10

Ozone

Development of Indian Ozone sonde by Instrument division of IMD in 1964. IMD is collaborating at both the national and international levels through international inter-comparison of instruments. IMD's National Ozone Centre in New Delhi is designated as Secondary. Regional Ozone Centre for Regional Association II (Asia) of the World Meteorological Organization.

Surface ozone measurements using the electrochemical method were recorded continuously at 11 stations including one in Antarctica. These sensors are developed and fabricated at SID Pune and recording systems are procured from Indian manufacturers to promote the Make In India policy of the Government of India.

High Wind Speed Recording network

India Meteorological Department strategically installed 35 high wind speed recorders (HWSR) along the East and West Coast of India to monitor cyclones. These HWSRs are critical observation network which gives in-situ observation of wind speed, wind direction and pressure.

The present network station covers the east coast of India with a spatial resolution of about 100km. It is very useful during the landfall of cyclones. The data from the HWSR network is shared with the DSS server in Delhi. The data from the network is archived in the NDC server from Jan 2024. IMD has 35 HWSR stations in the coastal districts.

Surface Observatories

Surface meteorological observatories of the India Meteorological Department are divided into six classes;

Class –I : These are observatories equipped with both eye-reading and self-recording instruments.

Class – II : Most of these observatories are equipped only with eye reading instruments. Regular observations are taken at least twice daily.

Class – III : These observatories are same as class-II only difference is here observations are recorded only once in a day.

Class – IV, V & VI: These observatories have a lesser number of instrumental equipment or take non-instrumental observation only.

The basic surface instruments at surface meteorological observatory are

1. Mercury Barometer and Digital barometer
2. Four Thermometers i.e. Dry Bulb, Wet Bulb, Maximum and Minimum fixed inside the
3. Thermometer screen (Stevenson screen).
4. Raingauge and Measure glass.
5. Wind instruments – Wind vane and Anemometer.

All IMD Surface Observatories have been upgraded with Digital Barometer in 2015-2016 to measure Atmospheric pressure as mercury-based devices are being banned around the world, this can become a challenge for National Meteorological, Services (NMHS) which have depended on mercury barometers for decades.

NABL accreditation for Surface Instrument Calibration Laboratory for Pressure and Temperature calibration was achieved in 2024.

Automated Weather Stations

INSAT AWS LAB is the nodal office of Surface Instrument Division for installation of maintenance of Automatic Weather Stations all over India. The history of Automatic Weather Stations (AWS) in India can be traced back to 1980 when India Meteorological Department (IMD) conducted a pilot experiment with Indian Space Research Organization (ISRO) to operate a small network of Data Collection Platforms (DCP) via SEO satellite to the receiving station at Shriharikota Rocket Range.
Subsequently, IMD established a network of 100 Data Collection Platforms (DCPs) across India. Due to system design limitations, network performance achieved was not satisfactory both in terms of data reception and data quality. In 1997, the AWS network was upgraded by induction of 15 new state of the art microprocessor/ microcontroller-based systems across India under Test and Evaluation mode.

A network of 125 Automatic Weather Stations (AWS) has been set up by India Meteorological Department (IMD) during the year 2006-07 across India. Each station transmits a data stream at an interval of an hour in a Pseudo Random Burst Sequence (PRBS) manner via UHF transmitter and a dedicated meteorological satellite KALPANA-1/ INSAT-3A to the central AWS data receiving Earth Station facility established at IMD, Pune.

A TDMA type data receiving Earth Station has been established at IMD Pune for reception of 423 AWS and 1350 ARG station data in 2008-2009. A GPRS based receiving Server has also been established at IMD Pune in 2018 to receive AWS with GPRS based communication at an interval of 15 minutes or even 1 minute interval. The AWS/ARG received data are being processed and disseminated to IMD Delhi and also to AWS website in real time. Another network of 400 AWS has been established with GPRS communication all Over India during 2021-2024. A network of 85 AWS in Kerala and 99 AWS in North East States have been established by IMD. A network of 10 AWS has been established in Ladakh in 2023 and 12 AWS in Andaman & Nicobar Island in 2024.

IMD has established a network of 1008 AWS, 200 AGRO AWS and 1382 ARG Network. The received raw data is decoded in real time and engineering values of meteorological parameters are retrieved, disseminated and archived.

Solar Radiation Measuring stations

Solar Radiation Measurements started by India Meteorological Department in 1879 at Kolkata. India Meteorological Department started four radiation stations at Pune, New Delhi, Kolkata and Chennai in 1957.specifications. The years 1985 and 1986 saw a further addition of 14 stations to the radiation network density on specific requirements for those stations and a network of 45 established. In 2020, One Radiation Station Jammu added to Network and another one added Agartala in 2022.

Presently, IMD has established a network of 47 Solar Radiation Station all over India. Long wave Radiation, UV A and UV B Solar Radiation measurement started in 2009-2014. The Data logger have been upgraded with GPRS communication to have real time data in IMD Pun Server during 2014-2015 onwards.

1.1.2 Gap Areas in Surface Observation

Despite the significant efforts made by the India Meteorological Department (IMD) to expand its surface observational network, there are still several gaps that impact the accuracy and timeliness of weather predictions. Some of these gaps include:

Spatial Coverage: Certain remote or difficult-to-reach areas, particularly in the Himalayan region, deserts, and north eastern states, remain underrepresented. The sparsity of stations in these regions leads to gaps in real-time data collection, affecting localized weather prediction. There is a need to install AWS at block level (6612 numbers), ARG at panchayat level (2,50,000 numbers), Solar Radiation Measuring stations at district levels (800), District Rainfall monitoring stations (10,000) to have sufficient spatial coverage.

Data Resolution: The current density of stations might not always provide sufficiently granular data for highly localized forecasting, such as for urban microclimates or areas with complex terrain. Increased station density and more localized monitoring are needed to address this issue.

Technological Gaps: Some older weather stations/observatories still rely on out dated equipment, which can lead to errors or inconsistencies in data collection. The transition to more advanced technologies like automatic weather stations (AWS) and satellite-based observations is ongoing but not yet uniform across all stations.

Real-Time Data Availability: Data transmission from remote or difficult-to-access locations can be slow or unreliable especially during challenging weather. Delays in data transmission can lead to out dated information being used for forecasts, especially in regions where immediate weather changes are critical for disaster management and agricultural planning.

Quality and Consistency: In some regions, especially in rural or economically disadvantaged areas, maintaining the quality and consistency of observational data can be challenging due to inadequate infrastructure or lack of skilled personnel to manage equipment.

Human Resources: There is a need for skilled personnel and regular training to maintain and operate the growing network of observational stations. Overcoming staffing challenges is essential for improving the accuracy of data.

Addressing these gaps requires sustained investment in infrastructure, technology, and human resources. Enhancing the coverage, resolution, and reliability of data collected from the IMD

Surface Observational Network would significantly improve weather forecasting and climate monitoring capabilities across India.

1.1.3 Short-term Vision (next two years)

❖ **Automated Meteorological Observational Network**

- Expansion of automated observational network at district (800) & block level (1,50,000)
- Display of data and forecast to the public at the observatories (150) and other prominent tourist places (500).
- Application of AI/ML to pre-process the archived data and fill the gaps in climate observation.
- Expansion of High Wind Speed Recorder at 25 km in the coastal area (110)
- Establishment of Meteorological Towers in the coastal area (5) and North East India (3).
- Establishment of Automated Climate reference satiation at all RMCs (25).
- Regulation to allot space for the meteorological park along with the Mega infrastructure projects of Central and state Govt.
- **Smart Weather Stations:** An intelligent, autonomous AWS with advanced sensors integrated with AI algorithms for real-time Quality Control (150).
- Induction of advanced sensors for measurement of solar radiation for better understanding of energy balance and providing insights into renewable energy potential (Long wave and short wave).
- Establishment of a network of Automatic Snow Gauge/Snow Depth Stations comprising of weighing gauges, acoustic snow depth sensors and radar sensors for better understanding of snowpack dynamics (50).
- Establishment of a network of disdrometers for measurement of size and velocity of falling raindrop, hailstones etc. for calibration of DWRs (25).

❖ **Automation of Surface Observatories**

- Introduction of Data entry portal for manned Observatories to feed online data to a centralised server.
- Implementation of a primary level data screening and feedback to the operator about the quality of the data.
- **Chartless digital Observatory**: Replacement of conventional autographic instruments with digital autographic instruments (200).
- To improve the AWS data quality in Comparison with manual observation.
- To establish more observatories spatially in view of climate change studies (500).

❖ **Atmospheric Electric Field Observation**

- Study of Thunderstorm cells for improving nowcast warning
- Atmospheric Electric Field Mills in select regions with high lightning activity (100).
- Extensive research to understand the correlation between atmospheric electric fields and thunderstorm behaviour.

❖ **Renewable Energy/Green Energy Utilisation & reduction of carbon emission**

- Development of Low-power weather stations for deployment in remote, inhospitable or off-grid areas (300).
- Solar and Wind-powered Surface Observatories and automated stations (100).
- Meteorological instruments designed and produced with sustainable material and powered by renewable energy sources reducing environmental impact (100).

❖ **Calibration of Instruments & Sensors**

- SOP on calibration and quality policy
- Establishment of NIST traceable calibration laboratory for all meteorological parameters (3)
- Utilisation of existing calibration laboratories in the country
- Training on Quality Assurance to the concerned section.
- Establishment of Calibration Laboratory at each RMC (6).
- Integration of automated calibration systems to ensure the accuracy of measurements over time.
- Self-monitoring and diagnostic capabilities to identify and address malfunction.

❖ **Research & Development**

- Establishment of Centre of Excellence for R&D in instruments & sensors with dedicated manpower, infrastructure and budget allocation (1 number).
- To identify thrust areas for surface meteorological instruments, sensors and prioritise them for in house production.
- Research collaboration with academic institutes in India and aboard to jointly work with the centre.
- Establish and promote incubation centre/start-up as an outcome.
- Special scheme to encourage research and intellectual property rights, ToT
- **Interdisciplinary Research**: Foster interdisciplinary research that integrates meteorology with other fields to address complex weather-related challenges.

❖ **Public Weather Observation**

- Mandatory training to Aapda Mitra volunteers to report data from geohazards prone areas (every six months at RMC).
- API to receive data from a wide range of operators/gadgets (Establish servers in Pune and Delhi)
- **Crowd sourced Weather Observations:** Continued development of platforms for crowdsourcing weather data from citizens, incorporating data from visual observations, personal weather stations, smartphones and other sources. Crowdsourcing leverages the collective power of individuals to contribute meteorological data. The potential of crowdsourcing to enhance the understanding and prediction of weather patterns by increased data volume, diverse data sources, real-time monitoring, improved spatial

resolution and availability of microclimate data will be tapped. Issues related to data quality, privacy and standardization will be addressed (50,000 stations).

1.1.4 Medium-term Vision (next ten years)

❖ **Automated Meteorological Network**

- Automated Observational network at Panchayat level (2,50,000)
- Meso-network of AWS in all smart cities of India for monitoring UHI, micro-climatic features, disaster management etc for urban settlements (50).
- AI/ML technique to generate extreme weather event warnings using real-time data from automated stations.
- High wind Speed Recorder at district level in the coastal area (200)
- Satellite telemetry in HWSR and selected Automated Stations (100)
- Automated Climate reference satiation at MC level and gap areas
- Automated reference satiations at the RMC level for validation of remote sensing data
- Meteorological Towers near major ports and wind farms (500)
- Telemetry through polar satellite (1000)
- **Road Weather Information System**: Establishment of automatic road weather station network for monitoring weather conditions that impact roadways in collaboration with NHAI. Installation of stations at strategic locations along the highways for monitoring road conditions, visibility rainfall, hailstorms, landslides etc (1500).
- **Weather stations for transportation through Rivers**: Installation of weather stations along the major river transport routes for providing information to ships on voyages. Real time information pertaining to precipitation, visibility, wind, fog etc. to be made available for ship operators (200).

❖ **Automation of Surface Observatories**

- Application of electronic sensors in Surface Observatories.
- AI/ML-based primary-level data screening and feedback to the operator about the quality of the data
- Automated data reporting to a central server
- To establish more observatories in the areas prone to geo-hazards (flood-150 districts, Cyclone-150 districts, Heat wave -100 districts, drought-150 districts, landslides-150 districts)
- Observatories to adopt energy efficient practices and sustainable technologies, including the use of renewable energy sources, to minimize their environmental impact.
- Minimal manned observatories and maximum automatic weather stations across the country.

❖ **Atmospheric Electric Field Observation**

- Training and Capacity Building (Establishing a Laboratory infrastructure)

- To conduct extensive research and field study to understand the correlation between atmospheric electric fields and thunderstorm behaviour
- Explore the integration of advanced technologies, such as lightning detection systems and satellite observations, to enhance the predictive capabilities of thunderstorms and lightning nowcasts
- Expand the Atmospheric Electric Field Mills across the IMD observation network, ensuring comprehensive coverage (500).

❖ **Renewable Energy/Green Energy Utilisation & reduction of carbon emission**

- Utilisation of Small hydro, Biomass and Fuel cell energy sources for Surface Observatories and automated stations (230)
- Induction of fuel cell technology for remote observatories, High altitude observatories, and Antarctic observatories (300)

❖ **Calibration of Instruments & Sensors**

- Periodic Audit on the calibration system
- Periodic training and evaluation of QA staff
- Calibration Laboratory at MC level
- Calibration details as part of the metadata of the sensor
- Calibration plan for all instruments and sensors

❖ **Research & Development**

- **Cutting-Edge Technology**: Continuously invest in cutting-edge technology and research to remain at the forefront of meteorological advancements
- ToT to Indian industries
- To introduce scheme to encourage IMD staff to work with industries
- **Public-Private Partnerships**: Forge partnerships with the private sector to enhance forecasting capabilities and provide value-added services to various industries.

❖ **Public Weather Observation**

- Publicity about the programme and training to NCC, Scouts & Guides, NGOs and Volunteers (District level)
- Introduction of Geo-tagged data submission portal
- Implementation of GIS-based data mapping and visualisation

1.1.5 Vision 2047

❖ **Automated Meteorological Network**

- Beyond traditional meteorological parameters, observatories will incorporate environmental monitoring, including air quality measurements, to provide a comprehensive view of atmospheric conditions.
- UAVs for surface and boundary layer meteorological observations (at all radiosonde stations).

- Induct weather monitoring to study area that requires weather modification for rainfall, pollution, fog, hail etc. To achieve excellence in enhancement and suppression of weather as per requirements. (Metro cities that has poor air quality)
- Establishment of Automated Climate reference satiation at State level (50)
- Establishment of Automated reference satiations at MC level for validation of remote sensing data
- Observation at Voluntary homes (10,00,000)
- Disposable IOT sensors at the home/ward level (100 geo hazard prone areas)
- Telemetry through emerging technologies

❖ **Automation of Surface Observatories**

- Implementation of Electronic sensors-based observatory in the country (300)

❖ **Atmospheric Electric Field Observation**

- Expand the network of Atmospheric Electric Field Mills across the country to cover all regions prone to thunderstorms and lightning. Implementation of advanced algorithms and data analytics for real-time lightning detection and prediction systems (7000).

❖ **Renewable Energy/Green Energy Utilisation & reduction of carbon emission**

- Utilisation of Energy from waste to power the Surface Observatories and automated stations (all surface observatories)

❖ **Calibration of Instruments & Sensors**

- Portable calibrators at all observatories (at all RMC/MC/MWO/AMO)
- Automated calibration planner

❖ **Research & Development**

- Global Leadership: Attain recognition as a leading meteorological agency at the global level, exporting instruments to meet the global demand
- Establish state of the art Surface Instrument Laboratory for meteorology and atmospheric studies (1)
- Promote Make In India policy and achieve the goals of Atmanirbhar by 2047 in manufacturing of instruments and sensors
- Implement guidelines of Amrit Kaal Vision 2047 in the field of instruments and sensors

❖ **Public Weather Observation**

- Involvement of all stakeholders in weather reporting (aviation, railways, power, wind and solar farms).
- An integrated portal/Mobile APP for weather reporting, issue forecast and guidance, seasonal advisory, advisory during hazards events

❖ **New sectors / New type of observation- In view of climate change impact**

- In the wake of the escalating impact of climate change, there is a compelling need for a new type of observation and data collection in both coastal and Himalayan regions.

- In coastal regions, rising sea levels, increased storm intensity, and coastal erosion pose significant threats to ecosystems, infrastructure, and local communities. Precise observations, including continuous monitoring of sea-level rise, ocean temperature, and salinity, are essential for understanding and predicting the dynamics of coastal systems.
- In the Himalayan region, the changing climate has led to shifts in weather patterns, glacier melting, and altered precipitation, affecting the region's water resources and downstream communities. Observations like glacier monitoring, snowpack measurements and hydrological data are crucial for assessing water availability and mitigating the risk of glacial lake outbursts.
- The establishment of these new observational capabilities is not just needed but imperative to adapt and mitigate the impacts of climate change in these critical regions, safeguarding both the environment and the livelihoods of millions of people who depend on them.
- Flash flood /heavy rainfall monitoring

❖ **New sectors / New type of observation- In view of technological advancement**

- Technology-driven smart sensor
- Mobile weather station
- Geo-tagged data
- Self-reliance instruments and sensors under make in India
- 3D printing technology
- Application of Quantum computers and satellite-based internet technology /telemetry
- Application of AI/ML
- Application of Robotic
- Increased processing capability of portable systems/observatories
- Need of space observation
- Floating stratospheric air balloons
- Aerosol based ground observation for Wind observation/jet monsoon current/ ocean dynamics

1.2 UPPER AIR OBSERVATIONAL NETWORK

1.2.1 Current status and major achievements during the past 10 years

Upper air observations are an essential component of meteorological data collection. This involves recording atmospheric variables at different heights above the Earth's surface. This data is invaluable for predicting the weather, studying climate, and gaining insights into atmospheric phenomena.

Currently, IMD has 56 RS/RW stations and 62 pilot balloon stations (25 GPS-based).

Modernization of the IMD upper air network started in 2007, and in the initial stage 10 stations were upgraded with a new upper air system based on Global Position System (GPS) during 2009. At these stations, the data quality has improved and has been validated by NCMRWF and ECMWF. Six more stations were upgraded to GPS-based radiosondes from 2010 to 2012. IMD upgraded 16 radiosonde stations out of 39 with a new GPS-based sounding system in 2013. Later in 2015, all 39 upper air radio sounding (RS/RW) stations were upgraded with GPS-based radio sounding. Among them, 6 stations were upgraded as per WMO Global Climate Observing System (GCOS) Upper Air Network (GUAN) standard. IMD increased the number of RS/RW stations to 43 in 2016 with all GPS-based radiosonde systems. The major upgrade in the radiosonde network happened in 2019 and 13 more stations were added with a special emphasis on North East India and the total number of radiosonde stations became 56.

Apart from the RS/RW stations, IMD also has Pilot balloon (PB) networks, which make observations every six hours viz 00, 06, 12, and 18 UTC. PB observations are used to measure the upper air wind speed and wind direction by tracking the balloon using an optical theodolite. During 2015 IMD had 62 PB stations in India. PB station upgradation with GPS-based sondes started in 2018 with the upgradation of first GPS PB observation at RMO Ayanagar on 23rd March, 2018 on the occasion of World Meteorological day. At the same time, a GPS-based pilot-sonde has been developed and is being manufactured in-house in IMD Workshop. The same has been implemented in the PB network at PB stations in New Delhi, Mumbai, and Lucknow in 2019. Currently, IMD has 25 indigenous GPS-based pilot balloon stations, of which 5 are in-house manufactured/ assembled in IMD New Delhi.

1.2.2 Challenges and Gap Areas

- Over the past 10 years, India has achieved significant milestones in upper-air observations. Currently, several upper-air observation initiatives have been successfully launched. However, the leading countries in upper-air observation with higher spatial resolution are the USA, China, and Japan. China maintains the largest operational radiosonde network, with 120 radiosonde stations and over 100 wind profilers. The USA follows with the second-largest operational radiosonde network, consisting of 92 stations. Among these, 69 are located in the contiguous United States, 13 in Alaska, 9 in the Pacific, and 1 in Puerto Rico. Additionally, the NWS supports the operation of 10 other stations in the Caribbean. The USA also operates 30 wind profilers. Meanwhile, Japan runs 16 radiosonde stations and 31 wind profilers across its territories, providing a dense spatial resolution of 130 km on average over the main islands.

Maintenance and coordination of all 56 RS/RW and 62 PB stations and initiation of more secure and reliable data monitoring and dissemination methods are essential.

- None of the Indian radiosondes are WMO certified. The WMO recommends RS/RW with a minimum score of 3.0 or higher for all parameters in regular operation.
- Procuring Hydrogen (H_2) gas is difficult for remote stations, including some of the Meteorological Centres (MCs). The induction of electrolyzers for local H_2 gas generation at all network stations is required.
- Upgrading GPS-based Pilot Balloon observations is in progress. However, there is a need to reduce dependence on private firms and increase the use of indigenous IMD-manufactured/assembled PB stations.
- Currently, IMD has 56 RS/RW observation stations, which are insufficient to accurately monitor upper air observations in a tropical country like India. More dense upper air observation network should be established.
- Prediction and tracking of tropical cyclones and thunderstorms remain challenging. High-quality RS/RW observations are required for better prediction and forecasting. Increasing the frequency of upper air observations and spatial coverage during major events like cyclones and cloud bursts is essential.
- Currently, IMD lacks upper air observations from other platforms capable of producing data with higher temporal resolutions. These instruments include SODAR, Lower Atmospheric Wind Profilers (LAWP), microwave radiometers, ceilometers, and LIDAR.
- Upper air observations from commercial aircraft are sparse in India compared to the USA, European, and East Asian regions.
- Maintaining stations in very remote areas and taking observations at 0000 UTC (0530 IST) is always challenging. This can be addressed by installing automated radiosonde launching stations at these remote locations. Such systems have the capability to launch 30 to 60 balloons per month and require minimal monthly maintenance.
- One of the main challenges in the operation of radiosondes is cost. This can be reduced by introducing reusable systems. Drone observations could provide basic atmospheric parameters such as Temperature (T), Relative Humidity (RH), Pressure (P), Wind Speed (WS), and Wind Direction (WD). Additionally, drones may be used for ozone, aerosol, and cloud particle observations. Information on aerosols and cloud particles will be valuable for understanding aerosol-cloud interactions and improving cloud parameterization. These observations will also benefit climate data services.
- India currently has limited observations from islands; the majority of observations are from coastal regions or inland areas. RS/RW observations from research vessels would improve NWP in the future.
- Major upper air observatories in the USA, Japan, China, and European unions have started to make regular observations of high-resolution water vapour and aerosols observations using balloons. No such regular observations from India have yet been initiated on a

regular basis other than a few campaigns conducted during winter or monsoon seasons by IITM Pune, ISRO, and IITs.

1.2.3 Short-term Vision (next two years)

The short-term vision is to restore and maintain observations from all 56 RS/RW stations without data gaps. Addition of 30 new RS/RW stations in the network will also be undertaken. IMD also aims to ensure that no observations are missed in data assimilation due to technical errors in observation. Additionally, IMD is upgrading all conventional PB stations, equipped with optical theodolites, to GPS-based PB observations to ensure more reliable data from the surface to the lower stratosphere. Currently, IMD has 25 indigenous-manufactured PB stations (20 outsourced from Indian manufacturers and 5 in-house), and based on their performance, IMD plans to upgrade all 62 stations within the next 2 years. IMD currently uses either indigenous RS/RW equipment purchased from local firms or RS/RW equipment obtained through global tenders. IMD is planning to use indigenously manufactured radiosondes for operational purposes, with the development of in-house RS/RW initiatives commencing within the next two years.

Multiplatform upper-air observations are currently lacking at IMD stations. Instruments such as LAWP and microwave radiometers can provide observations in the troposphere with higher temporal resolutions. These observations can be used not only for short- or medium-range forecasting but also for nowcasting. The installation of such systems in metro-cities and areas prone to extreme weather events would significantly improve forecasting quality. The major objective of the upper-air observation network is to establish upper-air observations at a 100x100 km grid, complemented by multi-platform satellite and aircraft-based profiler observations, Doppler Radars, wind profilers, Radiometers, lightning detectors, and LIDARs. Augmentation of the observational network is crucial for improving the initial state of the atmosphere and, consequently, enhancing the accuracy of short to medium-range weather forecasts

1.2.4 Medium-term Vision (next ten years)

- ❖ Increase the RS/RW network to 116 stations, and the number of GUAN stations will be increased to 25.
- ❖ Increase the number of PB stations to 80.
- ❖ Upgrade IMD-manufactured PB stations to 30.
- ❖ Increase the frequency of observations and the number of stations by using portable radiosonde launching stations during extreme weather events for better forecasting.
- ❖ Initiate observations using indigenously manufactured/assembled GPS Radiosondes from 10 stations.
- ❖ Introduce software-defined receivers for IMD radiosondes.
- ❖ Design lightweight radiosondes and register patents for the technology.
- ❖ Support more indigenous manufacturers to achieve international standards and become self-sufficient and self-reliant in technology.
- ❖ Begin exporting GPS RS/RW sondes to developing countries.

- Currently, two Indian RS/RW sondes participated in WMO's 2022 upper air instrument inter-comparison. IMD may support at least 2 more Indian vendors to obtain WMO certification, aiming to use only Indian systems in the entire IMD network, thereby reducing imports.
- Augment LAWP, microwave radiometer, SODAR, and LIDARs in metro cities and regions prone to extreme weather events.
- Establish IMD/WMO-defined standard data formats with quality checks. Implement encrypted data transfer using the Internet of Things (IoT) for secure and quick data dissemination of quality-checked data.
- Implement real-time system performance monitoring and data analysis.
- Develop a performance score as a tool to assess the effectiveness of IMD upper-air stations across the country and enhance data accessibility, quantity, and quality.
- Create a mobile app/ dashboard to coordinate RS/RW stations and monitor the launchings.
- Induct H_2 gas generators at all RS/RW stations to avoid MISDA due to the non-availability of H_2 gas.
- Introduce recoverable/reusable radiosondes: Especially to probe the boundary layer.
- Expand upper-air observations to include trace gases, aerosols, and cloud particles either with balloons or drones.
- Augment automated radiosonde launching stations at remote locations on a trial basis.
- Commence regular RS/RW ascents from research vessels.
- Initiate regular observations from domestic commercial aircraft. Currently, India has poor spatial resolution compared to the USA, Europe, and East Asia.
- Use biodegradable radiosondes and balloon threads.

1.2.5 Vision 2047

- Strive to become self-sufficient and self-reliant in technology and emerge as a global leader.
- IMD will initiate the export of GPS RS/RW Sondes to developing/least developed countries.
- Ensure round-the-clock upper atmosphere monitoring through multiplatform observations.
- Establish upper air observations at a 100x100 km grid with multi-platform satellite and aircraft-based profiler observations, Doppler Radars, wind profilers, Radiometers, lightning detectors, and LIDARs.
- Produce high-quality data for forecasting and climatology services.
- Transform IMD's upper air observation stations into a world-class calibration facility for satellite and model data.
- Conduct RS/RW ascents from strategically important yet remote locations using automated radiosonde launching systems.
- Profile the lower atmosphere/boundary layer with high-resolution recoverable radiosonde (drone observations).
- Obtain vertical profiles of aerosols, trace gases, and cloud particles from GUAN stations using balloon/drone observations. Additionally, the number of GUAN stations will be increased to 50.

- Collaborate closely with ISRO to pioneer the development of a hyperspectral Infrared Sounder. This cutting-edge technology aims to deliver highly accurate temperature and humidity observations crucial for enhancing space-based data used in Numerical Weather Prediction (NWP) systems.

1.2.6 Strategy

- The first priority is to make all 56 RS/RW stations operational and upgrade all conventional PB stations to GPS-based PB stations.
- Upgrade all GPS-based PB stations to IMD-manufactured GPS-based PB stations upon satisfactory system performance.
- Expansion of the IMD upper-air observation network from 56 to 126 so on to have one observation for every 100 km x 100 km is the second stage, which includes RS/RW and PB stations, SODAR, LAWP, LIDAR, recoverable radiosondes (drones), and Doppler Weather Radars.
- Develop power-efficient, accurate, and precise radiosonde sensors (temperature, humidity, and GPS module) in collaboration with SAMEER, MeitY, and others.
- IMD will support at least two Indian vendors in obtaining WMO certification with the goal of using only Indian systems throughout the entire IMD network, thereby reducing imports.
- During severe weather events, IMD will maintain an Intense Observation Period (IOP) by deploying portable radiosonde stations and increasing launch frequency during disturbed weather conditions.
- Real-time data monitoring using IoT and data quality checks with the aid of AI/ML before sending for model assimilation.
- Deploy automated radiosonde launching stations at strategically important remote locations and conduct RS/RW ascents from research vessels to ensure accurate upper-air data for model initialization.
- Obtain upper-air observations from commercial aircraft and transfer data in real-time for assimilation.
- Conduct drone-based observations of basic atmospheric parameters, aerosols, trace gases, and cloud particles with higher temporal resolution in the lower troposphere/boundary layer to improve aerosol-cloud parameterization and further enhance model assimilation.
- The induction of H_2 gas generators will eliminate any issues in RS/RW ascents caused by the unavailability of H_2 gas.
- The development of a Hyperspectral Infrared Sounder in collaboration with ISRO will provide highly accurate temperature and humidity observations from space, thereby enhancing Numerical Weather Prediction (NWP).

1.2.7 Outcome

All of the aforementioned strategies and adaptations aim to make IMD self-sufficient and technologically independent, paving the way for IMD to emerge as a global leader in upper-air observations across various platforms. IMD is poised to establish a state-of-the-art upper-air observation network with a spatial resolution of 100 km x 100 km, enabling continuous monitoring of fundamental atmospheric parameters. By 2047, India aims to achieve self-reliance in Radiosonde Radiowind (RS/RW) production, thus reducing reliance on imported sondes. IMD will prioritize eco-friendly payloads to diminish its carbon footprint. Introducing real-time data monitoring through a mobile app and website will further optimize the performance of RS/RW and upper-air observation stations, fostering seamless coordination. Utilizing AI/ML technology to promptly analyse sounding data post-launch will significantly enhance data quality. Additionally, implementing stringent data policy and encryption will minimize unauthorized data usage.

All the above would result in 100% detection of severe weather and its uncertainties and it gives the physical understating. It will also lead to significant improvement in the NWP model's performance and, hence, improvement in the forecast accuracy of IMD for all severe weather, i.e., nowcast to short and medium as well as extended range forecast up to 15 days.

1.3 DOPPLER WEATHER RADAR NETWORK

1.3.1 Current Status and Major Achievements during the Past 10 Years

- The weather radar network of IMD has increased to 39 Doppler Weather Radars (DWRs) from that of 15 in the year 2014.
- There are 20 S-band radars installed at Agartala, Bhopal, Bhuj, Chennai, Goa, Gopalpur, Hyderabad, Karaikal, Kolkata, Kochi, Lucknow, Machilipatnam, Mohanbari, Mumbai, Nagpur, New Delhi (Palam), Paradip, Patiala, Patna, Vishakhapatnam.
- There are three C-Band DWRs installed at Jaipur, New Delhi (HQ) and Solapur (IITM).
- IMD also utilizes the data from DWRs of ISRO located at Vikram Sarabhai Space Centre (VSSC) Thiruvananthapuram (C band), Sohra (S band) and Sriharikota (SHAR) Andhra Pradesh (S band).
- Apart from one X-Band DWR installed at Srinagar, 10 state-of-the art SSPA X-Band DWRs have been installed and commissioned in the Central and Northern Himalayas at highly remote stations in order to provide better radar coverage in the Himalayas. These radars are installed at Mukteshwar, Surkanda Devi and Lansdowne in Uttarakhand, at Kufri, Murari Devi and Jot in Himachal Pradesh, at Jammu and Banihal Top in Jammu & Kashmir, at Leh (portable radar) in Ladakh and at Aya Nagar (Delhi).
- Recently, two more indigenously developed SSPA DWRs i.e., one X-band at Pallikarnai, Chennai and one C-band at Veravali, Mumbai have been added in IMD radar network.

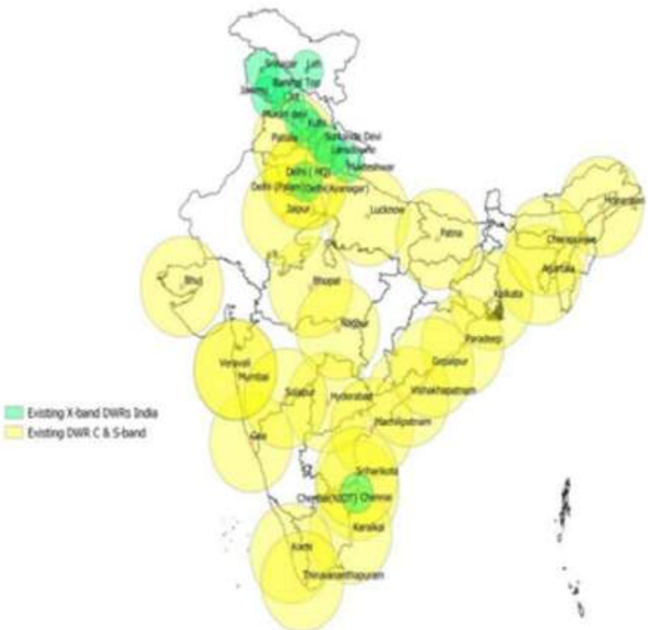


Fig.1 IMD's Existing DWR network

1.3.2 Challenges and Gap Areas

To enhance the effectiveness of meteorological services, a multi-faceted approach is imperative. First and foremost is addressing data gaps in remote or less accessible regions by 100% radar coverage of the country. Second, upgrading radar technology to the advanced ones. Moreover, providing more comprehensive radar data products is unwavering. Furthermore, enhancing the coverage span, regular radar calibration has to be taken into consideration.

Induction of an adequate number of DWRs in the network is the need of the hour for plugging the existing gaps in the meteorological observational network of Radars, desirable for effective & efficient analysis and consequent forecasting, in particular at the mesoscale. The availability of countrywide weather radar coverage and its integration, including overlapping regions of the proposed network, would provide adequate warning in the event of the approach of Cyclonic Storms, Monsoon Depressions, etc. DWR network would also provide vital information for nowcasting purposes on mesoscale convective weather developments anywhere in the country. Radar observations would also stimulate research on the dynamics and microphysics of convective weather phenomena. The assimilation of DWR data in numerical weather prediction (NWP) models can help in improving weather forecast in very short to short range.

The network of ESSO-IMD Doppler Weather Radar (DWR) has increased from 4 in 2006 to 39 in 2024; however the average distance between the existing radars is 432 km. If we look at other countries; the USA has 160 radars in 9857815 km^2, Canada has 33 S-Band DWR in 9984670 km^2, Japan has 20 radars in 378000 km^2, Germany has 17 radars in 357569 km^2, the UK has 17 radars in 242945 km^2, China has 217 radars in 9600000 km^2 and in India we have 39 radars in 3287263 km^2 area. This indicates approximately 84% of the Indian land area is only under Radar coverage. Further expansion of the Doppler Radars network is needed to cover the entire country. There's a need for a combination of X-Band, and S-band DWRs for 53 cities with > 10 lakh population. Additional X-Band Radars in hilly regions are needed to cover all shadow zones.

1.3.3 Short term vision (next two years)

- ❖ Expansion of radar network by identifying and filling data gaps through strategic radar installations.
- ❖ Up gradation of technology to new radar technologies like dual-polarization and SSPA enables discernment of various precipitation types, improves severe weather detection, and advanced cloud and precipitation microphysics research.
- ❖ Regular stringent calibration of radars in the network at fixed intervals makes radar data more accurate and consistent. This expanded radar network will significantly improve the capacity to monitor and forecast weather patterns throughout the country.
- ❖ A standardized data model for radar data in creating uniformity among all IMD Radars.
- ❖ Developing Quality Control mechanism for Radar data, and details stocked in meta-file.

- ❖ Taking a lead role in the region and making a regional Weather Radar Network, with framed one-to-one bi-lateral policies of data sharing with participating member countries.
- ❖ All new weather radars required to be installed will be manufactured in India.
- ❖ Products including lightning indication, hail identification, and 3D storm structure analysis would enable forecasters and researchers for more accurate severe-weather nowcasting and in-depth weather studies.
- ❖ Adaptive scan strategy based on the heterogeneous radar network would be addressed.
- ❖ To monitor and provide uninterrupted radar observations, establishment of a centralized centre such as National Weather Radar Operating Centre (NWROC) has been proposed
- ❖ Development of Radar Research and Training division will provide better opportunities towards in-house products development and capacity building. Radar Research and Training division associating with R&D labs and industries would enhance bridging the technology gaps.
- ❖ A total of 87 DWRs will be installed and commissioned in IMD's Radar network by 2026 covering the Indian subcontinent.
- ❖ India would be a regional leader in South, Southeast & Middle East Asia.

1.3.4 Medium-Term Vision (Next Ten Years)

- ❖ Upgradation of the weather radar network based on technology advancements
- ❖ Strengthening of Radar Network connectivity with dedicated multi-channel connectivity enabling centralized monitoring and operations, minimal support staff at site.
- ❖ Adapting advance technologies such as polarimetric Phased-Array Radar (PAR) may enhance better observations of severe-weather systems and in turn would enhance warning performance by means of rapid volumetric scanning (~once per minute) with features to enable cloudburst detections.
- ❖ To augment the radar combinations, enhancing coverage near the surface. Especially for Metropolitan and urban network and catchment areas.
- ❖ Using virtual reality to visualize and analyze the 3D or volumetric radar data.
- ❖ Using augmented reality to visualize and analyze the radar data, volumetric data and giving weather inference or details at the street level using apps.
- ❖ Utilizing machine learning and AI techniques to analyze vast amounts of radar data quickly. These technologies can identify patterns, make predictions, and assist meteorologists in interpreting complex weather phenomena and predicting them.
- ❖ Plan for the development and deployment of advanced weather nowcasting models using radar data and supportive additional data yielding alerts in very higher resolution both temporal (every 10 minutes valid for next 3 years) and spatial (at village level).
- ❖ Periodic calibration of radar automatically by advance software and hardware techniques without manual intervention.
- ❖ Induction of storm probing Airborne Phased Array Radar (APAR) in IMD's network enabling sampling the Cyclones/Thunder storms in situ and the surrounding atmosphere at higher spatial resolution enabling to understand storm dynamics and microphysics.

- ❖ Emphasis to be given towards the nowcasting of extreme events like extreme rain, severe thunderstorms with lightning and events like cloud bursts auto-alerting systems using Radar and supportive instruments.
- ❖ IMD would make efforts in creating a central axis with all the stake holders in India having Weather Radar operations/development, and would also involve friendly countries for an extended collaboration and a Regional Radar Hub with multilateral agreements.
- ❖ The development program for the next generation weather surveillance radar system should incorporate adequate provision for beta testing in the field in locations with diverse climatological and geographic situations.
- ❖ It is proposed to have a total of 126 DWRs in India in next five years, thus bringing each and every part of the country under Radar observation network.
- ❖ Regional Virtual Training Centre on Radar Technology will be established to enable training of radar meteorologists in the region. India would be a regional leader in Asia.

1.3.5 Vision for 2047

- ❖ Entire area of the country will be under the surveillance of weather radars manufactured in India.
- ❖ As the radar network increases, AI /ML techniques may be utilized to read the surveillance scan data and changing the scan strategy of two overlapping radars dynamically such that one radar will focus on the weather event and do rapid scan while the other radar will take care of other areas. This is to have a high resolution both temporally and spatially.
- ❖ Advancements in radar technology would lead to the development of smaller, more portable radar systems. This is particularly useful for deploying radar in areas where traditional, larger systems may be impractical.
- ❖ Using multiple low power radars which can rely upon the renewable energy sources.
- ❖ Incorporation of mobile radars to provide highly detailed views of weather events. Such observations are of prime observational and scientific interest.
- ❖ The capabilities of future space-based and air-borne radar systems to supplement ground-based systems and their integration demonstration.
- ❖ Satellite and other ground based inputs can be used to estimate area of operation more precisely and optimally to determine the dynamic scan strategy using dynamic machine learning models, ultimately enhancing the temporal resolution and avoid data gaps in storm studies.
- ❖ Plans for next generation weather radar systems should include provisions for real-time dissemination of data to support forecast, nowcast, and warning operations and data assimilation for numerical weather prediction, and certain research applications.
- ❖ Phased Array, Scan-while-track systems would greatly enhance the Terminal Doppler Weather Radar realization while also would serve aircraft tracking.
- ❖ India as a Global Leader in Doppler weather radar research and innovation, sharing expertise with other countries.

1.3.6 Strategy

- Promote public-private partnerships for manufacturing in India, data collection, analysis and dissemination to prospective users.
- Establish partnerships with academic institutions and research organizations to foster innovation and research collaboration.
- Focus on international collaboration for access to global weather data and sharing Indian meteorological expertise.

1.3.7 Outcome

- **No weather system will go undetected**
- Improved accuracy in weather nowcasts, leading to zero loss of life of humans and livestock, and property due to weather-related disasters.
- The characteristics of radar observations and associated error statistics are quantified in ways that are compatible with user community needs.
- IMD becomes a global leader in thunderstorm, lightning and cloud physics research, climate change adaptation and mitigation strategies.
- IMD would be housing an International hub in addressing guidance and support related to Radar technology for development and utility for WMO member countries, which already have a bi-lateral/multi-lateral agreement with IMD.

1.4 SATELLITE METEOROLOGY

There is a growing need for improved weather (at very short temporal scale to seasonal) and climate predictions at very high resolutions. The new generation of models along with availability of large computational infrastructure will demand data at a much higher spatial resolution with improved accuracy at least better than the model's accuracy. These models started having or will have capability to assimilate non-traditional data such as cloud microphysical products and lightning flash rate with availability of new data assimilation techniques. The demand for high quality observations and frequent observations demands through upgradation in the current space based Earth Observations (EO). The ongoing ambitious projects towards building climate resilient and smart cities & villages can be achieved only by having reliable geo-spatial information as well as suitable early warning systems. Similarly, with the implementation of national food security measures along with growing demand for foods, there is need for increase in agricultural productivity and at the same time reducing loss due to damage caused by weather vagaries. Efforts towards this is very challenging with ongoing uncertainties due to climate variations, projected increase in flash flood, urban flooding, wide spread river flooding, frequent agricultural droughts, increase in incidences of pests and diseases etc. This can only be addressed in sustainable manner with strategic planning through proper climate inputs, land use planning and weather information. The rapidly changing hydrological cycle in this warmer environment is also causing significant threat towards water resources and greater concern towards the national water security. All these will have greater societal impacts and will retard economic progress. Hence it requires early intervention by proper planning of EO and usage of space technology.

MoES under its long-term vision plan is gearing towards development of advanced Weather prediction system to provide advisories at higher spatial scale i.e. at administrative block level with lead time of 3-5 days with improved skill. This will be used to develop advisories for sectors like Agriculture, disaster Management, water resources, Power, Tourism and Pilgrimage, Smart Cities, Renewable Energy Sector and Transport. This information will help towards generation of clean energy (solar, wind and tidal) and its transmission and management, depending upon users' requirements. Because, it requires proper assessment of potential energy generation sources and devising early contingency plans. There is also plan for issuing severe weather warning (heavy rainfall, urban floods, Fog, air pollution emergencies, Heat and Cold waves) at district/block levels with above skills. There is need for development of Decision Support System for predictions of Tropical cyclones and associated damages over the Indian Seas, 7-days in advance with the 24/48/72-hour Land-fall errors of 30/60/100 km, respectively. It is also envisaged to have long-term plan for developing an Integrated Himalayan Meteorology Program for meeting the growing challenge and needs of the ecologically fragile and climate sensitive Himalaya and north-eastern states. The changing pattern and type of precipitation might be affecting the numerous glaciers and snow covered regions of these mountains. Hence, it is required to monitor the three dimensional variability of regional hydrological cycle and assess its expected changes and impacts in the future. But, there is to some extent lack of high resolution (space and time) observation for monitoring such events.

Even the current state of the art models are unable to predict these events with sufficient lead time. Similarly, there is no data yet with frequent sampling to validate cloud resolving models simulations. The skill of global extended range models is limited to 2-3 pentads, thus there is a need to improve model with improvement in observation for input to initial and boundary conditions.

There is a critical requirement to undertake the atmosphere and ocean process study that will lead towards the improvements in modelling of physical process by considering water vapour, cloud, precipitation, aerosol, radiation, atmospheric circulation and associated feed-backs. Thus it is very much required to enhance our understanding about the physical processes that are still unresolved in the numerical weather prediction models either due to the complexity of these processes or due to their spatio-temporal scales. Intensive observational efforts will be required in near future to understand these processes that are critical to our ability to predict the weather at desired space-time scales. It is also important to reduce the uncertainty in the future climate projections by the climate models.

There is also requirement of data from GEO for validating climate scenario as well as limiting the model uncertainty by constraining the hindcast simulations at least at regional level. The Madden Julian Oscillation (MJO) is already identified as a dominant mode of tropical intra-seasonal variability which originates over Indian Ocean and shows larger amplitudes while crossing Indian Ocean and west pacific. Its propagation is strongly modulated through cloud-radiation interactions. But, there is a lack of systematic observations of cloud vertical structure and three-dimensional distribution of vertical radiative heating in SW and LW components.

Convective clouds not only cause damage due to hail and strong winds associated with gusts/ squall and lightning, heavy rain leading to damage of property, power transmission and loss of life. Every year more than 2500 people in the country lose their lives and many more suffer injury due to lightning strikes. It is also hazardous to air traffic. It is observed that during recent years more number of people in the country die due to lightning strikes than any other weather related disasters. Many lives can be saved through nowcasting by real time lightning observations and public awareness. Lightning also causes forest fires, causing losses to natural resources, wild life and deteriorate ambient air quality. At the same time lightning is also indicator of convective intensity and proxy for tropical cyclone intensity as well as microphysical composition of clouds. Currently most of NWP model are inefficient to predict intensity of cyclone with appreciable accuracy, mainly its rapid intensification and weakening. However, lightning observation has shown skill in inferring this at an earlier stage. Continuous and long term monitoring from Geostationary platform will provide a basis for monitoring severe convection and extreme weather over a wider area and it will work as test bed for verifying observation of extreme events due to global climate change. Thus lots of precious lives can be saved with enhanced observations from satellites.

WMO Global Climate Observing System (GCOS) in its implementation plan-2016 has identified 54 essential climate variables over land, ocean and atmosphere that requires continuous observations with specified accuracies through not only terrestrial but also from space-based instruments to achieve climate quality observation.

Therefore, the proposed payloads from a Geostationary orbit in coming years will not only serve the operational needs, it will resolve several outstanding scientific issues and broaden our scientific understandings; it will help in the development of weather and climate models for forecasting.

The following instruments have been proposed for future Indian geostationary satellites that is also part of the CGMS baseline for geostationary satellite instruments for Global Observing System (GOS):

(i) Advanced Imager
(ii) Lightning Imager
(iii) Narrow-band High Spectral and Hyperspectral Resolution Vis/NIR Imager
(iv) Hyperspectral Infrared/Microwave Sounder
(v) Space Weather Monitor (solar imagery, particle detection, electron density)
(vi) Earth Radiation Budget Instruments

The present report suggests few important upgradations of imaging sensors for the 4th generation of Indian geostationary satellites. These are the multispectral imagers with limited capability for atmospheric sounding, nicknamed as pseudo-sounders, and the hyperspectral infrared sounders from GEO platforms. The multi-spectral imagers will provide the superior imaging of atmospheric processes with significantly enhanced spatio-temporal resolution. On the other hand, the use of hyperspectral infrared sounders would ensure the availability of the vertical profiles of temperature and humidity along with the information on the trace gases with high accuracy and significantly improved vertical resolution. Various international space agencies have already developed such advanced imagers with high spatial (1-2 km) and temporal (< 15 min) resolution, i.e., 12-channel MSG/SEVIRI by Eumetsat, 16-channel Himawari-8/AHI by JMA and 16-channel GOES-R/ABI by NOAA, whereas, a 16-channel GEO-KOMPSAT-2A/AMI is planned by KMA in 2018.

Another important sensor proposed by the study team is the Lightning Imager (LI) operable from the Geostationary platforms. The LI will improve nowcasting by providing real-time information on total lightning. This will enable forecasters to detect, monitor, track and extrapolate in time, the development of active convective areas and storm life cycles that is critical for nowcasting and very-short range forecasting of severe weather events. Assimilation of lightning data in mesoscale weather prediction models has shown great potential in improving the prediction of thunderstorms and high impact weather.

The report also suggests the space weather monitoring instruments for 4th generation INSAT series of satellites. Space weather monitoring instruments have long been in GEO platform starting from Meteosat-4 in 1989 and GMS by JMA in 1977. Subsequently, GOES-N series since 2006 and FY-2C since 2004 have these instruments. With increased number of communication/navigation satellites being launched by ISRO, it will be beneficial to have space monitoring instruments in future INSAT satellites.

There is also a need to reduce the gaps in technological advances in the field of instrument design and development with various other international space agencies in near future, about 10-15 years of timeframe. The mission continuity is also an area where a lot of focus needs to be given in order to have continuous observations as well as reliable long time-series of essential climate variables for climate monitoring.

Inadequacies (Gap Areas) of the existing INSAT datasets.

Geostationary platforms provide an advantage of continuous coverage of a particular location. However, due being situated at a height of 36000 km presents a difficulty in placing microwave instruments on board due large power requirement and the size of antenna required for producing meaningful ground resolution. The present INSAT-3D/3DR satellites provide sounding capability at 10 km spatial resolution from 18-Sounder channels and Imaging capability at 4 km for MIR/TIR1/TIR2 infrared channels and 8 km for the WV channel apart from 1 km from VIS and SWIR channels. The infrared remote sensing is severely affected by the presence of cloudiness and this makes it challenging to retrieve the clear-sky geophysical products from Sounder and Imager channels as more than 75% of the globe is covered by the clouds at a given point of time.

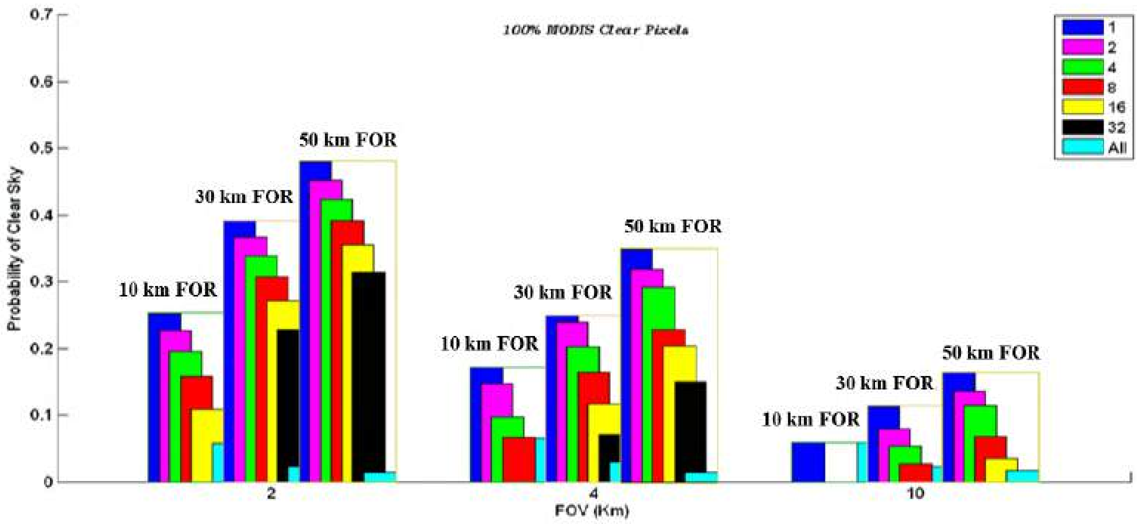


Fig.1: Annual probabilities of finding clear-sky pixels for spatial resolution of 2, 4 and 10 km and Field-of-Regard (FOR) of 10, 30, and 50 km

Fig.1 explains that for INSAT-3D Sounder having 10-km spatial resolution the probability of finding at least one clear pixel is only 5% for single pixel retrieval (10 km FOR), 10% for 3x3 pixel retrieval (30 km FOR) and 15% for 5x5 pixel retrieval (50 km FOR). The probabilities further reduce to less than 5% if all the pixels within FOR are to be clear-sky. This introduces an error in the retrieval due to the presence of a partial cloud cover within the pixel that goes undetected in the cloud detection algorithm. The probability of finding clear-sky pixels increases sharply with increase in the spatial resolution, e.g., 40-50% for the FOR size of 30-50 km.

The advanced Sounding/Imaging instruments onboard polar orbiting satellites make use of simultaneous microwave observations or high resolution (~1 km) infrared observations to perform cloud-clearing of the coarser hyper-/multi-spectral sounder observations and thereby, provides high quality clear-sky equivalent sounding. Example of such combination are Metop – IASI using AMSU or AVHRR, Aqua – AIRS using AMSU or MODIS, Suomi NPP – CrIS using ATMS or VIIRS, NOAA – HIRS using AMSU and AVHRR. Such capabilities are non-existent in the latest INSAT series of satellites, INSAT-3D/3DR. These issues are being resolved by other geostationary satellites belonging to various international space agencies by using very high spatial resolution (< 2 km) of infrared sounding channels. The first such satellite was Meteosat Second Generation (MSG) having 12-channel SEVIRI with spatial resolution of 2 km launched by Eumetsat in 2002. This was followed by Himawari-8/9 by JMA, Japan, launched in 2014/2016 having 16-channel Advanced Himawari Imager (AHI) with 2-km spatial resolution. Recently, NOAA launched GOES-R in 2016 having 16-channel Advanced Baseline Imager (ABI) with 2-km spatial resolution. These multichannel advanced Imagers (SEVIRI, AHI, and ABI) have enhanced the observational potential of geostationary satellites tremendously providing critical information for high impact severe weather events. The combination of many Imaging and Sounding channels with high spatio-temporal resolution observations are providing a number of important geophysical parameters, such as cloud microphysical properties, cloud classifications, atmospheric stability indices, atmospheric layer precipitable water vapour, water vapour wind vector at 2-3 layers etc. These three satellites cover Atlantic and Pacific oceanic regions leaving a big data gap over Indian Ocean. Other gap areas include the absence of a lightning detector that has capability of locating regions under severe thunderstorm activity.

Apart from the advanced Imager that will combine the advantages of Imaging and Sounding capabilities in one instrument, INSAT satellites also lack a hyperspectral infrared sounder that can provide very high resolution vertical thermodynamic structure in the atmosphere. So far none of the geostationary satellites have hyperspectral sounder onboard, but Eumetsat has plans for such instrument in the future Meteosat Third Generation (MTG) satellites.

Background Requirements for future INSAT series

One Key feature for geostationary satellites is to have them distributed approximately uniformly along the equator, in order to have no gap between their respective observation disks in the tropics and mid-latitudes, so that they can provide a global, frequent (15-30 minutes) continuous data coverage, except for polar regions (~ pole ward 70° latitude). To meet the (current and future) different requirements, at least 6 operational geostationary satellites are needed, with an interval of ideally no more than 70° longitude for their positions along the equator. During recent decades the continuity of coverage over the Indian Ocean has been the main concern. Currently, the interval along the equator between GOES-W and MTSAT, 80 to 85°, is also larger than recommended. At present, to fill this gap

EUMETSAT drifting its older satellite towards the Indian Ocean and likely to stop this practice in near future.

Thus, the continuation INSAT program is required to fill the gap. Further, declaring it as an operational satellite system beyond 2024 and bringing it under WMO program not only make the visibility of our country and allows us to seamlessly get the other five satellite data sets . This is an absolute requirement for Indian Global NWP system.

Based on WMO guidelines the following sensors may be considered in the 4th generation INSAT program. For climatic change studies the satellite system should continue for a longer period (~2036).

1. High-resolution multi-spectral visible/infrared imagers.
2. Hyper-spectral infrared sounders
3. Lightning imagers/Mapper
4. High bandwidth for two communicating with Remote Observing platforms over land and ocean.
5. For Our Indian monsoon studies, 183 GHZ Microwave sounder.
6. Space Weather Monitor

High-resolution multi-spectral visible/ infra-red imagers.

The GEO imagers are used in several applications, primarily for nowcasting and Very Short Forecasting (VSRF). They are very useful for detecting dangerous weather phenomena and for monitoring their rapid development and motion. They observe the clouds (amount, type, temperature of the top). From tracking clouds and water vapour features on image time series, wind observations are derived: atmospheric motion vectors (AMVs). Surface temperature is derived over sea and over land, as well as atmospheric stability indices. The GEO imagery is also used to detect precipitation, aerosols, snow cover, vegetation cover, including Leaf Area Index (LAI) and Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), fires and volcanic ash. By 2024, an increased space/time resolution is expected for most of the GEO satellite imagers, and it is important to improve the data collection and the data exchange accordingly.

Hyper-spectral infrared sounders :

These planned sounders put the emphasis on high horizontal resolution (better than 10km), and on high vertical resolution (about 1km). Their main objective is to provide frequent information on the 3D structure of atmospheric temperature and humidity, for the whole Earth disk seen by the satellite (except in and below clouds). They will be used, together with the imagers, to produce high resolution winds (AMVs from clouds or water vapour features), to track rapidly evolving phenomena, and to determine surface temperature (sea and land). They are also designed to have an important role in the frequent observation of atmospheric chemical composition. The evaluation of the potential of hyper-spectral sounders on GEO was performed with the GIFTS and Hyper-spectral Environmental Suite (HES).

Lightning Imager/Mapper :

As lightning is strongly correlated with storms and heavy precipitation, another objective of a lightning mission is to serve as proxy for intense convection and convective rainfalls. It could serve as a proxy for diabatic and latent heating to be assimilated in NWP models. It will also help the generation of a complete lightning climatology, together with the surface-based lightning observing systems. Finally, lightning plays a significant role in generating nitrogen oxides, and lightning observations could be an important source of information for atmospheric chemistry models.
A lightning imaging mission is planned before 2024 for most of the geostationary satellite programs: the European MTG (LI: Lightning Imager), the American GOES, from GOES-R onwards (GLM: Geostationary Lightning Mapper), the Russian GOMS55 and the Chinese FY-456.

Meteorological Communication:
India is having ambitious atmospheric and oceanographic observation program to deploy remote observation platforms (data buoys, ARGOS, ARG, AWS etc.) over ocean and covering remote land areas. The transponders are required for disaster warning and rescue operations. So sufficient bandwidth for two way communication is required.

183 GHZ Microwave sounder:
183 GHz water vapour channel on-board of MT-Saphir found to be very useful in NWP community and many operational centers assimilating this data. The reviews of recently available/possible technologies now show that this channel is now possible at GEO platforms. For Monsoon studies this channel is very useful and hence should be considered.

Observational Accuracies and requirements:
The observational requirements for various meteorological applications are well discussed and prepared in detail under the aegis of WMO. The consensus of these discussions is available at https://www.wmo-sat.info/oscar/requirements The requirement of various observation parameters in terms of resolution, accuracies and application wise tabulated The target of accuracies observations from above sensors should be above the breakthrough achieved so far and should be to near the goals set as per that table.

Space Weather Watch
India by 2025 may enter into observing and forecasting Space Weather. A comprehensive space weather observation network, that includes ground-based and space-borne observatories will be set up. Both the ground-based and the space-based segments shall contain a combination of remote sensing and in-situ measurements. Further, it is required to develop a plan for maintaining and improving space weather observations of the plasma and energetic particle environment along the following priorities:
i. Maintain long-term continuity, and if possible improve the spatial resolution, of measurements at all altitudes from LEO through GEO orbits;
ii. Improve the sharing of existing and planned plasma and energetic particle measurements; (3) include energetic particle sensors on HEO satellites; and

iii. Conduct research to incorporate the plasma and energetic particle data into numerical models to give flux estimates at all locations where our satellites are in orbit.

Thus future INSAT series instruments like EXIS, SUVI, SEISS that are on GOES-R can be considered.

1.4.1 Challenges and Gap Areas

IMD faces various challenges and gaps in their efforts in meteorological satellite data monitoring for various weather events. These challenges can hinder their ability to provide timely and effective meteorological support to the environment. Here are some common challenges and gaps:

- Limited real time meteorological and air quality parameter observation for developing accurate early warning and decision support systems.
- Limited data availability for generation of cloud microphysics and precipitation product.
- Limited real time space-based instrument to monitor air pollutants across the nation.
- Need for effective capacity building to be provided to different sub- offices to delineate the precise weather information from the satellite imagery and respond to the satellite observation issues and forecast related challenges.
- Ineffective communication of environment-related impact to policy makers, regional/local governments, other decision-makers and public can lead to reduced awareness and preparedness.
- The long-term impacts of environment on climate change are complex and require on-going research and adaptation effort.
- Limited role in informing policies to mitigate, degradation and adapting to the inevitable changes due to climate change.
- Collaborating with national/international organizations and sharing data globally can be hindered by logistical challenges.
- Keeping pace with rapidly evolving technology in satellite meteorology is essential to providing accurate forecasts and warnings.
- Assessing the effectiveness of environmental services to public and gathering feedback for continuous improvement can be overlooked.

1.4.2 Short-term Vision (next two years)

❖ IMD should focus on improving the integration of satellite meteorology related data to create more accurate and timely meteorological forecasts and early warnings over India and neighbouring regions.

❖ Under the Earth Observation Systems (EOS) program of ISRO, during this period a new satellite GISAT-2 will be launched. It will carry new payloads with improved capabilities as compared to the existing satellites of INSAT-3 series. Data available from this satellite can be used for research work related to improvements in operational services of the Department. Hence there is a possibility of more improvements in this time frame.

- ❖ IMD can also invest in strengthening satellite related monitoring networks (air pollutants) and provide real-time air quality information to policy makers, regional/local governments, other decision-makers and public.
- ❖ IMD can develop and implement environment related advisories to protect vulnerable populations during extreme weather events, providing guidance on staying safe in all weather conditions.
- ❖ IMD can develop a public adaptable and valuable user-friendly tool for weather information based on satellite with accurate, reliable and scientific information for citizen of India.

1.4.3 Medium-term Vision (next ten years)

In this time frame, data from 4th generation of INSAT satellite series will be available. Based on the more advanced payloads being planned on this satellite series, we can certainly hope for lot more improvements in operational weather services of IMD

- IMD can develop comprehensive early warning and decision support systems to predict and respond to accurate weather forecast based on satellite meteorology and an integrated observation system over India and neighbouring regions.
- IMD can enhance the collaboration with national/international organizations and sharing satellite data to facilities the extreme weather events, ensuring they can continue to provide critical services during emergencies.
- IMD can invest more in research and innovation projects to better understand the complex relationship between weather and atmospheric chemistry, leading to the development of new technologies and strategies for environmental protection using AI/ML techniques.
- IMD can implement community resilience programs that empower local communities to prepare for and respond to meteorological related threats, including training for different agencies and first responders over India and RA-II regions.
- IMD can devise a framework for inclusion of improved cloud and rainfall microphysical parameter and utilization of space borne instruments for lightning detection.This is being planned under future INSAT-4 series of satellites.
- Utilization of hyper spectral sounder data for improved detection of vertical profile information. This is being planned under future INSAT-4 series of satellites.
- Improved usability of satellite products by end user as per their region of interest to be achieved by simple and easily understandable language. Perhaps intention is to emphasize need for practical oriented training where examples from real weather situations are taken to explain and demonstrate improved usability of satellite products. If so, it can be done by suitably redesigning the training programs.
- Monitoring of soil moisture and soil temperature product from Indian satellites.

1.4.4 Vision 2047

- ❖ Incorporation of CubeSat and nanosat technology for identification and tracking of individual extreme weather systems. Any technology that is best suited to meet all requirements of the users can be used.
- ❖ Availability of data from 5th generation of INSAT satellites with more advanced payloads which can detect environmental conditions even before formation of severe weather phenomenon. Such capability will increase the lead time for warnings.
- ❖ **The goals of the future INSAT/Polar series must be:**
  - Maintain continuous, reliable operational environmental, and storm warning systems to protect life and property
  - Monitor the Earth's surface and space environmental and climate conditions
  - Introduce improved atmospheric and oceanic observations and data dissemination capabilities (increased spatial, temporal and spectral resolution)
  - Develop and provide new and improved applications and products for a wide range of federal agencies, state and local governments, and private users.

❖ **Geophysical variables includes**:

Land – upper-air

- Upper-air synoptic and reference stations: Wind, temperature, humidity, pressure
- Remote sensing upper-air profiling remote stations: Wind, cloud base and top, cloud water, temperature, humidity, aerosols
- Atmospheric composition stations: Aerosol optical depth, atmospheric composition variables (aerosols, greenhouse gases, ozone, air quality, precipitation chemistry, reactive gases)

Land – surface

- Surface synoptic and climate reference stations : Surface pressure, temperature, humidity, wind; visibility; clouds; precipitation; present and past weather; radiation; soil temperature; evaporation; soil moisture; obscurations
- Lightning detection system stations: Lightning (location, density, rate of discharge, polarity, volumetric distribution)
- Application specific stations (road weather, airport / heliport weather stations, agromet stations, urban meteorology, etc.

Following Instruments may be proposed for future INSAT series of satellites in a single or multiple platforms based on their applications potential:

(1) 16-Channel Advanced Imager (similar to GOES-R-ABI, Himawari-AHI, MTG-FCI) with high spatial (1 km) and temporal resolution (< 15 minute)
(2) Hyper-spectral infrared sounder (similar to GOES-HES/GIFTS, MTG-IRS)
(3) Lightning Imager (similar to GOES-R-GLM, MTG-LI)
(4) Space weather monitoring Instruments (similar to GOES-R Space Environment In-Situ Suite SEISS)
(5) Microwave Radiometer for all weather capability

The benefits of the Advanced Imager (ABI, AHI, FCI):

- True colour imagery.
- Improved meteorological information about the rapid processes of the atmospheric water cycle — resulting in improved severe weather forecasts and early warnings.
- Improved aerosol retrievals, especially over land — important for volcanic ash and air quality monitoring.
- Daytime total column precipitable water, especially over land.
- Improved detection of very thin cirrus clouds, not currently seen.
- Improved retrieval of cloud microphysics.
- Improved fire detection and an increase in the quality of climate relevant products, through higher spatial resolution.

These applications can be developed based on data from the existing MSG-SEVIRI, GOES-ABI and Himawari-AHI.

Benefits of the Lightning Imager (LI/ GLM):

- Detecting, monitoring, tracking and extrapolating, in time, the development of active convective areas and storm life-cycles.
- Improving the quality of information essential for air traffic routing and safety — measurements of total lightning complementing global measurements of ground based systems, e.g. Arrival Time Difference network (ATDnet).
- Climate monitoring using total lightning information:
- Will help in assessing the impact of climate change on thunderstorm activity by monitoring and long-term analysis of lightning characteristics.
- Aid the study and monitoring of the physical and chemical processes in the atmosphere regarding nitrogen oxide (NOx), which plays key role in the ozone conversion process and acid rain generation.
- Providing information on a global scale with known error-characteristic, a prerequisite for assimilation in regional models to improve very short-range forecasts of convective events verification/validation of algorithms to nowcast (time and location) convective initiation.

Benefits of Advanced hyper-spectral Sounder (HES/ GIFTS/ IRS)

The new geostationary sounder service is a requirement of the Numerical Weather Prediction (NWP) community to deliver spectral information and/or retrieved products as horizontal and vertical gradients of humidity and temperature. The deduced information on atmospheric dynamics (e.g. vertically resolved ~2 km Atmospheric Motion Vectors (AMVs) surpassing present height assignment) will be invaluable to numerical models used in operational forecasting in the future. In particular, a breakthrough regarding a better precipitation forecast is expected by using this new information within these advanced models, coupled with advanced data assimilation capabilities.

- The 30-min repeat cycle over India will fill large spatial and temporal voids in the 12-hour standard radiosonde observations, and will provide time and space interpolation of moisture/temperature observations taken from the polar orbiting satellites.
- Derived information on tropospheric moisture structures and their variation in time is expected to lead to a better depiction of the hydrological cycle in models, potentially providing better precipitation forecasts.
- Three-dimensional (3D) information on humidity, temperature, and wind will support Nowcasting applications — giving improved warnings on location and intensity of convective storms.
- Information on vertically resolved atmospheric motion vectors with improved height assignment is beneficial for the tropical areas.
- The IRS will provide information to identify pre-convective situations supporting Nowcasting applications to forecast convective initiation.
- Forecasting pollution and monitoring of atmospheric minor constituents will be helped by estimates of diurnal variations of tropospheric contributions of atmospheric trace gases as O3 and CO.

Benefits of UVN Sounder

The primary objective of the UVN is to support air quality monitoring, and forecast over land region with a high revisit time (~1 hour or better). The primary data products will be ozone, nitrogen dioxide, sulphur dioxide, formaldehyde and aerosol optical depth.

Benefits of Space Environment Suite

Space Environment Suite monitors proton, electron and heavy ion fluxes at geostationary orbit. This is useful in assessing radiation hazards to astronauts and satellites and to warn of high flux events, mitigating damage to radio communication.

The parameters to be measured from satellite with required accuracies as well as resolutions.

Accuracy of Satellite Derived Met Parameters:

- T(p) within 1.5 C of raobs for Surfece to 10 hPa
- SST within 0.5 C of buoys (Day and Night)
- Q(p) within 10-15% of raobs Surfece to 300 hPa
- TPW with 2.5 mm of ground based MW
- TO3 within 30 Dobsons of ozone profilers
- LI adjusted 2 C lower (for better agreement with raobs) gradients in space and time more reliable than absolute
- AMVs within 5 m/s (upper trop) and 2-3 m/s (lower trop)
- CTPs within 50 hPa of lidar determination
- Geopotential heights within 20 to 30 m for 500 to 300 hPa
- For TC, Psfc within 6 hPa and Vmax within 10 kts (from MW ΔT250)
- Trajectory forecast 72 hour error reduction about 10%

1.4.5 Strategy

This comprehensive strategy aligns the efforts of IMD with the goal of safeguarding public in the face of meteorological-related challenges, helping to create a more resilient and informed society. It emphasizes collaboration, data-driven decision-making, and a proactive approach to emerging environmental assessments related to climate, and air quality.

- 100% use of all satellite data and derived products for day-to- day operations as well as for research , along with data from other platforms
- Improvements in NWP models and full use of satellite derived information for checking NWP products and modifying them whenever required
- Fully focused efforts to specifically tackle the challenging problems of Cloud bursts, lightning strikes, severe thunderstorms, Heavy Rainfalls of various categories and Flash floods etc. with the objective of minimizing death tolls due to such events (Long Term Goal for this will be Zero deaths)

1.4.6 Outcome

a) Improved Weather Forecasting and Accuracy

- **Real-time Data**: Satellites provide continuous, real-time data on weather patterns, such as cloud cover, temperature, rainfall, and wind patterns, enabling IMD to produce more accurate and timely weather forecasts for a range of time scales (short-term, medium-term, and long-term).
- **Early Warning**: Significant improvement in the department's ability to monitor and predict severe weather phenomena like cyclones, storms, heavy rainfall, and droughts, which will help to minimize loss of life and property.

b) Enhanced Disaster Management

- **Cyclone Monitoring**: India is prone to tropical cyclones, and satellite meteorology has been instrumental in monitoring and predicting the track, intensity, and potential landfall of cyclones. Enhanced usage of satellite data to issue advisories will help in better preparedness in cyclone-prone areas.
- **Flood Forecasting**: Satellite data helps monitor rainfall patterns, river flow, and the formation of water bodies, which are critical for forecasting floods. This will greatly enhance India's disaster preparedness and management, particularly during the monsoon season.
- **Drought Monitoring**: Satellite data assists in tracking drought conditions by observing rainfall deficits and changes in vegetation, allowing the IMD to issue warnings and plan for agricultural and water resource management.

c) **Monitoring of Environmental Changes**

- **Air Quality and Pollution**: Satellite meteorology has been used to track pollutants, dust storms, and air quality in urban and rural areas. This aids in public health monitoring and policy-making related to environmental issues.
- **Agricultural Monitoring**: Through satellite images, the IMD can track crop health, soil moisture, and land use, helping to predict agricultural yields and supporting farmers in decision-making.

d) **Improved Forecast Models**: The data provided by satellites is incorporated into weather models, helping the IMD to refine its prediction models and improve the spatial resolution of forecasts. This may result in more localized predictions, which are crucial for agriculture, aviation, and everyday life.

1.5 AVIATION WEATHER MONITORING NETWORK

1.5.1. Current status and major Achievements during the past 10 years

Aviation Weather Service is one of the department's major activities. Weather influences all phases of aircraft operations, and the safety and economy of air transport depend to a large extent on the availability of reliable current weather information and forecasts. IMD has state-of-the-art modern instruments at Airports. Digital Current Weather Indicating Systems (DCWIS) installations were started with 12 numbers in 2010 and 17 in 2017. Presently IMD installed 139 Digital Current Weather Indicating Systems (DCWIS) for observing Barometric pressure, wind speed and direction, Atmospheric Temperature and Humidity and Runway Visual Range (RVR). DCWIS are operational at 91 Public Airports. IMD had only 8 transmissometers in 2010 which increased to 14 in 2013. IMD inducted a Forwarded scatterometer-type RVR for aviation observation in 2021. Presently, IMD installed 170 RVR instruments in 79 Airports. An advanced state-of-the-art observation system AWOS is installed at 7 Airports and 11 more are under process of installation. IMD provides aviation meteorological services to 112 Airports.

As part of modernisation, the observation system for aviation safety was upgraded with advanced instruments in the Airports. 79 Airports are equipped with 170 RVR instruments with adequate redundancy. Most of the meteorological parks in the airports have redundant power supply and telemetry systems. This modernisation significantly improved the reliability of meteorological observation at Airports. As a result, there were no flight diversions due to meteorological instrument failure during winter seasons in 2022, 2023 and 2024. Another major achievement was enhancing the instrumental observations at Airports by installing DCWIS and phasing out of Digital Indicating Wind Equipment. 130 numbers of DCWIS are operational at 79 Airports. Yet another upgrade to meet ICAO standards, IMD installed these systems on frangible masts (120) as per ICAO standards in the last four years. 30-40% of these systems/materials are procured from Indian manufacturers to promote the Make in India programme.

Installation process of Heliport-AWOS (H-AWOS) at 10 heliports has been completed by IMD. H-AWOS performs the measurements of aviation meteorological parameters namely wind field, wind direction, temperature, humidity, pressure, present weather, visibility. In addition, it aids in data processing, auto-generation of meteorological reports, and their dissemination through suitable communication systems. Advent of Doppler Weather Radars (DWR) has revolutionized the weather forecasting and nowcasting. Observations from DWRs aid to improved aviation observations/forecasts/nowcast of aviation hazards. At present IMD has 39 DWRs (working in X, C and S band) installed across India

IMD is in the process of developing a Decision Support System (DSS) by combining the observed meteorological data of crucial meteorological parameters from runway, products from Doppler Weather Radars, data obtained through satellite imagers and sounders with the NWP model and synergizing all the information for improved forecasts and to give a reliable warning against severe aviation hazards. This will contribute to the safety and enhance operational efficiency at the airports. Development of an automated Decision Support System for trend forecast at IGI airport, New Delhi is in progress.

1.5.2. Challenges and gap areas

Despite the significant efforts made by the IMD to expand its Aviation Weather Monitoring network, there are still several gaps that impact the accuracy and timeliness of weather predictions. Some of these gaps include:

- Forecast and real-time observation of convection and associated hazards (e.g. thunderstorm, lightning, turbulence, wind shear, icing).
- Forecast and real-time observation of precipitation types products (e.g. freezing precipitation, hail, super cooled large cloud droplets).
- Real-time monitoring of significant weather (e.g. Lightning used to track storms, mountain waves). This is particularly relevant for aerodromes located in coastal areas or in mountainous areas.
- Forecasting and real-time monitoring of other aviation hazards (e.g. volcanic ash cloud, ash concentration) particularly over data sparse areas.
- Forecast of wind shear and turbulence around the runway.

1.5.3. Short term vision (next 2 years)

Augmentation of aviation observational network: IMD is planning to augment its observational capabilities by installation of 18 AWOS, 19 wind profilers, 30 microwave radiometers, 20 transmissometer RVR systems, 40 DCWIS and 100 FSM RVR systems. Typical operation of a wind profiler produces a vertical profile of the winds every hour from near the Earth's surface to above the tropopause. Integrated observations from proposed wind profilers, microwave radiometers and existing radiosonde data will be very crucial for the identification and forecast of the aviation hazards.

Advanced technology for high impact weather monitoring: IMD to strengthen the foundation of aeronautical meteorological technology to respond to high impact weather events. To construct a three-dimensional aeronautical meteorological observation system and optimize the operations

Monitoring of equipment health: Development of a software tool for monitoring the health of the aviation equipment. It will contribute significantly towards the improved data quality and data assurance.

1.5.4. Medium term vision (next 10 years)

- **Use of unmanned Aircraft Systems or Drones for improved aviation meteorological observations**: Drones created specifically for weather purposes will be flown into the boundary layer, which is the lowest part of the Earth's atmosphere. They will have sensors that can collect data on the temperature, humidity, and wind in the atmosphere, which will help to enhance weather forecasting models and closing the meteorological Data Gap in earth's lower atmosphere.
- **Development and use of all in one weather sensing solution for unmanned runways and landing zones**- Micro weather station with advanced sensors and software that will autonomously report a number of aviation meteorological parameters including cloud height, visibility, wind shear, convection etc.
- **Use of wind shear alert system**: An ensemble of automatic observation system, laser wind radar, boundary layer wind profile radar, Doppler weather radar and other detection equipment to explore real time monitoring of wind shear around the airports
- **Use of IoT devices for observations and forecasts:** A unique integration of advanced aviation equipment with IoT device for delivering real time smart data for improved observations and forecasts.

1.5.5. Vision for 2047

Observations and forecasts of aviation hazards are the lifeline of an effective aviation weather information system. A comprehensive analysis of the plans and opportunities for weather observations that would contribute to improved aviation weather services is essential. It has been observed that despite continual advances in observing and forecasting practices, weather/meteorological conditions – or rather, the intended or unintended penetration by aircraft into adverse conditions such as thunderstorms and strong gusty winds or wind shear – continue to be a contributory factor in aviation incidents and accidents such as loss-of-control in-flight, controlled flight into terrain and runway/taxiway excursions. These threats have increased over recent years, perhaps partly due to changing weather patterns (e.g. more intense, more frequent convective activity in some regions) and perhaps partly due to operational pressures. This is a situation that deserves increased attention by various stake holders if the threats posed by adverse weather/meteorological conditions are to be mitigated.

IMD will aim to achieve the following by the year 2047:

- By the modernization and augmentation of aviation Meteorological Equipment, higher-resolution and more-accurate observations of key atmospheric variables will be available. This includes installation of Automatic Weather Observing System (AWOS), wind profilers, ground based microwave radiometers. This will contribute in the improvements in observational capability. Detailed accurate information about aviation hazards with higher-resolution computer analyses and forecasts, including Aviation Gridded Forecast System, will produce detailed information of interest to aviation is essential.

- Development of a State-of-the-Art Support System for Aviation Safety with the advanced meteorological instruments and advanced forecasting tools for all the civil airports in the country. This will include inputs from augmented observational facilities at the airports and improved forecasting capabilities.

- Setting up an improved weather information system that could be available in the near future would allow pilots, controllers, dispatchers, and flight service specialists to access interactive, three-dimensional visualizations of critical aviation impact variables and decision aids that are specific to route, altitude, and decision aids that are specific to route, altitude, and aircraft type and that, in some cases, present alternate routes or altitudes for avoiding adverse weather. A critical feature of this system would be the capability for pilots and controllers to view the same information simultaneously and, when necessary, to communicate about avoidance strategies without having to discuss the weather because both parties would have the same accurate, timely, and relevant information.

1.5.6. Strategy

Vision -2047 can be achieved through the implementation of following:

A) Aeronautical Meteorological Information Service and Governance system

- Information and data exchange policies, quality management system standards and cost recovery principles
- Integration of meteorological information into air traffic management
- Service delivery development and best practice

B) Aeronautical Meteorological Hazards Prediction system development

- Innovation through scientific research and technological advancement
- Transition from research into operations
- Probabilistic and impact-based forecasting in support of aviation operations.

1.5.7. Outcome

By equipping all airports of the country with advanced instruments like wind profilers/ Doppler Lidars, Microwave Radiometers, Ceilometers, Wind Shear alert systems, RVR systems, DCWIS etc., IMD will be able to meet the demands of growing aviation sector leading to smooth aircraft and helicopter operations across the country.

1.6 ENVIRONMENT MONITORING NETWORK

1.6.1 Current status and major achievements during the past 10 years

IMD conducts monitoring and research related to atmospheric constituents that are capable of forcing change in the climate of the Earth, and may cause depletion of the global ozone layer, and play key roles in air quality from local to global scales. IMD also provides specific services to Ministry of Environment and Forest & Climate Change and other Government Agencies in the assessment of air pollution impacts. IMD contributes in the field of atmospheric environment to the World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) programme. The main objective of GAW is to provide data and other information on the chemical composition & related physical characteristics of the atmosphere and their trends, required to improve understanding of the behaviour of the atmosphere and its interactions with the oceans and the biosphere.

Ozone Monitoring Network:

National Ozone Centre of EMRC, IMD is designated as secondary regional ozone centre for Regional Association II (Asia) of World Meteorological Organization. The centre maintains a network of ozone monitoring stations including Maitri and Bharati in Antarctica:

- Total Columnar ozone measurement using Dobson spectrophotometer.
- Surface Ozone monitoring network
- Measurement of Vertical Distribution of Ozone.

Precipitation and Particulate Matter Chemistry Monitoring:

IMD is monitoring Precipitation Chemistry through a network of eleven stations since 1970s. The rainwater and particulate matter samples collected from these stations are analysed in Air Pollution Chemistry Laboratory at IMD, Pune which is equipped with Ion-chromatograph, UV-VIS Spectrophotometer, Semi-micro Balance, pH & Conductivity Meter, Ultra- pure Deionized Water Purification System. A new Atomic Absorption Spectrophotometer has been installed in the laboratory. The IMD laboratory participated in Laboratory Inter comparison Study 64 and 65 held in the year 2021 and 2022 organized by Quality Assurance/Science Activity Centre – Americas, one of five QA/SACs operating to ensure data quality and support science activities in the WMO GAW.

Aerosol Monitoring Network:

IMD has established Aerosol Monitoring Network covering different geographic regions of India. The Aerosol Monitoring Network consists of following sub-networks:

(i) **Sun-Sky radiometer Network:** Environment Monitoring and Research Centre, India Meteorological Department has established Aerosol Monitoring Network by installing sky radiometer at twenty locations. The network is used to measure optical properties of aerosols such as Aerosol Optical Depth, Single Scattering Albedo, Size Distribution, Phase Function etc.

(ii) Black Carbon Aerosol Monitoring Network: Black Carbon Monitoring Network of 25 stations for measurement of Spectral Aerosol Absorption Coefficient, Equivalent Black Carbon Concentration and bio-mass burning component is operational.

(iii) Multi-wavelength Integrating Nephelometer Network: IMD has established a network for measurement of aerosol scattering coefficient at twelve locations is operational at New Delhi, Ranichauri, Varanasi, Nagpur, Pune, Port Blair, Visakhapatnam, Guwahati, Kolkata, Jodhpur, Bhuj, Thiruvananthpuram.

(iv) Chemical Characterization of Aerosols: High Volume Samplers for collecting PM_{10}, $PM_{2.5}$ and Total Suspended Particulate Matter have been installed at Delhi, Ranichauri, Pune and Varanasi. The filter papers are being analysed for chemical characterization of aerosols at Air Pollution Section, O/o CRS, IMD, Pune.

Air Quality Forecasting and Research:

The latest version of Air Quality forecast model "System for Integrated modeLling of Atmospheric coMposition (SILAM v5.8)" has been operationalized for Indian region. Hourly air quality forecast for 96 hours of all criteria pollutants (PM10, PM2.5, O_3, CO, NO_2, SO_2 and other species) is being generated for the domain 60-100^{o}E, 0-40^{o}N. SILAM is coupled with hourly 3-km IMD-WRF meteorological forecasts model. A very high resolution city scale air quality model "**ENvironmental information FUsion SERvice (ENFUSER)**" has been also operationalized for Delhi. Hourly air quality forecast for 72 hours of all criteria pollutants (PM_{10}, $PM_{2.5}$, O_3, CO, NO_2, SO_2) is generated for the domain (28.362^{o}N-28.86^{o}N, 76.901^{o}E-77.56^{o}E) at 30m spatial resolution. The model uses and assimilates a large amount of Geographic Information System (GIS) data to describe the modelling area on a high resolution. This includes a detailed description of the road network, buildings, land-use information, high-resolution satellite images, ground elevation, population data, traffic density etc. SILAM and ENFUSER are developed under a collaborative project with Finnish Meteorological Institute.

IMD has started the air quality forecasting services, the Air Quality Early Warning System (AQ-EWS) was developed under the aegis of Ministry of Earth Sciences in 2018, jointly by Indian Institute of Tropical Meteorology (IITM), Pune, India Meteorological Department (IMD) and National Centre for Medium-Range Weather Forecasting (NCMRWF), Noida. This year the air quality forecast services were extended to other cities. As of now, the services are being provided to 41 cities.

The Early Warning System for air quality over Delhi consists of:

i. Real-time observations of air quality and other relevant meteorological parameters.
ii. Predictions of air pollutant concentration and air quality index for next 4 days and outlook for further 6 days. Prediction of contribution in air quality from biomass burning and dust is also provided.
iii. Air Quality forecast, Bulletin, Warning Messages and Alerts for pollution control authorities and general public.

iv. The system also has a feature whereby user can create possible emission reduction scenario to examine the possible projected improvement in air quality in Delhi for the next five days.

For other cities, prediction of air quality for next 3 days is provided.

1.6.2 Challenges and Gap Areas

IMD faces various challenges and gaps in their efforts in Environment Monitoring. These challenges can hinder their ability to provide timely and effective meteorological support to the environment. Here are some common challenges and gaps:

- An optimal environmental monitoring network should be comprehensive, flexible, and equipped with state-of-the-art technology. It should cover a broad range of parameters, ensure high data quality, and be capable of informing policies and actions that protect and manage natural resources effectively. By integrating diverse data sources, fostering collaboration, and maintaining adaptability, such a network can help meet the environmental challenges of today and the future.
- Limited air quality, Green House Gases (GHGs), black carbon, aerosol, solar radiation and aerosol chemical characterisation monitoring network data for developing of accurate early warning and decision support systems.
- Limited capacity and expertise within the meteorological departments to understand and respond to the environment monitoring issues and air quality forecast related challenges.
- Many bad air quality events are associated with stagnant conditions. Lack of predictability for such type of weather conditions.
- Ineffective communication of environment-related impact to policy makers, regional/local governments, other decision-makers and public can lead to reduced awareness and preparedness.
- The long-term impacts of environment on climate change are complex and require on-going research and adaptation efforts
- There is a lack of integrated studies on how physical and biological climate-related processes affect air pollution.
- Limited role in informing policies to mitigate air quality degradation and adapting to the inevitable changes due to climate change.
- Collaborating with national/international organizations and sharing data globally can be hindered by logistical challenges.
- Keeping pace with rapidly evolving technology and modelling advancements in air quality is essential to providing accurate forecasts and warnings.
- Assessing the effectiveness of environmental services to public and gathering feedback for continuous improvement can be overlooked.

1.6.3 Short-term Vision (next two years):

- Focus on improving the integration of environmental related data to create more accurate and timely air quality forecasts and early warning services over all non-attainment cities. The forecast accuracy will be improved by 20% for the base year of 2024.
- Augmentation of Solar Radiation Monitoring Network- 55 Nos. (with 5 BSRN stations)
- Commissioning of 10 Aerosol / Raman LiDARs, 20 Skyradiometers, Expansion of BC Aerosol Network (BC, EC/OC)- 25 stations, Ozonesonde Network 3 (India+ Maitri+ Bharati), Total Columnar Ozone (TCO3) - 5 Nos.
- Develop and implementation of coupled Chemistry-Atmosphere-Land (CAL) high resolution regional and local forecast modeling system for better prediction for weather, fog, dust and air quality.
- Launch public awareness campaigns to educate the policy makers, regional/local governments, other decision-makers and public about the environment impacts of weather and climate, including air quality, and climate change.
- Strengthening environment related monitoring networks and provide real-time air quality information to policy makers, regional/local governments, other decision-makers and public.
- Develop and implement environment related advisories to protect vulnerable populations during extreme pollutions and dust events, providing guidance on staying safe in all weather conditions.
- Develop a public adaptable and valuable user-friendly tool for air quality information with accurate, reliable and scientific information over citizen of India.
- Develop an emergency response unit with development of capabilities e.g. installation of various point source / area source air quality models, preparation of Standard Operating Procedure (SOP) etc. to provide guidance to the stake holders with prediction of the air quality impact zone of chemically disastrous events such as Bhopal Gas Tragedy, Jaipur Oil Depot Fire etc.

1.6.4 Medium-term Vision (next ten years)

- Develop comprehensive early warning and decision support systems to predict and respond to accurate air quality forecast and environment related issues over urban and rural area of India. The forecast accuracy will be improved by 40% for the base year of 2024.
- Expansion of Solar Radiation Monitoring Network - 100 Nos., Expansion of Precipitation Chemistry Network – 25 Nos.
- Commissioning of 30 Aerosol / Raman LiDARs, 50 Skyradiometers, Expansion of BC Aerosol Network (BC, EC/OC)- 50 stations, Ozonesonde Network 10, Total Columnar Ozone (TCO3)- 10 Nos, Expansion of GHG monitoring network- 03 background stations.
- Augmentation of supersite of air quality and fog chemical composition monitoring network for major cities of India: 4 Nos (Proton-Transfer-reaction-Time of Flight(PTR-TOF), CCN counters, Fog monitors, HTDMA, Aerosol Mass Spectrometers etc).
- Augmentation of urban and rural GHGs Emission Monitoring Network- 5 stations

- IMD can invest in strengthening air pollutants/GHGs monitoring using geostationary satellite and provide real-time air quality information to policy makers, regional/local governments, other decision-makers and public.
- Leverage current knowledge and prediction capabilities in air quality and climate and its change to identify low-hanging fruit to make tangible progress in addressing the impacts of climate extremes (e.g., heat waves, wildfires and droughts).
- Enhance the collaboration with national/international organizations and sharing data to facilities on the extreme pollution's events, ensuring them to continue to provide critical services during emergencies.
- Invest more in research and innovation projects to better understand the complex relationship between weather and atmospheric chemistry, leading to the development of new technologies and strategies for environmental protection using AI/ML techniques.
- Implement community resilience programs that empower local communities to prepare for and respond to environmental-related threats, including training for different agencies and first responders over India and RA-II regions.
- IMD would be a regional leader on environmental monitoring in line with GHGs initiative of WMO.

1.6.5 Vision 2047

- India would be a global leader in environmental monitoring and air quality warning services.
- The forecast accuracy will be improved by 80% for the base year of 2024.
- Expansion of Solar Radiation Monitoring Network - 200 Nos.
- Commissioning of 100 Aerosol / Raman LiDARs, 100 Skyradiometers, Expansion of BC Aerosol Network (BC, EC/OC)- 100 stations, Ozonesonde Network 20, Total Columnar Ozone (TCO3)- 20 Nos, Expansion of GHG monitoring network- 05 background stations.
- Augmentation of supersite of air quality and fog chemical composition monitoring network for major cities of India: 10 Nos (Proton-Transfer-reaction-Time of Flight(PTR-TOF), CCN counters, Fog monitors, HTDMA, Aerosol Mass Spectrometers etc).
- Augmentation of urban and rural GHGs Emission Monitoring Network- 10 stations
- Develop and implementation of coupled Chemistry-Atmosphere-Land-Ocean (CALO) high resolution regional forecast modelling system for better prediction for weather, fog, dust and air quality.
- New services like environmental impact on health, hydrology, power, transport, Urban, agriculture and many other sectors.
- Develop comprehensive long-term strategies to address the environmental impacts of climate change, including strategies to mitigate the spread of vector-borne diseases, address food and water security, and protect vulnerable populations.
- Enhance forge strong international partnerships to share data, knowledge, and best practices, creating a global network of meteorological and environmental organizations focused on improving global environment resilience.

- ❖ Invest more in cutting-edge technology and predictive models that can forecast environment-related with greater accuracy, allowing for more targeted interventions.
- ❖ Establish educational programs and workforce development initiatives to train the next generation of meteorologists and environment professionals who can work collaboratively to address environment-related challenges over India and RA-II regions.

1.6.6 Strategy

This comprehensive strategy aligns the efforts of IMD with the goal of safe guarding public in the face of environment-related challenges, helping to create a more resilient and informed society. It emphasizes collaboration, data-driven decision-making, and a proactive approach to emerging environmental assessments related to climate, air quality and the long-range transport of pollution between regions.

1.6.7 Outcome

Over all, the outcomes of IMD involvement in the environment monitoring, early warning and decision support system will help in getting accurate and reliable, science-based environmental information, development of products and decision support tools that are relevant and useful to policy makers, industry, regional/local governments and other decision-makers to plan for environmental degradation, climate variability and change and promotion of integrated service delivery at the national and regional scales.

- ❖ Ensure quantified high-resolution monitoring of environmental and impact of climate.
- ❖ Air quality forecast and early warning services for all cities and towns.
- ❖ Better informed decision making with IMD monitoring and predicted data and information could ensure early action leading to reduction of mortality and morbidity, better health for human and live strain, better productivity and economy, sustainable development.

Chapter 2 Numerical Weather prediction Modelling

2.1 NUMERICAL WEATHER PREDICTION (SHORT TO MEDIUM RANGE)

Vision: To be the global leader in cutting-edge numerical weather prediction, empowering humanity to proactively adapt to a changing climate and build resilient communities, economies, and ecosystems.

Mission:

- **High-Resolution Global Forecasting**
  - Develop and maintain a state-of-the-art numerical weather prediction system that provides high-resolution, global weather forecasts with frequent updates over every location across the globe with lead times of up to one month, supporting decision-making across various sectors.
- **Extreme Weather Prediction:**
  - Enhance prediction capabilities for extreme weather events, such as cyclones, heavy rainfalls, heatwaves, cold waves, droughts, thunderstorm & lightning and floods, with the goal of improving early warning systems and mitigating impacts.
- **Regional Precision:**
  - Customized accurate forecasts to provide region-specific information, including localized weather, and environmental data, to help communities make informed decisions regarding agriculture, water resources, energy, and disaster preparedness.
- **Impact-based forecast:**
  - Impact-based decision support services based on NWP models for the protection of life and property and enhancement of the national economy.
- **Machine Learning and AI Integration:**
  - Utilization of artificial intelligence and machine learning techniques to improve model performance, increase the accuracy of predictions, thus earlier prediction of events.
- **Advancing Scientific Understanding:**
  - Continuously push the boundaries of atmospheric and climate science to enhance our understanding of Earth's complex systems, enabling more accurate and precise predictions.
- **Public Engagement and Education:**
  - Promote public understanding of weather and climate science including NWP model products, ensuring that individuals are well-informed about the impacts of weather and climate on their lives and communities.

- **Global Collaboration:**
  - Collaborate with international partners, research institutions, and organizations to share knowledge, data, and resources, fostering a global network dedicated

to improving weather and climate prediction. Expand IMD Participation in global science initiatives.

- **Continuous Innovation:**
  - Encourage a culture of innovation, research, and development within the field of numerical weather prediction from time to time, staying at the forefront of emerging technologies and methodologies.
- **Environmental Sustainability:**
  - Lead by example in adopting sustainable practices and technologies to reduce the environmental impact of numerical weather prediction operations.
- **Climate Resilience and Adaptation:**
  - Integrate long-term climate projections into everyday weather forecasts, allowing governments, businesses, and individuals to make informed decisions that promote climate resilience and adaptation.
- **Data Accessibility and Openness:**
  - Foster a culture of data openness and accessibility, ensuring that weather and climate data are available to researchers, policymakers, and the public, facilitating innovation and collaboration.

2.1.1 Current status and Major Achievements

In 2006, IMD came under the umbrella of Ministry of Earth Sciences (MoES) with an ambition that Earth, Ocean, Atmosphere should be considered in an integral manner to improve the weather & climate services. No. of models increased for short to medium range forecast upto five days from a single model to 5 models through bilateral cooperation with countries like USA, UK, Europe, Japan and France. Monsoon Mission was taken up to improve the forecast in all spatial and Temporal scales. Workstation of 600 GB data exchange was established in 2009.The High Power Computing System (HPCS) was installed in 2010. Dynamical Statistical Modelling of tropical cyclones, Ensemble Prediction systems, Multi Model Ensemble were introduced during 2009-11.

The Ministry of Earth Sciences (MoES) installed high resolution computing system AADITYA (790 TF) in 2015. Subsequently the HPCS capability was further enhanced in 2018 with purchase of additional computing power of 6.8 Peta Flops. MoES installed two HPC's in 2018; One at NCMRWF, Noida (MIHIR) and other at IITM Pune (PRATYUSH). The MoES combined HPC capacity became 8.0 Peta Flops and India is placed at 4th Position after Japan, UK, USA for dedicated HPC resources for Weather/Climate services. The NWP division at IMD, New Delhi uses these HPC capacities for its operational needs. With the availability of HPCS by MoES, IMD gradually improved its modelling capability by running high resolution, regional, global and coupled models for catering to the need of forecasting at different time scales. There was the introduction of 12 km resolution global model in 2016, ensemble prediction model in 2018, extended range forecast system in 2017, dynamic MMCFS for seasonal forecasting in 2017 followed by multi model ensemble based seasonal forecasting model in 2021 were the major backbone improvement for weather & climate forecasting. Introduction of ocean atmosphere coupled cyclone specific model (HWRF) in

2017 & 2019. Meso-scale WRF Model with 3 km resolution in 2019. WRF Polar Model for Antarctica in 2019. Hy-SPLIT Model for trajectory forecasting in 2021. Nowcast model High Resolution rapid Refresh (HRRR) 2 km resolution in 2021 and Electrical WRF (EWRF) for lightning prediction in 2022, integrated urban flood warning system in 2020, South Asia Flash Flood Guidance system in 2020, Severe Weather Forecasting System in 2016 were the major interventions for regional and location specific forecasting.

On September 26, 2024, the Hon'ble Prime Minister launched the MoES High-Performance Computer (HPC) systems at two critical institutions: the Indian Institute of Tropical Meteorology (IITM) in Pune, which houses Arka, and the National Centre for Medium-Range Weather Forecasting (NCMRWF) in Noida, which operates Arunika. These systems are the result of a significant collaboration between MoES and Eviden, a leading Atos business in advanced computing. With a contract valued at around $100 million, Eviden has built two state-of-the-art supercomputers based on the Bull Sequana XH2000 architecture, which will deliver a combined computing power of up to 21.3 petaflops. Arunika, located at NCMRWF, will provide 8.3 petaflops for weather and climate modeling, integrating 2,100 CPU nodes, 18 GPU nodes, and 2PB all-flash and 20PB disk-based storage. Meanwhile, Arka at IITM will focus on atmospheric and climate research, offering 13 petaflops of computing power, with 3,000 CPU nodes, 26 GPU nodes, and 3PB all-flash and 29PB disk-based storage. These advancements represent a threefold increase in computing capabilities of MoES compared to the existing infrastructure at NCMRWF (2.8 petaflops) and IITM (4 petaflops). The augmented systems will enhance India's ability to improve weather predictions, climate research, and real-time data processing, thus supporting disaster management, agriculture, environmental monitoring, and overall national preparedness for climate challenges. Additionally, the ongoing expansion of the observational network across the country, combined with these high-performance computing facilities, plays a crucial role in advancing weather and climate research in India.

1. **IMD-GFS for Medium Range forecasting**

The GFS model was initially implemented at IMD in 2010 with T382L64 resolution and the system subsequently upgraded to T574L64 in 2012. During this phase 3D Variational assimilation system are used and system upgraded to hybrid 3D Ensemble variational assimilation system in 2016 with 80 member T254 ensembles. System upgraded with T574 ensembles in 2016 and hybrid 4D Ensemble variational assimilation system implemented in 2017. IMD has been operationally producing forecasts at T1534 resolution using the IMD-GFS model for 10 days since 2016. In 2018, model was upgraded from spectral based sigma framework to NOAA Environmental Modelling system (NEMS) framework with a modular structure for all NCEP models and associated changes in land surface, cumulus parameterization schemes and introduction of Near-Surface Sea Temperature (NSST). GFS data assimilation system employs hybrid 4D Ensemble Variational (EnsVar) assimilation system with 80 member EnKF ensembles. In 2022 operational GFS model micro-physics scheme is upgraded with the changes implemented by IITM. One of the major drawbacks of the model is dry bias and low skill in prediction of heavy rainfall events. Another drawback of the system is large bias in temperature forecasts over some particular regions. The IMD-GFS global model is run with a ~12 km horizontal resolution four times a day to generate (i) 10-day forecast based on the 00 UTC and 12 UTC runs, and (ii) 5-day forecast based on the 06 UTC and 18 UTC runs.

2. IMD-GEFS for Medium Range forecasting

GEFS model operationally implemented at IMD in 2016 with 21 ensemble members at T574L64 resolution and was upgraded to T1534L64 resolution in 2018. In 2018 again the model was upgraded to the NEMS framework with the introduction of NSST. At present the GEFS model is providing forecasts at T1534L64 resolution for 10 days. In this ensemble system, initial conditions are produced by combining Ensemble Kalman Filter (EnKF) based ensemble forecasts from previous cycle and current cycle GFS analysis. Here ensemble forecast perturbations are created from EnKF ensembles and converted to analysis perturbation using Ensemble transform rescaling (ETR) techniques combined with GFS deterministic analysis from the current cycle. Since June 2018, the IMD-GEFS global ensemble model (with 21 members) has been run twice a day at a ~12 km horizontal resolution, based on the 00 UTC and 12 UTC cycles, to generate a 10-day forecast. Until 2022, it was the highest-resolution global ensemble model operationally run in the world.

3. Dynamical-Statistical modelling for Tropical Cyclone Forecasting

The Cyclone Genesis Potential Parameter (GPP) based on GFS model, Multi-Model Ensemble (MME) technique for cyclone track prediction and Statistical Cyclone intensity Prediction (SCIP) & decay models for tropical cyclone intensity forecast are run to provide objective guidance for tropical cyclone forecasting.

4. IMD-HWRF-HYCOM/POM coupled model

IMD-HWRF ocean coupled model is triple nested (18x6x2km) and runs 4 times a day over North Indian Ocean (NIO) to give 5 day forecast products including tropical cyclone track and intensity forecast at RSMC regions. It is the only regional ocean coupled modelling system being run operationally in India for Tropical Cyclone forecasting. The coupled HWRF system with both ocean models, viz., POM-TC and HYCOM was operational simultaneously and model guidance products were provided from both the variants. The HWRF modelling system skill is further improved by improving data assimilation capabilities by ingesting satellite data (INSAT-3D/3DR) into the system. At present, the HWRF modelling system is capable of tracking and forecasting only one tropical cyclone and thereby efforts are required to have basin scale capability whereby the model could also track more than one tropical cyclone simultaneously removing the requirement to run the model separately for each cyclone.

5. Regional Models for short range forecast

IMD-WRF is a cloud resolving Mesoscale model, run at 3 km resolution four times a day covering the entire Indian region. Forecast products are available for the next 3 days. IMD-

WRF model was initially run-in nested domain configuration with 9 km horizontal resolution covering the entire India, Bay of Bengal, Arabian Sea and SAARC countries and inner domain at 3 km horizontal resolution over India. During 2019-20 the model was transitioned to a single domain covering the entire India, SAARC countries, Bay of Bengal, Indian Ocean at 3 km horizontal resolution. The model was also made operational to run four times a day based on 00,06,12&18 UTC from two times a day. New products with increased temporal resolution (hourly) have been added for the forecasters. The model data assimilation feature was also transitioned from WRFDA based system to regional GSI based data assimilation system (3DVAR).

6. IMD-HRRR model for Nowcast Applications

The High Resolution Rapid Refresh Model (HRRR) is cloud resolving non- hydrostatic model which is run every hour at 2 km resolution giving forecast for next 12 hours using the observations available from Doppler Weather radars every 10 minutes. IMD established the IMD-HRRR modelling system in January 2021 in collaboration with Space Applications Centre, Indian Space Research Organisation (SAC-ISRO).The IMD-HRRR system (based on WRF-ARW) is a real-time 2-km spatial resolution, hourly updated, cloud-resolving, convection-allowing atmospheric model. At present, the model is updated every hour using the radar wind (radial), radar reflectivity and surface observations (prepbufr) data. The forecast for 12 hours lead time is made available to the forecasters at every 2-hour interval. IMD-HRRR model system domain extends for the entire Indian mainland by dividing it into three high-resolution domains viz. Northwest (NW), East & Northeast (E&NE) and South Peninsular (SP) India domain.

7. IMD-EWRF model for Nowcast Applications

The Electric WRF is a 3 km mesoscale modelling system, where a dedicated Bulk Lightning module has been incorporated to calculate the parameters like electric field of cloud. Another important component of this modelling system is the lightning data assimilation; first time in India, lightning data has been assimilated into the EWRF modelling system through nudging. Presently, the model is operational all over the country and IMD forecasters are using it on a daily basis. The model is run twice a day (00 UTC and 12 UTC) and each time the latest lightning data are assimilated for better initial conditions. Four specialised products are generated in every hour including, 1) Lightning Flash Density ii) Max Reflectivity iii) Rainfall iv) Significant Hail Parameters.

8. Multi-model ensemble/dynamical statistical model for city, district, met-subdivisions, coastal regions, river basins and marine area weather forecasting

Multi-model ensemble based forecasts for Indian cities, districts, meteorological subdivisions, Indian coastal regions, marine areas and river basins are generated from seven global models viz. viz. Global Forecasting system (GFS) runs at IMD and National Centres for Environmental Prediction (NCEP), Global Ensemble Forecasting System (GEFS) runs at IMD, Unified model (NCUM) and Ensemble prediction System (NEPS) runs at National Centre for Medium Range Weather Forecasting (NCMRWF), Integrated Forecasting System runs at European Center for Medium Range Weather Forecasting (ECMWF), and Global Spectral Model (GSM) runs at Japan Meteorological Agency (JMA). The MME based forecast products are also generated for entire RSMC domains, river basins, sea areas, fleet areas etc. These forecast products are also used for automation of different weather bulletins. CMC and UKMO

The IMD (India Meteorological Department) signed an MoU with ECMWF (European Centre for Medium-Range Weather Forecasts) in 2021 to use ECMWF's IFS-TC-Tracker source code for IMD's operational Tropical Cyclone Track forecasts. IMD utilizes this TC-tracker to process different global model forecasts to generate individual model TC-tracker line plots and to calculate multi-model means. The system incorporates nine different global models: IMDGFS, NCUM-G, ECMWF, NCEP, CMC (Canadian Meteorological Centre), UKMO (UK Met Office), IMDGEFS-Mean, NEPS-Mean, NCUM-R, and HWRF for generating TC-tracker forecasts over the North Indian Ocean (Bay of Bengal and Arabian Sea). Additionally, a provision has been made for forecasters to assign dynamical weights to individual global and regional model forecasts during each cycle of tropical cyclone forecasts. A dynamically weighted multi-model mean is generated through the Decision Support System (DSS) to determine the final track movement, landfall location, and timing.

9. Mausamgram

In pursuit of the vision "Har Har Mausam, Har Ghar Mausam," the Indian Meteorological Department (IMD) has unveiled a groundbreaking webportal named "mausamgram." "In this portal, 'mausam' refers to weather, and 'gram' means village. Here, you can access weather forecasts tailored to every village, providing localized and accurate information." This platform empowers the common person to access detailed weather forecasts for their chosen location with a simple click on the map including ocean. The forecasts are available on an hourly, 3-hourly, and 6-hourly basis upto next 10-days, covering crucial weather parameters such as rainfall, temperature, humidity, wind speed, and cloud cover. The module is developed using stateof-the-art tools and technologies, ensuring accuracy and reliability. To enhance user convenience, the "mausamgram" module offers several options for accessing forecasts: (1). Coordinate-Based Information Retrieval: Users can input specific coordinates to obtain precise and personalized weather forecasts. (2). Location Search: The module supports location-based searches where users can type in the name of their desired location. Once selected, the module provides a detailed forecast for that specific area. Search option embedded within map also. (3). Block-wise Forecast: Users have the option to search by block, enabling them to select their respective block and access tailored weather forecasts. (4). Pincode Selection: By selecting the pincode, users can obtain forecasts customized for their area of interest. (5). GPcode / GP Name Selection: By selecting the pgpcode, users can obtain forecasts customized for their Gram Panchayat of interest. Additionally, the module boasts an interactive interface presenting weather parameters in chart format, allowing users to zoom in and out for a more detailed analysis.

Comparison of performance of different global Numerical Weather Prediction (NWP) models is a common practice in meteorology and atmospheric science. The 500 hPa geopotential height is often chosen as a standard level for such comparisons because it represents an important level in the atmosphere, typically found in the mid-troposphere and less affected by surface variability. Anomaly correlation coefficient (ACC) greater than 0.6 for 500 hPa geopotential height indicates that the model is skilful in the context of evaluating the performance of numerical weather prediction (NWP) models. Over northern hemisphere, most of the global models including GFS has a ACC greater than 0.6 up to a lead time of 8 days, whereas ECMWF models has a better skill up to day 9 (Figure 1). Over tropics, most of the NWP models have better skill up to day 9.

India, through its GFS (India) and NCUM models, demonstrates that it stands on par with other leading global agencies in the realm of Numerical Weather Prediction (NWP). Both Indian models feature a competitive spatial resolution of 12 km, aligning closely with the standards set by international centers such as ECMWF, GFS (USA), and UKMO. However, the spatial resolution of GFS (India) is poorer than that of ECMWF, UKMO, and CMA (China). Additionally, the vertical resolution of GFS (India), at 64 layers, is the lowest among all global models, and its forecast period of 10 days is six days less than that of ECMWF and GFS (USA). Despite these differences, the GFS (India) model updates four times daily, showcasing its robustness and reliability. NCUM further enhances India's standing with a higher vertical resolution of 70 layers. These capabilities, along with frequent updates and sophisticated forecasting, highlight India's significant advancements and alignment with the standards of prime global agencies in meteorological predictions. A comparison of different global models with its specifications in terms of spatial resolution, vertical resolution, forecast days, and update frequency is given in Table 1.

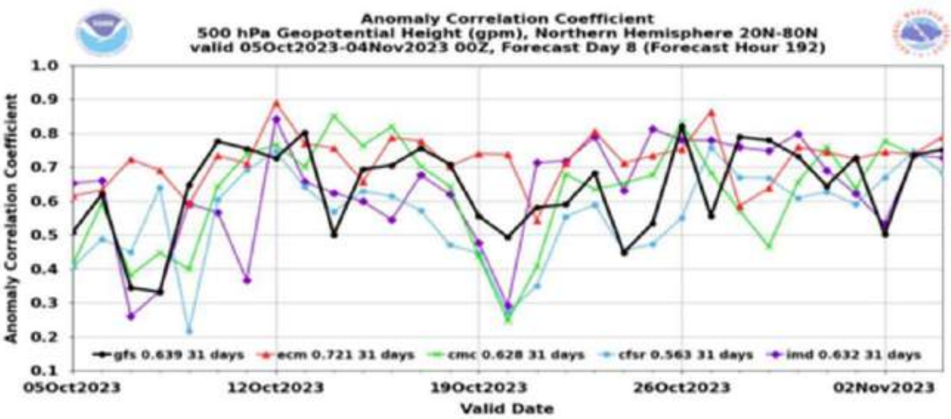


Figure-1: Anomaly correlation coefficient (ACC) in 500hPa geopotential height over Northern hemisphere for different global models up to a lead time of 8 days

SN	NWP Center	Spatial Resolution	Vertical resolution	Forecast Days	Frequency/day
1	GFS (INDIA)	12 km	64 layers upto Mesopause	10 day	4
2	NCUM (INDIA)	12 km	70 layers upto Mesopause	10 day	2
3	ECMWF	9 km	137 layers upto Mesopause	16 day	4
4	GFS (USA)	13 km	127 layers upto Mesopause	16 day	4
5	JMA GSM (JAPAN)	13 km	128 layers upto Mesopause	10 day	4
6	UKMO (UK)	10 km	70 layers upto Mesopause	10 day	4
7	CMA (China)	10 km	70 layers upto Mesopause	12 days	4

Table 1. A comparison of different global models with its specifications

India, through its GEFS (India) and NEPS (India) models, demonstrates its capability in ensemble forecasting, positioning itself alongside other leading global meteorological agencies. Both models feature a spatial resolution of 12 km, which is poorer than that of ECMWF (9 km), though still consistent with many international standards. The vertical resolution of GEFS (India), at 64 layers, is the lowest among all global ensemble models, in contrast to ECMWF's 137 layers and JMAEPS (Japan) with 128 layers. The ensemble members for GEFS (India) and NEPS (India) are 21 and 22, respectively, which is the lowest compared to other modeling centers, such as ECMWF with 50 members and JMAEPS with 33 members. Both Indian models provide a 10-day forecast period, which is six days less than that of ECMWF and GEFS (USA), offering 15 and 16 days, respectively. Despite these differences, the frequent updates and the inclusion of a substantial number of ensemble members reinforce India’s advancements in ensemble weather forecasting, aligning closely with the standards of premier global meteorological centers. A comparison of different global ensemble models with its specifications in terms of spatial resolution, vertical resolution, forecast days, and number of ensembles are given in Table 2

SN	NWP Center	Resolution	Vertical resolution	Forecast period	Members
1	GEFS(INDIA)	12 km	64 layers upto Mesopause	10 day	21
2	NEPS(INDIA)	12 km	70 layers upto Mesopause	10 day	22
3	ECMWF	09 km	137 layers upto Mesopause	15 day	50
4	GEFS(USA)	25 km	127 layers upto Mesopause	16 day	30
5	JMAEPS(JAPAN)	20 km	128 layers upto Mesopause	14 day	33
6	UKMO(UK)	17 km	70 layers upto Mesopause	15 day	24
7	CMA (China)	32 km	70 layers upto Mesopause	12 days	25

Table 2: A comparison of different global ensemble models with its specifications

2.1.2 Challenges and Gap areas

a. **Data Assimilation**: Accurate initialization of NWP models is crucial. Incorporating observational data into the model (data assimilation) is challenging due to the assumptions in the methodology, data quality, coverage, and the need for advanced techniques to merge diverse data sources.
b. **Model Resolution**: Achieving higher spatial and temporal resolutions is an ongoing challenge. High-resolution models require substantial computational resources, and there's a need to strike a balance between accuracy and computational efficiency.
c. **Parameterization**: Many physical processes at small scales (e.g., turbulence, convection) cannot be explicitly resolved in NWP models due to limited computational resources. Developing accurate parameterization schemes for these processes is an ongoing challenge.
d. **Model Physics**: The representation of physical processes in NWP models, such as cloud microphysics and land surface interactions, is a challenge. These processes have a significant impact on weather and climate, and improving their representation is crucial.
e. **Model Uncertainty**: NWP models inherently have uncertainty, and quantifying and reducing this uncertainty is a challenge. Ensemble forecasting techniques are used to address this, but further improvements are needed.
f. **Data Gaps**: There are regions with sparse or no observational data, especially over oceans and southern hemisphere. Observations are also limited over remote or developing areas. Filling these data gaps is essential for accurate global and regional forecasting and also fore model verification.
g. **Extreme Weather**: Predicting extreme weather events, such as cyclones, heavy rainfall, heat waves, cold waves, and flash floods, remains a significant challenge due to their complexity and rapid development. Location specific forecast also remains a challenge.

h. **Climate Change Integration**: NWP models need to be adapted to account for long-term climate change and its effects on weather patterns, which requires the development of climate-resilient forecasting techniques.
i. **Computational Resources**: Running high-resolution NWP models requires substantial computational power.
j. **User Engagement**: Bridging the gap between NWP scientists and end-users (e.g., forecasters) to effectively communicate forecast uncertainty and improve decision-making remains a challenge.
k. **International Collaboration**: Global weather systems are interconnected, and international cooperation is necessary for data sharing, model development, and forecasting accuracy. Ensuring effective collaboration can be challenging.
l. **Model Verification**: Developing the meticulous methods for model verification and validation is essential to assess the accuracy and reliability of NWP models.
m. **Post processing**: There is a huge scope for post-processing of NWP model products to minimize the error & biases and also develop the required products as per the requirement of forecasters.

2.1.3 Short Term vision (for next two years)

Statistical post processing of NWP products to meet the requirement of forecasters.

To improve the performance of individual NWP models by developing a platform for real-time bias and error evaluation, along with monthly and seasonal bias and error assessments, to enhance the MME technique for weather forecasting. The mission is given below.

1. **High-Resolution Forecasting (Global and Regional scale):** Implement high-resolution numerical models tailored to the diverse geographical and climatic conditions across India. This will provide more precise and localized weather forecasts.

2. **Model Physics:** Fine-tuning and improving model physics play a pivotal role in enhancing NWP model forecasts for a wide range of meteorological phenomena, including monsoons, cyclones, thunderstorms, hailstorms, floods, heatwaves, cold waves and more. Accurate prediction of the genesis of monsoon depression and its life will help agriculture, water management, and disaster preparedness. This regional customization will also allow better forecasting.

3. **Capacity Building:** Invest in training and capacity building for meteorologists, and researchers, to enhance their skills in utilizing advanced numerical prediction tools, and also in different post processing techniques.

4. **Model Evaluation:** Compare NWP model outputs to the observational data to assess the model's biases and errors spatially and temporally (For all available NWP models). This will help the forecasters to issue more accurate weather forecasts.

5. **Bias Identification and removal:** Identify systematic biases in the available NWP model outputs. These biases may include errors in temperature, precipitation, wind speed, humidity, and other meteorological variables. Further, various bias correction methods can be applied to adjust the NWP model outputs.

6. **Temporal and Spatial Considerations:**

   Apply bias corrections considering the temporal and spatial scales relevant to the specific weather variables and forecasting tasks. Different biases may be present at different times and locations.

2.1.4 Medium-term Vision (For next 10 years)

- Implementation of high-resolution (5-6 km) global models and kilometre to sub-kilometre resolution regional models
- Implementation of application specific regional models like WRF-Hydro, WRF-Fire, etc.
- Implementation of regional Ensemble prediction models
- At least 40% improvement in the NWP model forecast accuracy
- User enabled products and platform

The mission to reach this goal is given below

- **Upgradation of High-Performance Computing and storage facilities:**

Meeting society's need for high accuracy weather forecasts delivered in a timely manner will require an increase in high-performance computing and data management resources (fig. 2) by a factor of 100 to 1,000 – which is generally called the 'exascale computing'. To make this possible, weather and climate prediction is undergoing one of its biggest revolutions since its beginnings in the early 20th century. This revolution encompasses a fundamental redesign of mathematical algorithms and numerical methods, the adaptation to new programming models, the implementation of dynamic and resilient workflows and the efficient post-processing and handling of big data.

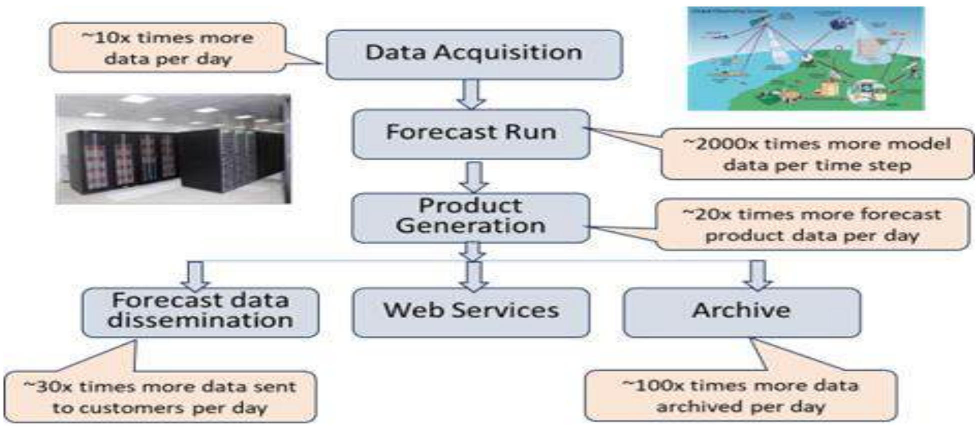


Fig. 2: Flow Diagram of HPCS

The next ten years are expected to see a dramatic increase in data volume across the IMD forecast production chain. The above diagram shows the increase in data volume across the NWP production chain.

Easy to use and interpret NWP model products across the community:

In the next ten years, the awareness about weather forecasting and its applications will increase dramatically across the community and subsequently the user access to NWP products and forecasts. Hence, it is very important to develop the NWP forecast products user friendly and self-explanatory, such as:

a. Forecast products should be attractive 3-D animated graphics

b. Forecast products should be self-explanatory graphics with overlapping exposures, such as Airport, Railway station, Bus Stop, School, shopping complex, housing, hospital, etc

c. Forecast web portal should have location specific auto alert and warning system during extreme weather events such as tropical cyclone, thunderstorm, dust storm, flash flood etc. for users

d. Forecast web portal should have enabled with location specific audio warning system with regional languages for users

- **Integration of AI & ML to NWP models for better microphysical parameterizations for cloud resolving model:**

The existing single moment and double moment bulk microphysics parameterizations are still not up to the mark while simulating the rainfall associated with tropical cyclone, monsoon and thunderstorm events over a tropical climate region. Hence, in the future multi-moment bulk-microphysics parameterizations need to be developed to address the existing uncertainties on tropical region rainfall simulation. Machine learning techniques are expected to have an increasing role in developing multi-moment bulk-microphysics parameterizations from detailed cloud model simulations with explicit bin and/or super-particle microphysics, and their coupling with cloud dynamics. Advances in machine learning and high-performance computing may transform the development of microphysical parameterization, its coupling with other processes such as turbulence, and entrainment-mixing mechanisms. More advanced machine learning methods that include a notion of time derivatives, therefore, have the potential to overcome these problems.

- **Enhancing Medium-Scale Forecast Accuracy in NWP Models**

As computational capabilities continue to evolve, higher-resolution models, improved parameterizations, and innovative data assimilation techniques will play pivotal roles in enhancing forecast accuracy. The integration of Earth system components and coupled modelling approaches will enable more comprehensive and skilful predictions, especially for phenomena such as tropical cyclones and monsoons. Leveraging the power of big data, artificial intelligence, and machine learning, these models will provide critical insights into long-range climate change and extreme weather events. These are expected to result in better forecasts characterized by higher skill scores.

- **High-Resolution Regional Forecasting system for short to medium range weather forecasting:**

Implement high-resolution (5-6 km) global and regional (1km/<1km) numerical models (including ensemble systems) across India. This will provide more precise and localized weather forecasts at village and panchayat levels with high temporal resolution.

IMD will continue to advance its global and mesoscale modelling development and application with GFS and WRF model in the areas that require Earth science information, such as

a. Renewable energy prediction (wind, solar, and hydro)

- WRF-Solar was developed to optimize prediction of global horizontal and direct normal irradiance for use in predicting generation of solar power.
- WRF-LES (large eddy simulation) has been enhanced and adapted for use in wind energy applications and supporting UAS operations.

b. Aviation hazard prediction (turbulence, icing, convection, lightning)

- Cloud Microphysics parameterizations are critical for improving predictions of super-cooled liquid within storms as well as the radiative impacts of clouds and aerosols.
- Continuous research and academic and industry collaboration to develop suitable physical parameterizations for tropical region-specific weathers and extremes

c. Hydrometeorology prediction (cloud physics, precipitation processes, land surface/hydrological modelling, long-term continental-scale hydromet simulations using convection-permitting models)

- WRF-Hydro an extensible multi-scale & multi-physics land-atmosphere modelling capability for conservative, coupled and uncoupled assimilation & prediction of major water cycle components such as: precipitation, soil moisture, snow pack, ground water, streamflow, and inundation.
- WRF-Hydro has capability for accurate and reliable streamflow prediction across scales (from 0-order headwater catchments to continental river basins and from minutes to seasons)
- WRF-Hydro model output can supply forecasters and decision makers with locations and timing of rapid river stage increase as well as the duration of high waters and inundation while accounting for landscape dynamics essential

to flood risks such as land cover change as well as the control effects of infrastructure such as dams and reservoirs.

d. Wild fire behaviour prediction (coupled atmosphere-fire behaviour modelling, fuel moisture content)

- WRF-Fire, has been significantly enhanced to model wild fire progression and interaction with the atmosphere to provide information for fighting wildfires

e. Agriculture management under changing climate scenario

- WRF-Crop couples the Noah-MP photosynthesis and soil hydrology components with agriculture management models (crop-growth, irrigation, tile drainage), and develops high-resolution continental-scale datasets required by executing WRF-Crop

- **Improved website for NWP product dissemination:**

Improving a Numerical Weather Prediction (NWP) website is essential to enhance user experience and provide valuable weather information to a wide range of users. Here are some key aspects to consider when improving an NWP website:

1. **User-Centred Design:**
    - Ensure that the website's design is user-friendly and intuitive, catering to both novice users and weather experts. Conduct user testing to gather feedback and refine the design.
2. **Responsive Design:**
    - Make the website responsive so that it functions well on various devices, including desktop computers, tablets, and smartphones. Mobile optimization is increasingly important for users on the go.
3. **Improved Data Visualization:**
    - Enhance data visualization with interactive and customizable maps, graphs, and charts. Provide overlays of various weather variables, such as temperature, precipitation, wind speed, and more, to give users a comprehensive view of the weather.
4. **High-Resolution Graphics:**
    - Offer high-resolution graphics for visualizing weather data. High-quality visuals are crucial for accurate interpretation of forecasts and models.
5. **Customizable Dashboards:**
    - Allow users to create personalized dashboards where they can select specific weather parameters, locations, and time frames for easy access to the information most relevant to them.
6. **Improved Search and Navigation:**
    - Implement robust search functionality and intuitive navigation menus to help users quickly find the weather information they need. Include auto-

suggestions for location names and features like bookmarks for saving favourite locations.

7. **Forecast Accuracy Metrics:**
   - Display forecast accuracy metrics to provide users with information about the reliability of the NWP model, including bias, root mean square error, and skill scores.
8. **Hourly and Long-Range Forecasts:**
   - Offer both short-term (hourly) and long-range (weekly or monthly) forecasts to cater to various user needs, from daily planning to climate monitoring.
9. **Weather Alerts and Warnings:**
   - Implement an alert system for severe weather conditions, such as cyclones, heavy rain, heat wave, cold wave, floods, etc. to alert the forecasters.
10. **Educational Resources:**
    - Include educational materials and explanations of weather phenomena for users who want to understand the science behind the forecasts.
11. **Multilingual Support:**
    - If applicable, provide support for multiple languages to make the website accessible to a broader audience.
12. **APIs and Data Access:**
    - Offer APIs (Application Programming Interfaces) to allow developers to integrate weather data into their applications. Ensure that the website provides access to raw data for researchers and experts.
13. **Performance Optimization:**
    - Optimize website performance to ensure fast loading times, especially for users with slower internet connections.
14. **Feedback Mechanism:**
    - Include a feedback mechanism, such as a contact form or user forums, for users to report issues, suggest improvements, or seek assistance.
15. **Accessibility Compliance:**
    - Ensure that the website complies with accessibility standards (e.g., WCAG) to accommodate users with disabilities.
16. **Regular Updates and Maintenance:**
    - Commit to regular updates and maintenance to keep the website current and functional, addressing bugs and incorporating user feedback.
17. **Security Measures:**
    - Implement security measures to protect user data and ensure the website's resilience against cyber threats.

2.1.5 Vision for 2047

- Integration of atmospheric, oceanic, and land surface processes into a high-resolution coupled model system, replacing the current standalone global forecasting system, to enhance forecast accuracy.

- Integration of advanced machine learning and AI systems for real-time processing of observational data (eg: Multisource Data Fusion, Automated Anomaly Detection,) for better initial condition of the atmosphere.
- Incorporating AI/ML models to analyze uncertainties in the subgrid-scale processes and identify complex patterns and dynamics that traditional parameterizations may miss, leading to improved model performance.

The mission to achieve the same is:

- **Migrating from Physical HPC servers to Cloud Computing:**

Weather forecasting and climate modelling are two of the world's most computationally complex and demanding tasks. Further, they're extremely time-sensitive and in high demand across the community and industries. To provide timely and meaningful predictions, weather forecasters usually rely on high performance computing (HPC) clusters hosted in an on-premises data center. These on-premises HPC systems require significant capital investment and have high long-term operational costs. They consume a lot of electricity, have largely fixed configurations, and the underlying computer hardware is replaced infrequently.

Using the cloud instead offers increased flexibility, constantly refreshed hardware, high reliability, geo-distributed compute node and networking, and a "pay for what you use" pricing model. Ultimately, cloud computing allows forecasters and climate modellers to provide timely and accurate results on a flexible platform using the latest hardware and software systems, in a cost-effective manner.

- **Development and Adaptation of next generation coupled data assimilation techniques:**

The observation networks and volume of observations are going to increase dramatically during the next ten years. Since the NWP models need an accurate initial state of the atmosphere for the model initialization, it is very important to make best use of the huge volume of observational data sets for future weather prediction.

An important development path is to drive towards a coupled ensemble data assimilation technology. A particular aspect of coupled DA is the use of interface observations; that is, observations that are sensitive to several parts of the Earth system. The coupled DA aims to provide an accurate and consistent initial condition to coupled atmosphere, ocean, and land surface models.

In the longer term, the coupled DA will be extended to account for more Earth-system components, such as atmospheric composition and other hydrological aspects, i.e., the impact of river discharge on the ocean system.

- **Global Seamless Modeling:**

By 2047, NWP models will have achieved seamless global modeling, effectively simulating the entire Earth system with remarkable accuracy. These advanced models will provide high-resolution forecasts, covering the upper atmosphere down to the Earth's surface, enabling meteorologists to predict weather phenomena with unprecedented precision. The resolution of global coupled NWP models is expected to increase significantly, reaching about 1 km, allowing for more detailed and accurate weather predictions. Additionally, the dual-engine concept, integrating both physical and AI-based models, will enhance forecasting capabilities by combining traditional meteorological techniques with the power of artificial intelligence, offering a more comprehensive approach to weather prediction.

- **Transforming Meteorological Forecasting: An 80% Leap in NWP Model Accuracy**

By 2047, the accuracy of Numerical Weather Prediction (NWP) models is projected to increase by 80% compared to 2024, marking a transformative leap in meteorological forecasting. This substantial improvement will be driven by advancements in computational power, high-resolution modeling, and the integration of artificial intelligence. Enhanced data assimilation techniques and increased observational inputs will further refine model outputs, reducing uncertainties and increasing reliability.

2.1.6 Strategy

- Implementation of physical perturbation scheme instead of statistical perturbation for ensemble prediction system.
- Lead period of global forecast to increase for current 10 days to 20 days by 2035 and 30 days by 2047.
- Lead period of regional forecast to increase for current 3 days to 7 days by 2035 and 15 days by 2047.
- Increase the frequency of run of global model every 3 hour by 2035 and every hour by 2047.
- Exchange of weather data [all observations] and reaffirms the commitment to the free and unrestricted exchange of comprehensive data policy with national and international agencies.
- Access to various global and regional model outputs run across the world for multi-model weather forecasts for different regions of world
- Better representation of physical parameterization schemes in particular over the tropics with the collaboration of research institutes, universities, laboratories, and stakeholders. Make use of machine learning, and deep-learning techniques for improvement.
- Data assimilation techniques will continue to improve, incorporating more diverse and high-frequency observational data. This will result in better-initialized models and more accurate forecasts
- Hybrid modelling approaches that combine traditional physics-based models with data-driven machine learning models will become more common, allowing for more accurate predictions of complex phenomena.
- Understanding the systematic errors and biases in the models and fine-turning timely with advanced statistical approaches.

- AI-powered decision support systems will integrate NWP model outputs with other data sources to provide tailored and actionable information for various sectors, including disaster management and agriculture.
- Continuously invest in research to improve the representation of physical processes in the model. Collaborate with atmospheric scientists to refine parameterizations and reduce model biases.
- Invest in energy-efficient computing solutions to reduce the environmental impact of running NWP models.
- Conducting the awareness programs to stakeholders, public, researchers, and communicating the errors/limitations of the model forecasts, which is crucial to ensure that the public and decision-makers should understand the range.
- Ethical consideration of NWP data privacy, accuracy, and the potential impacts. Meticulous methodology to develop to provide high-quality weather forecasts for various sectors with easy access to the public.
- Interacting with the state government authorities, farmers, stakeholders and taking feedback for further improvement in weather forecasts.
- Continuously evaluate model performance against historical data and conduct comprehensive verification to identify areas for improvement.
- Encourage staff to stay updated with the latest scientific and technological advancements through conferences, workshops, and research publications.
- Performance Metrics and Evaluation:
- Maintain flexibility in the NWP system to quickly adapt to emerging technologies and scientific advancements.

2.1.7 Outcome

- Accurate weather forecasts for various sectors with easy-access
- An improved guidance for each sectors including farmers, vendors, daily labours to heavy industries, “Gramin Krishi Mausam Sewa”, etc
- Minimizing the role of human intervention/element in NWP models.
- Comprehensive policies between IMD and government authorities, stakeholders.
- New workflows use better weather models to improve business outcomes, operations and responses to weather events.
- India would become a global leader in NWP modelling.

2.2 NUMERICAL WEATHER PREDICTION (EXTENDED RANGE)

2.2.1 Current status and major achievements during the past 10 years

- IMD has been issuing extended range forecast in experimental mode since 2009 using available products from statistical as well as dynamical model outputs from various centres in India and abroad. Empirical model products based on OLR anomalies, MJO indices and Self Organizing Map (SOM) which uses wind, geo-potential height, specific humidity and the mean sea level pressure for rainfall variation are used for ERF during this period. Apart from these ERF from ECMWF, NCEP, JMA and MME based on these models are also used in providing experimental extended range forecast.
- IMD implemented operational extended range forecasting in the year 2017 using the Climate Forecast System version 2 (CFsv2) coupled model with Modular Ocean model version 4 (MOM4) as oceanic model. This suite of multi-model ensemble is based on CFSv2 and GFS system at two different resolutions T126 and T382. Bias corrected oceanic SST from CFSv2 is used in running GFS model. Model runs operationally for 32 days based on every Wednesday initial condition with 16 ensemble members and provides week wise forecast for 4 weeks.
- Current ERF system is able to capture intra-seasonal variability of monsoon including onset, withdrawal, active and break period of monsoon with a good skill up to two weeks. The Met-sub division wise forecasts of two weeks are used for providing agromet advisory to farmers. Based on ERF system different products for hydrology, agromet, health sector and severe weather (cyclogenesis, heat wave) are generated.
- Globally major weather centres like ECMWF, NCEP and UKMO produces forecasts in extended scale operationally at different forecast lengths. The ECMWF produces extended-range forecasts for 46 days with 101 ensemble members at a horizontal resolution of around 36 km daily. Model has a usable skill of anomaly correlation values at 500 hPa Geopotential Height greater than 0.6 in Northern Hemisphere for two weeks forecast (up to 14 days). NCEP produces forecasts in extended range using Climate forecast System (CFS version 2) with 16 ensemble members at T126 resolution (~ 100km) daily and producing 45 days forecasts. The Global Ensemble Forecast System (GEFS version 12) with 31 member ensembles produces forecast up to 35 days at 25 km resolution as a support to sub-seasonal forecast with CFSv2. Both the models CFSv2 and GEFS v12 shows usable skill score for two weeks (up to 10 days), in Northern Hemisphere with GEFSv12 has higher skill than CFSv2. UKMO is producing forecasts in extended range using 28 ensemble members with N216 model with horizontal resolution of ~ 50 km for 60 days. Previous studies show models have best performance in first two weeks while ECMWF model is more skilful than UKMO and NCEP. Inter comparison studies done by IITM, Pune shows IMD ERF which is adapted from NCEP system has comparable skill with UKMO and ECMWF in first two weeks and while at longer lead time other models outperforms IMD ERF.

2.2.2 Challenges and Gap Areas

- In the extended range, model has a low forecast skill compared to medium range and seasonal scale. In this scale the role of both initial and boundary conditions are important.
- The uncertainty in performance of ERF models over the north Indian Ocean and South Asian region is mainly attributed to low performance of models in predicting convectively coupled equatorial waves, especially MJO in extended range.
- At present ERF predictability skill is limited to two weeks. Forecast skill needs to be improved beyond two weeks. The accuracy of the two weeks forecast needs to be improved apart from identifying new predictability sources beyond two weeks.
- Forecast skill needs to be improved in smaller spatial scales.
- Better representation of various sources of predictability (MJO, Soil moisture, land surface processes, SST, sea ice, role of stratosphere) and how it interacts with other sources of predictability and other time scales.
- Better representation of Interaction with synoptic scale system.
- Insufficient and unevenly distributed meteorological and oceanographic data can hinder the accuracy of extended range predictions.
- Better land surface initialization is required for better predictability of extremes.
- Improvement is needed in physical parameterization schemes
- More research is required to provide the impact based forecast for various sectors such as hydrology, agriculture, power and health
- More computing resources are needed for increasing ensemble size and resolution
- Addressing the impacts of climate change, including more frequent and intense extreme weather events, requires enhancing extended range prediction capabilities to support adaptation strategies.
- Collaborating with international meteorological centers and organizations can enhance the quality and accuracy of extended-range predictions through data sharing and knowledge exchange.
- Different centers are using different strategies in ERF and its verification process.
- Communicating the uncertainty in the extended range forecasts, and limitations is crucial to ensure that public and decision makers should understand the range.

2.2.3 Short-term Vision (next two years)

- Improved predictability in extended range forecast to 3-4 weeks at meteorological subdivision level.
- Implement a robust system for evaluating the performance of model forecasts to identify areas of improvement and adjust strategies accordingly.
- Improved guidance on extended range for applications in various sectors such as Agriculture, water Resource management, Energy, Health and Disaster Risk Reduction by developing customized products.
- Evaluation of error and biases and hence possible bias correction to improve forecast accuracy.

- ❖ Better forecasts of rainfall (active and weak phases of monsoon), Temperature (heat wave and cold wave), MJO, MISO and cyclogenesis.
- ❖ Develop user-friendly interfaces and communication tools for disseminating forecast information to the public, farmers, government agencies, and industries. Focus on clear and actionable information.
- ❖ Develop multi-model ensemble forecasting by incorporating ERF from other modeling centers.
- ❖ Increase the frequency of extended range forecast to twice in a week from current state of once in a week.

2.2.4 Medium-term Vision (next ten years)

- ❖ Develop and implement the high resolution model with improved spatial and temporal skill which should capture local-scale phenomena and sub-seasonal variations effectively.
- ❖ Improve the ensemble forecasting by enhancing the ensemble size. This will help in quantifying forecast uncertainty and improve decision-making for various sectors like agriculture, disaster management, aviation and energy.
- ❖ Extend Forecasts to 45-60 days and produce reliable forecasts beyond 30 days
- ❖ Enhance the accuracy and lead time of extreme weather predictions, which are crucial for Indian agriculture and the economy.
- ❖ Increasing the frequency of ERF from present status of once in a week
- ❖ Development of better indices for heat wave and cold wave which are effective in both the observation and model simulations.
- ❖ Develop better forecast products for various sectors by the use of AI/ML techniques.
- ❖ Establish a feedback mechanism to gather input from end-users and stakeholders to continually improve the accuracy and relevance of extended range forecasts.
- ❖ Improve data assimilation techniques to effectively integrate various observational data sources. This will provide a more accurate initial state for the models.
- ❖ Representation of Rossby wave packets in ERF can enhance predictability in sub seasonal scale.
- ❖ Improvement in forecast accuracy by 40% from the base year of 2024.

2.2.5 Vision 2047

- ❖ Accurate village level extended range forecast
- ❖ Develop and implement next generation models along with cutting-edge super computing technology to produce the sector-based forecast at various spatial and temporal scales with a sufficient lead time.
- ❖ Enhance the prediction accuracy by incorporating the advanced AI and machine learning algorithms into forecasting and models.
- ❖ Utilize AI for real-time data analysis, and early detection of extreme weather events at district levels for vulnerability-risk assessment and mitigation strategies.
- ❖ Enhance the understanding and prediction of complex interactions between the atmosphere, oceans and land in the changing climate.

- Enhance research on extreme weather events to formulate updated definitions for these occurrences within the context of a changing climate, ultimately improving forecasts for such events.
- Improvement in forecast accuracy by 80% from the base year of 2024.
- Extend ERF to 8 weeks and produce usable forecasts up to 6 weeks.

2.2.6 Strategy

- Implementation of latest models with better representation of physical parameterization schemes.
- Implement the high resolution model with improved spatial and temporal skill to reduce error due to model parameterization.
- Increase the ensemble size to gives a more accurate probability forecast.
- Implementation of Global Land data assimilation system
- Employing bias correction techniques to improve forecast.
- Utilize machine learning to improve model parameterization schemes and data assimilation.
- Make a research group to work on the following points
  - Understand systematic errors and biases in the existing system
  - Understanding the sources of predictability and their representation in the model.
  - Understanding the changing tele-connection associated with our weather and climate events in the changing climate and its better representation in model.
  - Analyze some past extreme events (heat wave ,cold wave, heavy rainfall etc) which leads to the better prediction of the evolution of these events with few weeks leads time
- Better high-performance computing (HPC) infrastructure for faster and more accurate simulations.
- Develop a collaboration with global meteorological agencies and research institutes for the continuous improvement of model

2.2.7 Outcome

- High quality forecast product for various sectors with easy access to the public.
- The government can make policy decisions related to disaster management, agriculture, water management resources, and urban planning, based on accurate forecast based on accurate forecast at village and household level by 2047.
- Prediction of extreme events well in advance by about one month helps authorities to plan better preparedness and mitigation strategies (e.g. evacuate vulnerable areas, set up relief camps etc.) and resilience at village and household level.
- Better forecast will lead to the improvement in agriculture productivity, water resource management, energy sector, tourism, health sector, and urban planning.
  - Agriculture: Based on accurate forecast farmers can take decisions regarding planting, irrigation, and harvesting which leads to the improvement in agricultural productivity, reduced crop losses, and improved food security

- Water Resource Management: based on forecast plan for irrigation, reservoir releases, and water conservation measures.
- Energy Sector: the energy sector can take proactive measures to efficiently manage and distribute energy, ultimately leading to more effective energy production and delivery.
- Urban Planning: Cities can better prepare for extreme weather events, minimize urban flooding, and develop climate-resilient infrastructure based on accurate forecasts.
- Health sector: Healthcare systems can prepare for weather-related health challenges, such as heat waves or the spread of vector-borne diseases, leading to improved public health outcomes.

❖ Better extended range forecast in India has the potential to lead to increased productivity, risk reduction, and economic growth across various sectors (Agriculture, water management, energy sector etc.), ultimately benefiting the overall economy and the well-being of the population.

2.3 DATA DRIVEN MODELING

2.3.1 Current status and major achievements during the past 10 years

During the past few years, the combination of AI/ML techniques and meteorology advances the weather and climate forecasting. With the advancements in computing power, data collection and machine learning algorithms, AI/ML techniques help meteorological agencies to make predictions faster and more accurate compared to before. It is well established in the literature that climate is a complex system. Hence, numerical models are not able to provide accurate forecasting due to the sensitivity to the initial conditions, incapability of the description of the realistic problems etc. AI/ML models can analyze large amounts of data in real time to provide better forecasting.

International status:

Numerous studies have been devoted to the use of AI/ML techniques to study predictability and make climate predictions. The ability of AI/ML techniques to forecast various aspects of temperature extremes on seasonal to decadal time scale is demonstrated in several studies using various methods. Decision tree based ensemble methods like Random Forest and XGBoost are often chosen for their robustness against overfitting. In general, AI in drought prediction involves predicting drought severity using several input data, including hydro-meteorological variables and tele-connection indices. AI techniques have been successfully applied to improve the prediction of both cyclones and heavy precipitation events. Examples of machine learning and deep learning methods used to predict tropical cyclone occurrence include Convolutional Neural Network and Random Forest. Random forest provides more interpretability on the role of different drivers and outperforms nonlinear regression models in predicting tropical cyclones in the western north Pacific.. A promising framework for seasonal to decadal prediction of cyclones is hybrid statistical dynamical predictions. This approach improves the skill of numerical prediction systems in representing weather extremes by finding relationships between large scale drivers and extreme events. It has been applied to precipitation fields, providing probabilistic forecast of precipitation at the sub-seasonal timescale. Regression based approaches have shown promising results for sub-seasonal predictions of precipitation. Hybrid climate predictions, which combine numerical forecasting techniques with AI methods, have emerged as a promising approach for improving the accuracy and reliability of climate predictions. Few AI/ML based models are described below which are popularly used by the operational agencies.

A collaboration involving NASA and IBM research has led to the development of a new AI foundation model for weather and climate: Prithvi-weather-climate. The model is pre-trained on 40 years of weather and climate data from NASA’s Modern-Era retrospective analysisfor Resarch and Applications, version 2 and fills a need to infuse AI/ML methods into weather and climate applications such as storm tracking, forecasting and historical analysis.

At ECMWF, AI/ML applications are spread over the entire numerical weather prediction through the following workflow: bias correction of satellite observations, the learning of model error within data assimilation, the emulation of model components to increase computational efficiency in the forecast model, local downscaling of model output to improve predictions, the monitoring of the IT infrastructure.

Five prominent global machine learning weather prediction (MLWP) model, Pangu-Weather, FourCastNet v2 (FCN2), GraphCast, FuXi, and FengWu, emerged.

FourCastNet system (FCN) is the first MLWP model producing 0.25^{o} resolution forecasts using ECMWF ERA5 reanalysis as its training data. The system applying Vision Transformer (ViT) with the Fourier Neural Operator (FNO) and Adaptive Fourier Neural Operators (AFNO for efficient computation in long-range dependencies in spatial-temporal data.

Pangu-Weather acquires promising medium-range performance with a multi-timescale model combination strategy based on 3D Earth-Specific Transformers (3DEST) in which the upper-air variables and the surface variables are embedded into a single deep network. The 3D data are propagated through an encoder–decoder architecture derived from the Swin transformer, a variant of the vision transformer.

GraphCast, a state-of-the-art AI model is innovated to make medium-range weather forecasts with unprecedented accuracy. This model is based on machine learning and Graph Neural Networks (GNNs), which are a particularly useful architecture for processing spatially structured data. GraphCast predicts weather conditions up to 10 days in advance more accurately and much faster than the industry gold-standard weather simulation system – the High Resolution Forecast (HRES), produced by the European Centre for Medium-Range Weather Forecasts (ECMWF).

FuXi model backbone is based on Swin transformer v2 with 3D cube embedding (called U-transformer) and is designed as a cascade of models (short for 0 ~ 5 days, medium for 5 ~ 10 days, and long for 10 ~ 15 days) optimized for different forecast lead times that is similar to the multiple time steps used in Pangu-Weather.

FengWu forecast system is constructed from a multi-modal and multi-task perspective in which each atmospheric state variable is treated as an individual modal and a cross-modal fuser transformer is applied to connect them.

GenCast, a probabilistic weather model with greater skill and speed than the top operational medium-range weather forecast in the world, ENS, the ensemble forecast of the European Centre for Medium-Range Weather Forecasts. GenCast is an ML weather prediction method, trained on decades of reanalysis data. GenCast generates an ensemble of stochastic 15-day global forecasts, at 12-h steps and 0.25° latitude–longitude resolution, for more than 80 surface and atmospheric variables, in 8 min. It has greater skill than ENS on 97.2% of 1,320 targets we evaluated and better predicts extreme weather, tropical cyclone tracks and wind power production.

QuickClim could quickly predict how global surface temperatures would change during the century under many carbon emission scenarios — about one million times faster than the conventional model could play.

ClimaX, a flexible and generalizable deep learning model for weather and climate science is developed that can be trained using heterogeneous datasets spanning different variables, spatio-temporal coverage, and physical groundings. ClimaX extends the Transformer architecture with novel encoding and aggregation blocks that allow effective use of available compute while maintaining general utility. ClimaX is pre-trained with a self-supervised learning objective on climate datasets derived from CMIP6.

National status:

- Short-range precipitation forecast based on deep learning models in the summer monsoon season using ground-based and satellite based observations.
- Deep learning model for precipitation downscaling from 0.25^0 (about 25 km) to multiple resolutions (6 km, 12km).
- A novel deep learning model (meteoGAN) has been developed for Delhi-NCR region and successfully tested for rainfall downscale using ground based and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) rainfall analysis at 300 meters spatial resolution.
- LSTM model is setup for forecasting heat stress for a lead time of 2 days. The modelling framework is available for real-time forecast.
- AI model is under development for medium range weather forecasting for 7 days on daily basis using ECMWF reanalysis v5 (ERA5) data. This model will be used for daily forecast based on the real-time NWP model outputs from IMD/MoES.

2.3.2 Challenges and gap areas:

- Meteorological observations at specific location (downscaling)
- Data collection is an important step in forecasting problems. The availability and accessibility of real-time and good quality weather dataset is still a challenging task.
- Low skill in forecast at smaller spatial domains like at district level.
- Low forecast skill of location specific heavy rainfall events and other extreme weather events like thunderstorm & associated weather.
- Impact based forecast (IBF) pertaining to all type of severe weathers
- Improvement in Numerical models for forecast at different timescales (Nowcasting to Long Range Forecasting) including pre-processing of the data.
- Post-processing of the model outputs and reducing model bias for effective decision making.

Innovations: Meteorological things possible with Machine learning & Data Science/ Big data

- We are planning to use AI/ML based technologies in weather forecasting specifically to predict extreme weather events in Nowcasting, short to medium range weather forecasting and over Indian region.

- Planning to use AI/ML based technologies for the intra-seasonal weather forecast like prediction of active-break cycle of monsoon, prediction of heatwave/coldwave.
- Application of AI/ML technique in crop management providing yield prediction.
- Post-processing of the model outputs and reducing model bias for effective decision making.
- It is also contemplated to use AI in remote calibration and data quality assessment for sensors & systems and apply correction factors before ingesting the data in models to further improve the forecasting.

2.3.3 Short term vision (next two years)

- Inadequate network of rain-gauges in urban area could be address by AI model to access rainfall at every 300 mt.
- LSTM based model for predicting heat stress conditions over the Indian region is tested and ready for operationalization. It adds to various methods used by IMD for impact based heat wave forecasting. It will be useful for issuing warning to heat-health, livestock, power, water sectors & better management.
- Enhancement and improvement in Atmospheric observational network with automated ML based Quality Control techniques and in-feeding of heterogeneous Big Data sources.
- Development of Hail/ Thunderstorm/ Squall/ Lightning prediction model in deterministic approach under spatially high-resolution mode and time of occurrences with study of root causes as cloud electric potentials etc. [24 hours lead time]
- Development of probabilistic location specific monsoon predictions.

2.3.4 Medium term vision (next ten years)

- The LSTM based model for predicting heat stress need to be improved by optimizing the model.
- Accuracy of the existing weather forecasting skill will be improved with the use of AIML based data driven models in all time scales (Now-casting to extended range).
- It is expected to improve the weather forecasting accuracy by 10-15% for all types of severe weather by 2030.
- Digital twin: embed machine-learning components inside physics-based models to produce hybrid models
- The following AI/ML data driven models will be implemented for the prediction of extreme weather events in all time scales.
    - Pangu Weather,
    - GraphCast
    - FourCastNet
    - AI-enhanced Advanced Dvorak Technique (AiDT) for cyclone intensity estimates

2.3.5 Vision 2047

- Hyper-Precision Weather Forecasting: By 2047, meteorologists will harness the power of AI-driven models that process an immense volume of data from satellites and Radars and other ex-situ sources, ground sensors, drones, and even emerging quantum computing technologies. Vision 2047 Pipeline is depicted as follows –
- Smart observational network with unified data assimilation
- Ultra-high resolution hybrid prediction modelling
- Customized/ location specific automated value-added forecast
- High-precision and Need specific Nowcasting, Short-Term Weather Forecasting, Long-Range Weather Forecasting , Climate Modelling and Prediction
- Deterministic early warning and disaster preparedness
- Agricultural sustainability and responsible resource management
- Customised meteorological services with AI-powered AWS
- Ultimate goals are following:
  - Making forecast services user and location centric over current practices of averaging forecast techniques such as district or block level.
  - Develop next-generation Heterogeneous machine learning models to better harness the remote sensing (Satellite and Radar) data to assimilate meteorological parameters at spatially high-resolution graphs.
  - Let's make people aware of its risk to come under the vulnerability of Storms or Lightning in its regular schedule in well-advance.
  - Let's make disaster mitigation agencies, relief managers and people aware of its risk to come under the vulnerability of flooding in its regular schedule in well-advance.
  - Let's make all socio-economic activities be planned in well advance by farmers, traders, country and State planners etc.
  - Let's think twice before you intercept existing resources in the Earth.
  - Reduce farmer's physical efforts, optimize its resources utilization and minimize the losses, ultimately to maximize qualitative yield production.
  - Let's machine become the part of farmer's decision making process.
  - Let's make weather forecast harnessed optimally in all allied sectors to enhance financial and social resources utilization with reduced input costs and improved management.

2.3.6 Strategy

- ❖ Indigenous development of next-gen observational algorithms.
- ❖ Incentivizing in-house R&D in AI model design.
- ❖ Department-Academics collaborations in strategic areas by attaching academic personnel in R&D activities and contribute in academic curriculum too.
- ❖ "Weather and Climate Modelling using explainable Artificial Intelligence and Dynamic Machine Learning" can be an alternate or compliment to existing dynamic physical models. So, let's conclude the existing physical or hybrid models can't perform and why.
- ❖ Improve computation framework such as provision of R&D specific IT resources and services specific IT resources.

- This vision will prioritise protecting users' privacy and data, being transparent about their operations, and providing equal access to all meteorological services. In order to ensure that AI and ML to be used responsibly, additional regulations and ethical frameworks are needed.
- The advancement of AI and ML applications in meteorology will be accomplished through global collaboration between meteorological organizations, academic institutes, technological companies, and governments. To accomplish these ambitious objectives, we will work to foster an environment that encourages creativity, innovation, and the exchange of information.

2.3.7 Outcome

By the year 2047, AI and ML will revolutionize our understanding of the atmosphere as well as our interactions with ocean, land and space. In the future, AI will become an indispensable part of state-of-the-art weather forecasting, climate monitoring and prediction, customized dissemination, etc. Recent advances in technology (transfer learning, data augmentation, etc.) could accelerate the impact of AI techniques in climate and weather prediction and reduce the need for an extra-large labelled dataset. We will build a society that is safer, more resilient, and more sustainable by using ethical concerns, collaboration, and innovation as our guiding principles. In this world, meteorological services will allow individuals, industries, and governments to prosper in the face of environmental challenges and climate change. The ultimate goal, says Schneider, is to create digital models of Earth’s systems, partly powered by AI, that can simulate all aspects of the weather and climate down to kilometre scales, with great accuracy and at lightning speed.

Chapter 3 Weather Forecasting and Early Warning Services

3.1 CYCLONE FORECASTING & WARNING SERVICES

3.1.1 Current status and major achievements during the past 10 years

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 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.

3.1.2 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 equipment 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 equipment 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 develops 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 modelling of hazards like wind, rainfall, wave, storm surge, etc.

The efficacy of forecast and mitigation measures strongly depends 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 its 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.

3.1.3 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 years 2025, 2030, 2040 and 2047 is presented in Table 2.

Table 2: 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

3.1.4 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.

3.1.5 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.

3.2 MARINE WEATHER FORECASTING AND WARNING SERVICES

3.2.1 Current Status and Major achievements during the past 10 years

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.

a) 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).

b) 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.

c) 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.

d) 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

Major achievements during the past 10 years:

- **Expanded Forecasting Area for Fleet Warnings:** Broadened forecasting responsibility to cover a larger portion of the Indian Ocean.
- **Automation of GMDSS and Fleet Bulletins:** Speeded up dissemination of crucial weather information in the region.
- **GIS-based Indigenous DSS for Fishermen Graphics:** Developed a semi-automated DSS for fishermen in the Indian Ocean to aid in visual comprehension of weather patterns.
- **Multi-model Ensemble for Fishermen Warnings:** Leveraged various models to enhance warning accuracy for fishermen in the region.
- **Inclusion of 3-hourly Wind Climatology in DSS:** The DSS now offers forecasters a reference, especially when no extreme weather event is predicted.
- **Location-specific Forecasts for Offshore RIGS during Cyclones:** Introduced tailored weather forecasts for offshore rigs, especially during cyclonic events.

3.2.2 Challenges and 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:

Real-time observations: 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.

Research and development: 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.

Probabilistic based forecasts: 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 develops 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.

Adverse weather forecast accuracy for landfalling cyclones: 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.

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

Last mile connectivity: 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.

Consideration of climate change: 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.

Inclusion of Blue Economy principles: 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.

Sustainable practices: 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.

3.2.3 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.

3.2.4 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:

Short-term (next two years)

- Encouragement of partnerships with neighbouring countries for data sharing.
- Launch mobile and web platforms offering real-time weather alerts and Blue Economy guidelines for maritime stakeholders.
- Amplify public awareness campaigns on climate change, its impact on marine weather, and the importance of sustainable maritime practices.
- Introduction of probabilistic forecast at high resolution over the marine area for all weather parameters about the location, intensity & impact.

Medium-term Vision (next ten years)

- Establish a framework to fully integrate Blue Economy principles into marine weather services, aiding stakeholders in sustainable decision-making.
- Develop a centralized research and data centre focused on understanding the impacts of climate change on the Indian Ocean's marine weather patterns.
- 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.
- 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.
- 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.

Vision 2047

a) Enhancement in observational network

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.

b) 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.
- 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.

c) 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, thunder-squalls 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.

d) 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.

e) Holistic Ocean Management:

Develop a comprehensive ocean management system 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.

f) Innovative Climate Resilience:

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 cyclonic events, and changing marine biodiversity.

g) Global Leadership:

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.

h) Innovative Climate Resilience

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 cyclonic events, and changing marine biodiversity.

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.

3.2.5 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.

3.3 HEAVY RAINFALL FORECASTING AND WARNING SERVICES

3.3.1 Introduction

The quality and accuracy of weather forecasting and warnings for all types of severe weather events including heavy rainfall have improved significantly during last decade (2015-2024) by about 40-50% compared to the earlier decade 2005-2014. Also, since Aug 2019, IMD has been providing IBF and RBW for heavy rainfall in color coded form upto district and sub-city scale, by adding 'impact likely' and 'suggested actions' for an area as per likelihood of the event and severity of impact and vulnerability from associated hazards like Landslide, Flash flood, riverine flood, urban floods etc. All these service have improved due to increase in both surface and upper air observational network, addition of new Satellite products for wind, cloud and rainfall monitoring and estimations. Also, India's enhanced weather and climate modelling capability coupled with new HPC capable upto 22 PTF and skilled man-power, have helped IMD to achieve this success. Today, weather plays a vital role in everyone's day to day life. **Now, IMD provides services for all almost every sector including disaster management, agriculture, aviation, transport, power, energy, marine and fishery, tourism, mountaineering, environment, health, urban, etc.** As IMD celebrate its 150 years, a critical review of its current capability in the field of heavy rainfall monitoring and early warning, has become necessary before bringing out the vision for 2047, which is the main objective.

3.3.2: Terms and Terminology in use for Heavy rainfall events

Rainfall intensity is classified into different categories (Table 1 a and 1b). At present IMD is using uniform classification across the country. Because of different geographical locations, the uniform classification cannot translate the same impact. **Accordingly, there may be different classification for different locations like hills, plains, coasts etc.**

Table 1(a):

Terminology for intensity of 24 hour accumulated rainfall

S. No.	Terminology	Rainfall (mm)	Rainfall (cm)	Percentile
1.	Very light rainfall	Trace -2.4		
2.	Light rainfall	2.5-15.5	Upto 1	Upto 65
3.	Moderate rainfall	15.6-64.4	2-6	65-95
4.	Heavy Rainfall	64.5- 115.5	7-11	95-99
5.	Very Heavy Rainfall	115.6-204.4	12-20	99.0-99.9
6.	Extremely heavy rainfall	Greater than or equal to 204.5 mm	21 cm or more	>99.9
7.	Exceptionally Heavy Rainfall	When the rainfall observed is a value near about the highest recorded rainfall at or near the station for the month or the season. However, this term will be used only when the actual rainfall amount exceeds 12 cm		

Table 1(b): Rainfall spell category

Category	Range of daily rainfall of a station
Light spell	1 cm/hour
Moderate spell	1-2 cm/hour
Intense spell	2-3 cm/hour
Very Intense spell	3-5 cm/hour
Extremely Intense spell	5-10 cm/hour
Cloud Burst(CB)	> 10 cm/hour

3.3.3 Review of Current capability (India)

3.3.3.1 Observations, Monitoring and Detection: For detection of heavy rainfall, IMD is maintaining manual observation network, automatic weather stations (AWS), automatic rain Guage (ARG), Agromet observatories, part time observatories (PTO) of IMD as well as states, state Rain Guage Stations, etc. Currently, a total of around 6600 number of rainfall monitoring station are functional across India **(Fig. 1).** All these data are shared and updated from time to time for generating various customized rainfall products for different applications at different spatial and temporal scales. Customized Rainfall products are available at 15-minute-3 hour gap to 24 hour at station level and 24-hour gap for District and City levels and then at met sub-division level to all India level. It is also available at various other time scales like weekly, monthly/seasonal scale and annual statistics in both table and map forms in IMD. A total of around 134 daily rainfall maps are generated daily and updated for different applications.

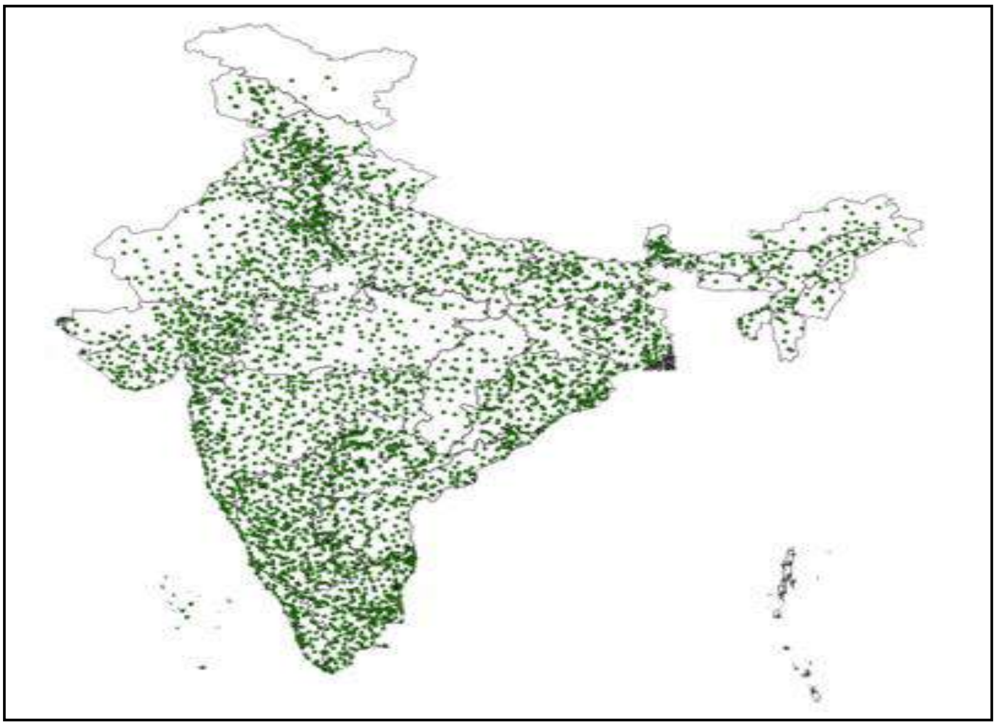


Fig1: Rainfall stations over India 2023-2024

Various rainfall products currently available in IMD:
Rainfall at real time with statistics is currently available for:

- 6380 Stations
- 695 Districts
- 36 Met Sub divisions
- 37 States and UTs
- 157 No. of river catchments
- 04 Homogeneous regions
- Country as a whole

Rainfall maps are prepared for

- Hourly Rainfall,
- 3 hourly rainfall
- Cumulative rainfall for any hour
- 24 hr cumulative rainfall

Total 134 numbers of maps are prepared daily.

To support clouds and rainfall monitoring further, IMD also has 39 DWRs functional at different locations over India as depicted below:

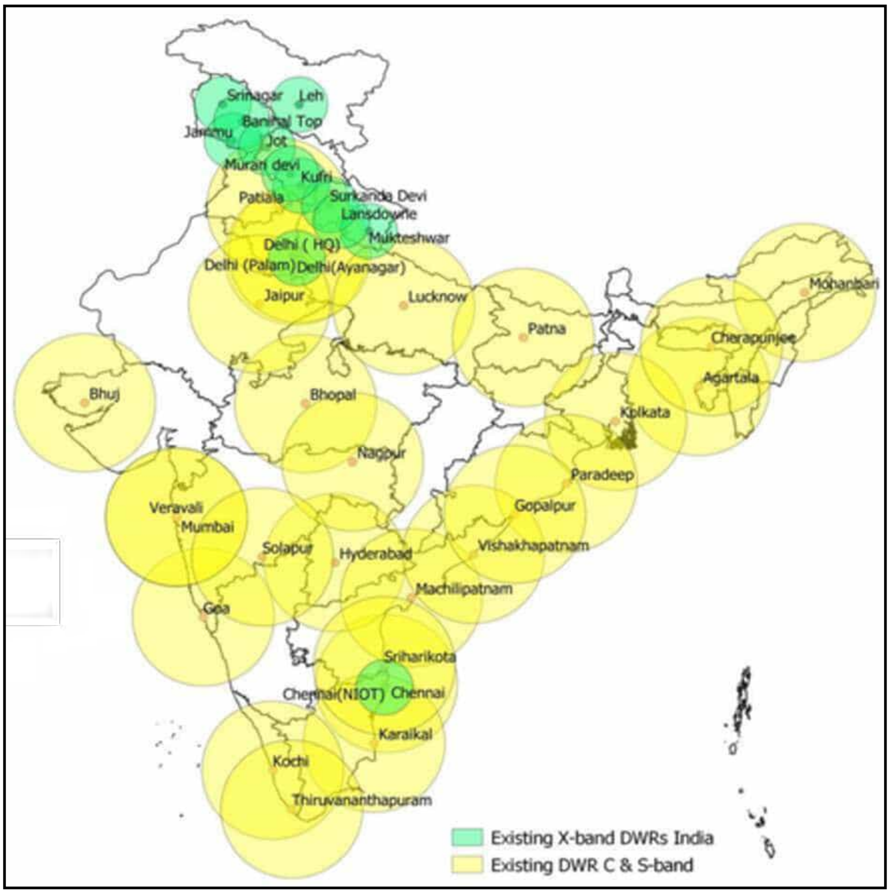


Fig. 2: Doppler Weather Radar Network

- Fig 2 shows the DWR network of IMD. Out of 39 DWRs, operational in IMD, 22 are S-Band, 5 are C-Band and 12 are X-Band DWRs.
- These DWRs are manned and operated 24x7 providing essential data utilized by the IMD in issuing accurate nowcasts and ingestion into Numerical Weather Prediction (NWP) models

IMD has following Satellite-based observation and monitoring system:

i. INSAT-3D

ii. INSAT-3DR

iii. Foreign SAT-METEOSAT/ HIMWARI

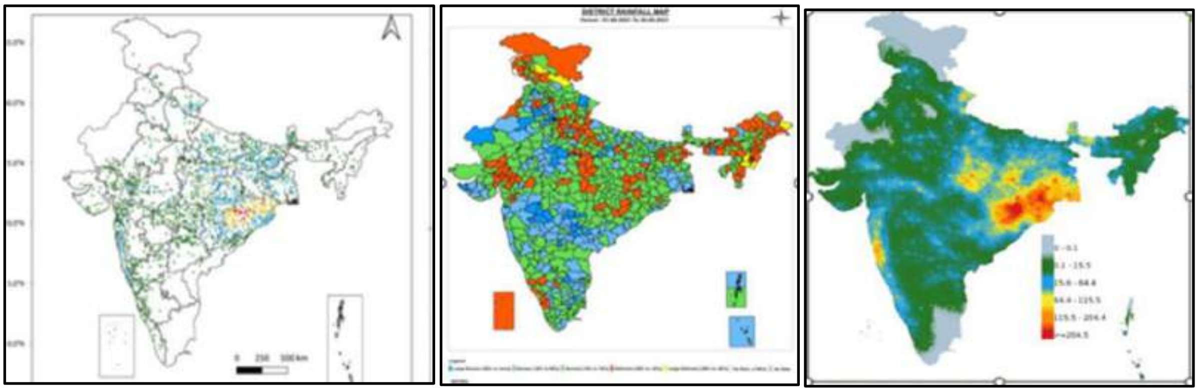


Fig.3 (from left to right) Point Rainfall Monitoring, District-wise Rainfall Monitoring, Spatial distribution of daily rainfall

Rainfall products:

- QPE of INSAT 3D and INSAT 3DR

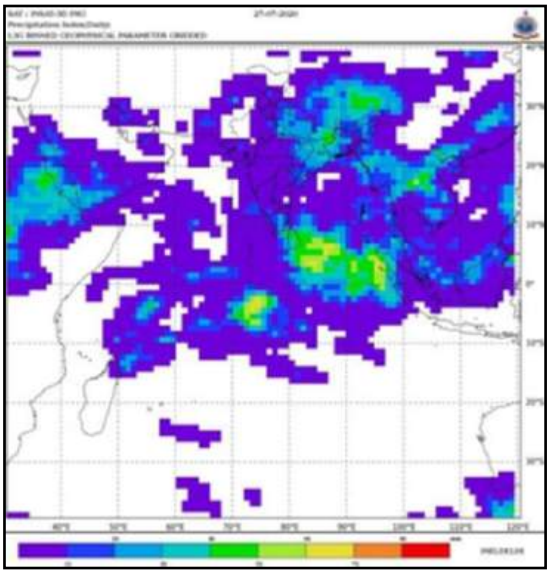


Fig 4a: QPE of INSAT 3D

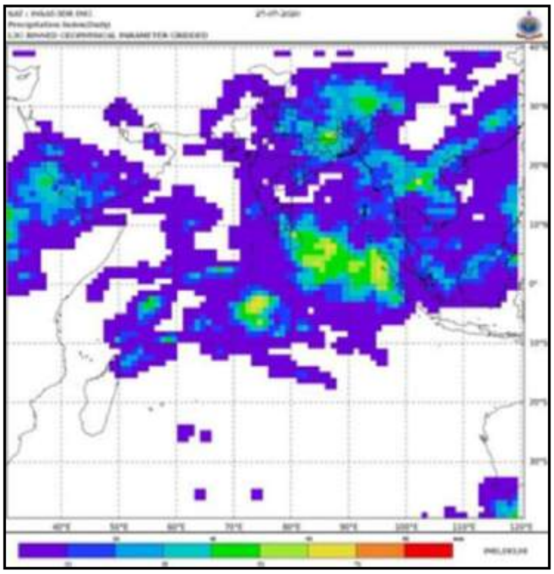


Fig 4b: QPE of INSAT 3DR

- Rainfall product of DWR

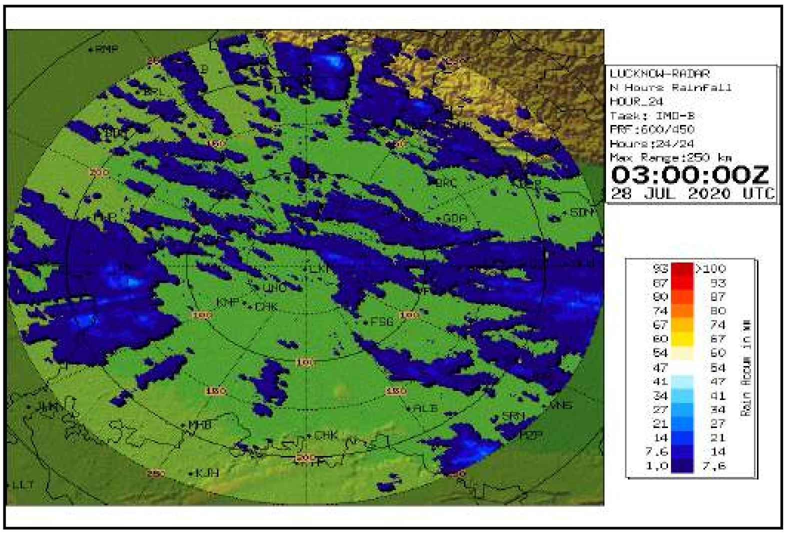


Fig 4c: 24-hour Rainfall by DWR

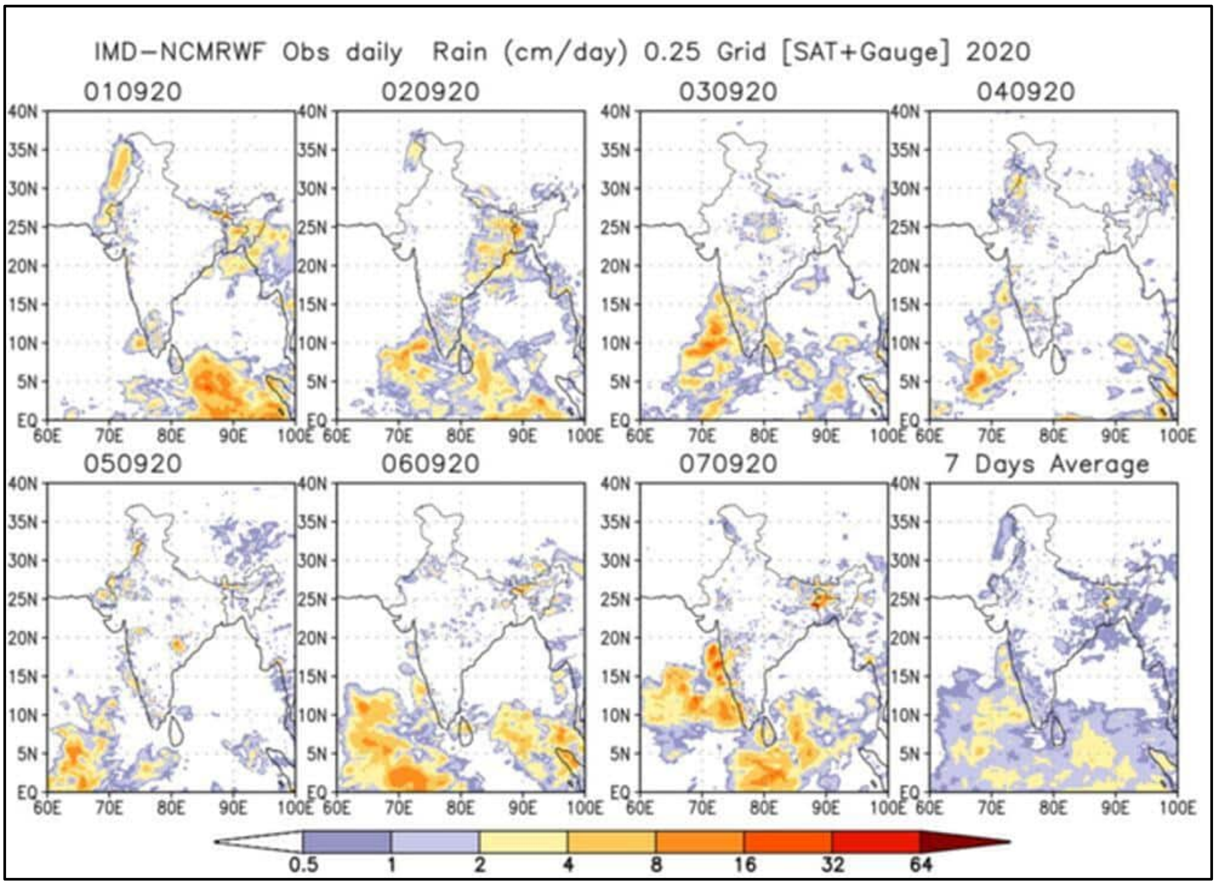


Fig 4d: Gauge and satellite gridded rainfall product of NCMRWF

3.3.3.2 Methodology of forecasting processes and Warning decision making-An IBF approach:

IMD is the Nodal National Meteorological agency mandated for issuing seamless operational weather forecast and warnings for weather hazards across the country. IMD has 3-tier structure, viz., National weather forecasting Center (NWFC) at Delhi for National level, Regional Meteorological Center (RMC) at regional level and Meteorological Centres (MC) at state level. The weather forecasts are issued for different temporal and spatial domains. The spatial domain ranges from venue, city, District, State and country - each having different temporal domain. The temporal domains based on their validity periods are (i) Nowcasting – a few couple of hours ahead, (ii) Short Range - up to 3 days, (iii) Medium Range - 3 – 10 days, (iv) Extended range - 10 days to 1 month and (v) Long range – Months to a whole season. However, the warnings are issued only in nowcast to short/medium range valid upto 5 days at district level and 7 days at met sub-division levels.

At the national level, NWFC issues sub-division wise Impact based Forecast (IBF) and Risk Based Warning (RBW) bulletin for heavy rainfall related to all types of hazards, four times a day valid for next 7 days with 3 days outlook based on 00, 03, 09 and 12 UTC observations for entire country. The heavy rainfall warning for met sub-divisional level is issued in both text and colour coded graphical form by NWFC. The warning are issued to all central and state disaster management agencies e.g. NDMA, MHA, NDRF, SDMA etc, press & electronic media, public, users and all stakeholders by various modes. At regional level, the heavy rainfall warning bulletin is issued at district wise level with Impact based Forecast (IBF) and Risk based warning (RBW) related to all types of hazards by MC. The warnings are issued to state agencies, state disaster management agencies, district collectors, press & electronic media, public, users and all stakeholders by various modes. In addition, the heavy rainfall warning is issued in text and colour coded graphical form by RMCs.

Table 2: Heavy Rainfall warning issued by different centres of IMD and validity

S.No.	Centre	Area of responsibility	Update	Warning type	Validity
1	National Weather Forecasting Centre (NWFC)	Meteorological Sub-division wise	4 times in a day	Text and colour coded form	10 days forecast with 7 days warnings
2	Regional Meteorological Centre (RMC)	Meteorological Sub-division and district wise	2-4 times in a day	Text and colour coded form	10 days forecast with 7 days warnings
3	Meteorological Centre (MC)	District wise	2-4 times in a day	Text and colour coded form	10 days forecast with 5 days warnings

Real time operational set up for Heavy Rainfall Forecasting and warning in IMD

At present, the heavy rainfall is predicted based on the synoptic, satellite, radar and NWP model inputs. All the available data/products are analysed to arrive at a consensus decision on likely occurrence of heavy rainfall over a Meteorological Sub-division or a part of it during next 5 days. For the issuance of heavy rainfall forecast and warning, IMD analyses all related products upto sub-city and district levels, round the clock at 10 min to 3hour gap for nowcast and at least at 6-hour gap for issuing daily warnings upto 5 days.

Methods of Heavy rainfall warning upto Met sub-division/Major City/ District levels

At present, the heavy rainfall event over an area/location is predicted based on the diagnostic meteorology covering synoptic and upper air data analysis and preparing synoptic climatology or pattern matching various NWP model products, and satellite & radar observations.

- **Synoptic and Diagnostic Method**

CLIPER, Synoptic, Synoptic analogues/Pattern matching are methods where past heavy rainfall cases are analysed and various products are diagnosed synoptically and dynamically to find various conditions that causes these events. NWP model analysis and forecasted winds, areas of stronger wind shear, moisture availability, dynamic features like vorticity, convergence and divergences at various levels of atmosphere (CIMMS and GFS diagnostic products) are also in use in this regard to get the pattern as past cases are associated with earlier events.

Some of the major features diagnosed which are favourable to cause heavy rainfall event are:

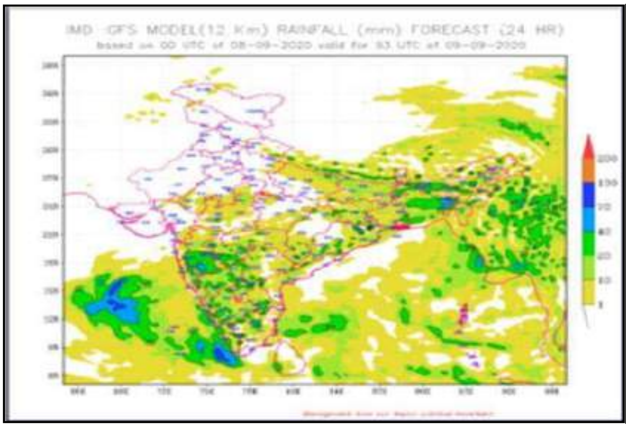
- ✓ Major cyclonic systems like CS/Dep, Monsoon Lows/Dep while moving, causes heavy rainfall events
- ✓ MTC and Active Monsoon trough/Off-shore trough/ vortex with stronger moist laden Easterly/westerly, along west coast and Gujarat.
- ✓ Orographic lifting and Mid-latitude system and Monsoon system interaction over western Ghats and Himalayan region
- ✓ During break/revival phase of monsoon-Synoptic-Meso-scale Convective interaction leading to MCC/MCZ formation
- ✓ **Features causing Extreme heavy rainfall events/Cloud Burst /Intense to very Intense spell over Himalayas and west Coast**
    - Eastern Himalaya- Convergence of moist southerly/south-westerly winds from Bay of Bengal across steep slope of orography where moist laden winds suddenly condensed and provide very high rainfall
    - Western Himalayas-Interaction of WD/mid-Latitude trough with LPS where southerly(southeasterly) moist monsoon winds from Arabian Sea or the Bay of Bengal aided by orographic uplift turning to severe convective events with CB grown upto 15km height.
    - West Coast and adjoining south Gujarat- MTC, east-west Shear zone, off shore trough and distance effect of LPS/Depression located over Odisha-Bengal coast or over eastern parts of Central India

- Besides above synoptic scale systems, **Large scale features of the day like low level jet, MJO, IOD, El-Nino, Ridge, easterly Jet position also enhance/supress convection in areas favourable of heavy rainfall over various parts of India over monsoon core zone along central India, west coast and east coast of India.**
- Dynamic features: Divergence, convergence, shear, shear tendency, vorticity etc.
- Thermodynamic features: CAPE, CINE, Temperature gradient etc. are also used.

➢ Heavy rainfall forecast Based on NWP Models:

Table 3: NWP Models

Forecast Range	Name of the modelling system	Horizontal resolution	Number of updates (per day/per week/per month)	Time of updates/interval
Nowcast to very short range (up to 12 hour)	High Resolution Rapid Refresh Modelling System (IMD-HRRR)	2 km	12 times per day	Every 2 hours
	Electric Weather Research and Forecasting (EWRF) for lightning forecast	3 km	2 times per day	Every 12 hour (based on 0530 hrs and 1730 hrs IST)
Short range (up to 3-5 days)	WRF model	3 km	4 times per day	Every 06 hour (based on 0530, 1130, 1730 and 2330 hrs IST)
	Coupled Hurricane WRF (HWRF) model	18x06x02 km	4 times per day during cyclonic disturbance	Every 06 hour (based on 0530, 1130, 1730 and 2330 hrs IST)
Medium range (Up to 3-10 days).	Global Forecast System (GFS)	12 km	4 times per day	Every 06 hour (based on 0530, 1130, 1730 and 2330 hrs IST)
	Global Ensemble Forecast System (GEFS) with 21 members	12 km	2 times per day	Every 12 hour (based on 0530 hrs and 1730 hrs IST)
Extended Range forecast (Up to 4 weeks)	Coupled Climate Forecast System (CFS) model with 16 members	38 km	Once in a week	Every Thursday
Monthly to Seasonal Forecast	Coupled Climate Forecast System (CFS) model with 20 members	38 km	Once in a month	End of every month



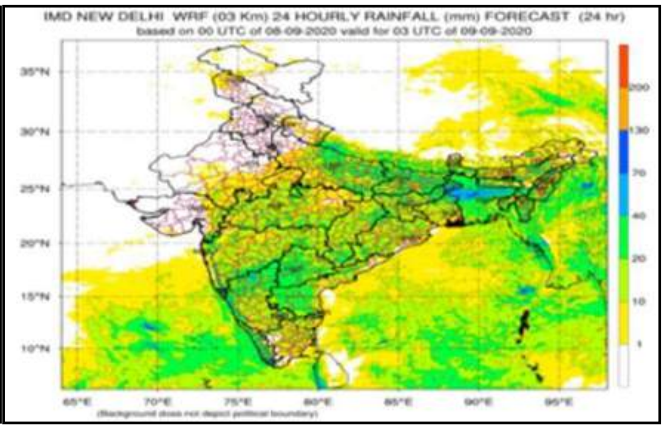
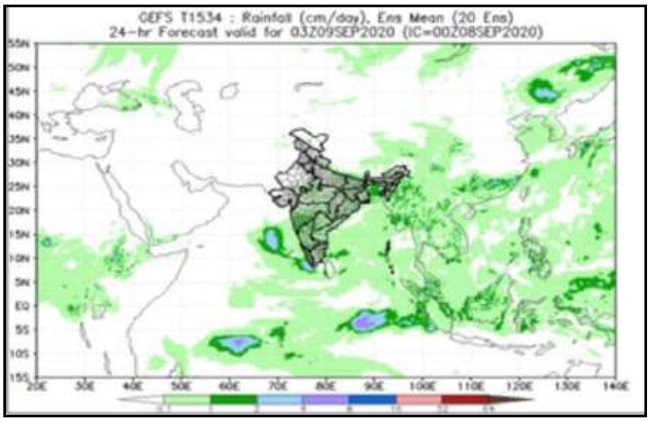


Fig 5a: IMD GFS (12 km)

Fig 5b: IMD WRF (03 km)



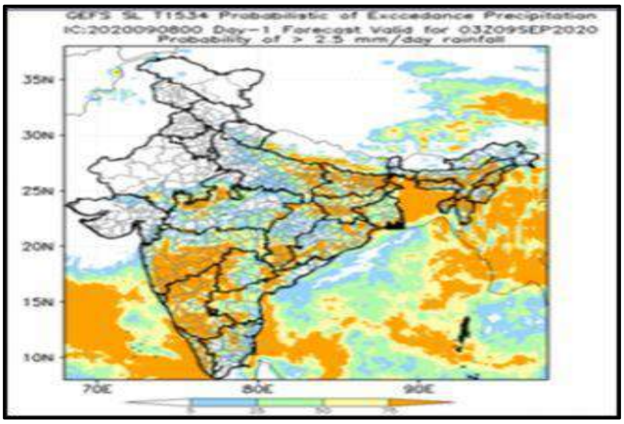


Fig 5c: GEFS (12 km)

Fig 5d: GEFS (12 km) (Probabilistic)

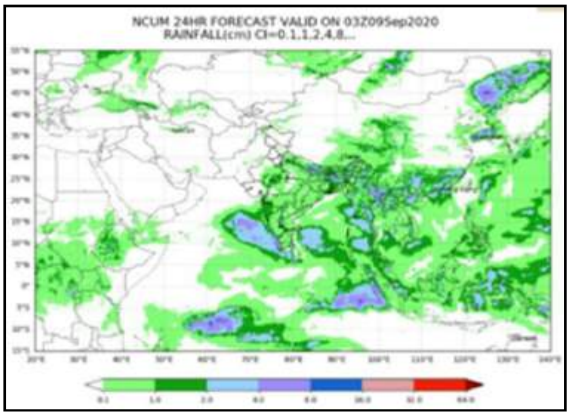


Fig 5e: NCUM

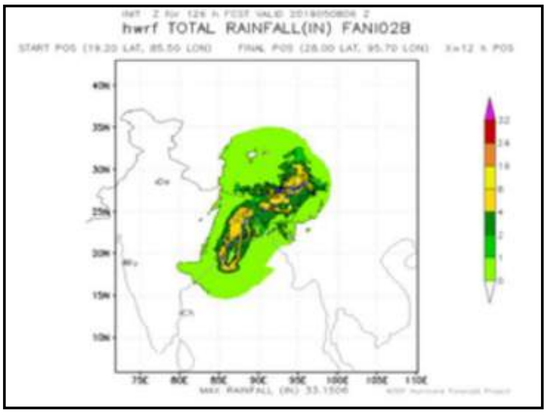


Fig 5f: HWRF

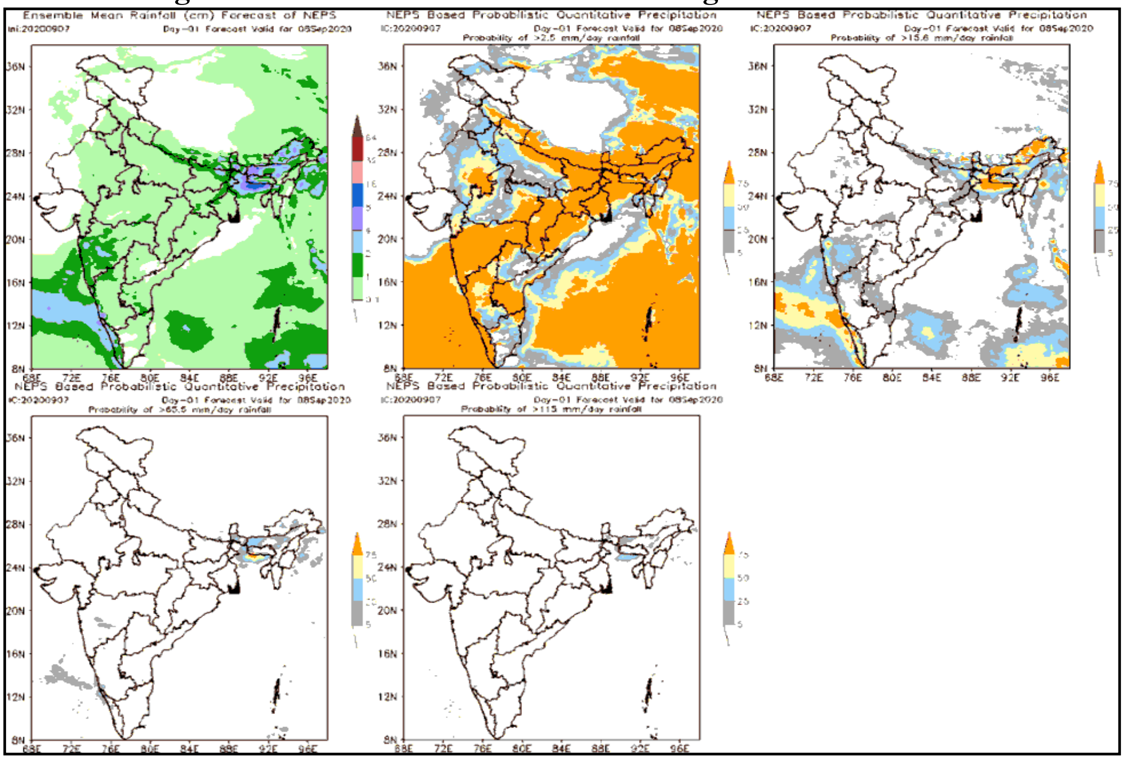


Fig. 5g: NEPS

Fig 5: a to g-Rainfall maps as forecasted by different NWP models

For quick look at Heavy rainfall intensity forecast upto 7 days using different NWP model rainfall amounts over a sub-division, IMD has started the forecast of rainfall averaged over the met-sub-division from 7- different models viz. available in a single click in tabular form as given below at https://nwp.imd.gov.in/models_intensity_ mme_07days.php.

Location specific heavy rainfall forecast: Methodology and Decision making

Local Forecasts for the Capital and other important cities/towns is very important for management of urban activities. These forecasts are very important particularly for special occasion like 15th August, 26th January, festival/fair/tourism and also for VVIP movements. Though the Local heavy rainfall Forecasts are issued for 7 days (or some time for special occasions the forecasts are issued 10 days to two weeks in advance) but its utility is increased manifold upto 48 hours so the forecasters need to be accurate in terms of time and space as the lead time decreases.

DAY-01 DAY-02 DAY-03 DAY-04 DAY-05 DAY-06 DAY-07

Please check the Date of Rainfall Intensity Forecast as different Models has different updation time

DAY-01 SUB-DIVISION HEAVY RAINFALL FORECAST

S.NO.	SUB-DIVISION	BASED ON:12Z07012025 :VALID FOR:09012025	BASED ON:12Z07012025 :VALID FOR:09012025	BASED ON:00Z31122024 :VALID FOR:01012025	BASED ON:12Z07012025 :VALID FOR:09012025	BASED ON:00Z31122024 :VALID FOR:01012025	BASED ON:12Z30122024 :VALID FOR:01012025	BASED ON:12Z07012025 :VALID FOR:09012025	BASED ON:00Z31122024 :VALID FOR:01012025
		GFS MEAN(MAX)	JMA MEAN(MAX)	NCUM MEAN(MAX)	NCEP_GFS MEAN(MAX)	GEFS MEAN(MAX)	NEPS MEAN(MAX)	ECMWF MEAN(MAX)	MME MEAN(MAX)
01	A & N ISLAND	9 (37)	7 (23)	5 (49)	7 (36)	3 (30)	4 (36)	13 (51)	3 (35)
02	ARUNACHAL PRADESH	1 (19)	2 (13)	1 (6)	2 (7)	1 (3)	1 (8)	5 (70)	0 (4)
03	ASSAM & MEGHALAYA	1 (7)	1 (9)	1 (2)	1 (3)	0 (0)	1 (2)	2 (8)	0 (1)
04	N M M T	1 (5)	1 (5)	1 (4)	1 (2)	0 (1)	1 (2)	1 (7)	0 (1)
05	SHWB & SIKKIM	0 (1)	1 (3)	1 (2)	1 (1)	0 (1)	1 (2)	1 (6)	0 (2)
06	GANGETIC WEST BENGAL	0 (0)	0 (1)	0 (1)	0 (0)	0 (0)	0 (1)	1 (6)	0 (1)
07	ORISSA	0 (0)	0 (1)	1 (1)	0 (0)	0 (1)	1 (1)	1 (3)	0 (1)
08	JHARKHAND	0 (0)	0 (0)	0 (1)	0 (0)	0 (0)	0 (1)	1 (4)	0 (0)
09	BIHAR	0 (0)	0 (1)	0 (1)	0 (0)	0 (0)	0 (1)	1 (3)	0 (0)

Fig 6. Met-sub-division forecast from 7 different models with MME at NWP site of IMD

Decision making & preparation of final forecast:

- Based on all these inputs from NWP models an objective consensus is drawn with respect to occurrence/non-occurrence of the event (Both deterministic and probabilistic), its time of occurrence, its duration, its dissipation **(Fig. 7).**
- Based on model diagnostic/prognostics and the observations from Satellite/Radar/AWS/ARG and synoptic station, a subjective guidance is developed to moderate the objective consensus.

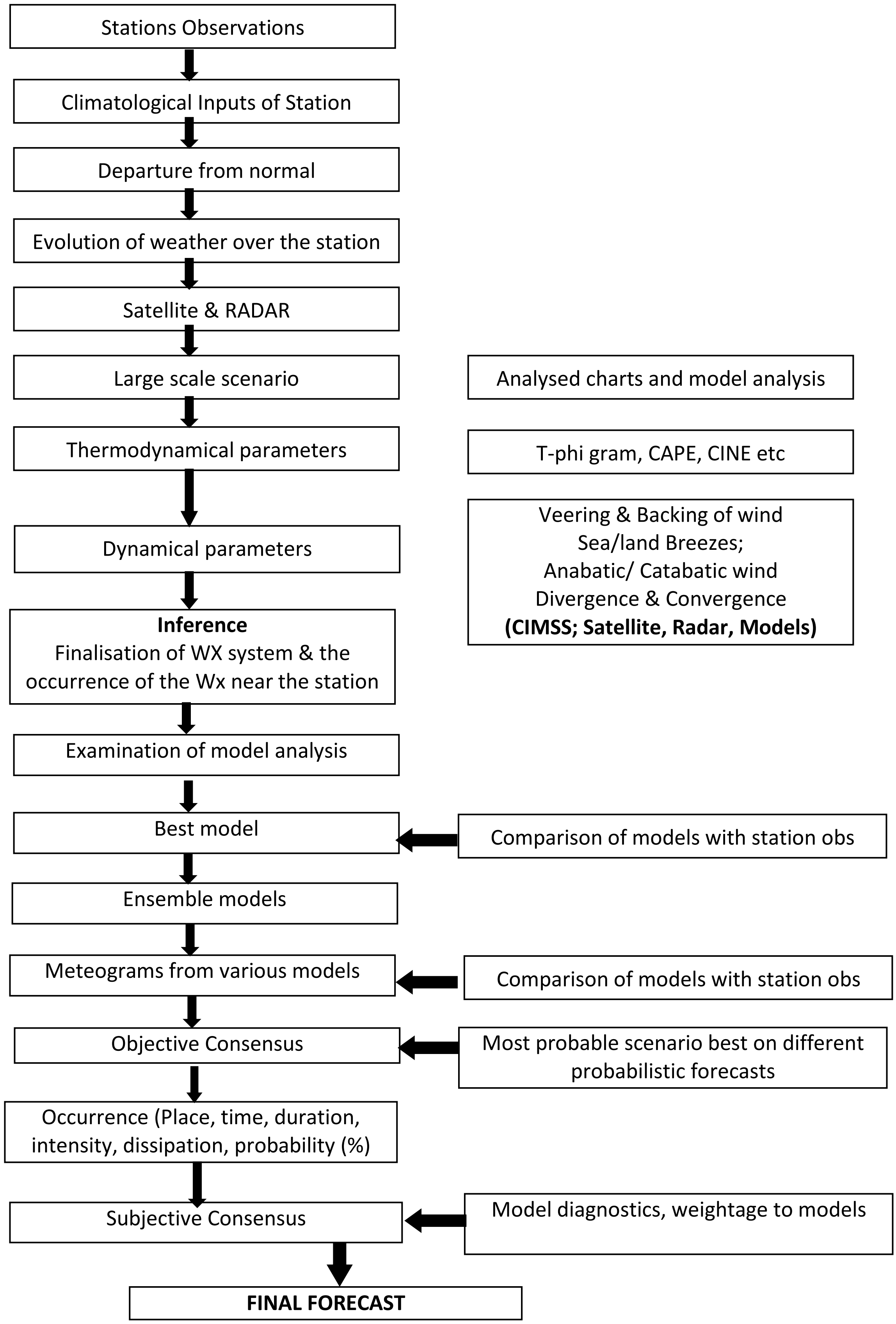


Fig 7: Decision Making Process for Local heavy rainfall Forecast

- For this purpose, the individual model analysis for that station is compared with the actual observation and hence the initial value of the model can be modified and hence the forecast can also be modified.
- The available forecasters consult with each other to exchange their knowledge, expertise, experience to arrive at subjective consensus.
- In case of forecast for VVIP user it has to be approved by Director General of Meteorology 2 days prior to the target date.
- In other cases, the MC/RMC in charge/Head (NWFC) approves the forecast.

Meteograms of Location:

Meteograms of various locations are also available based on GFS, WRF, NCUM and NEPS model.

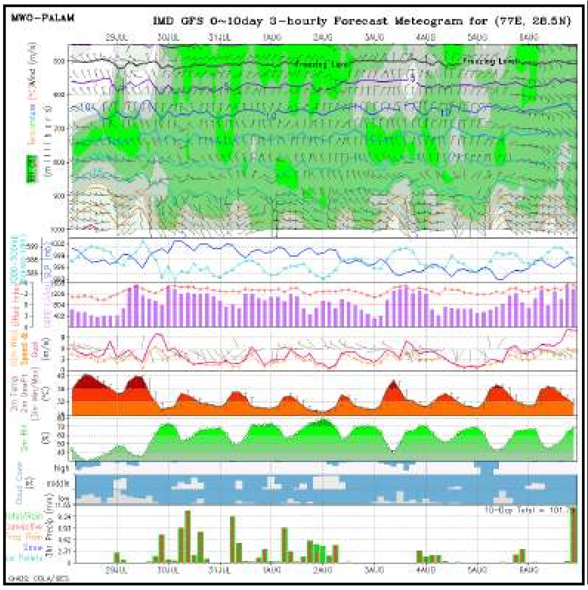


Figure 8a: GFS Meteogram

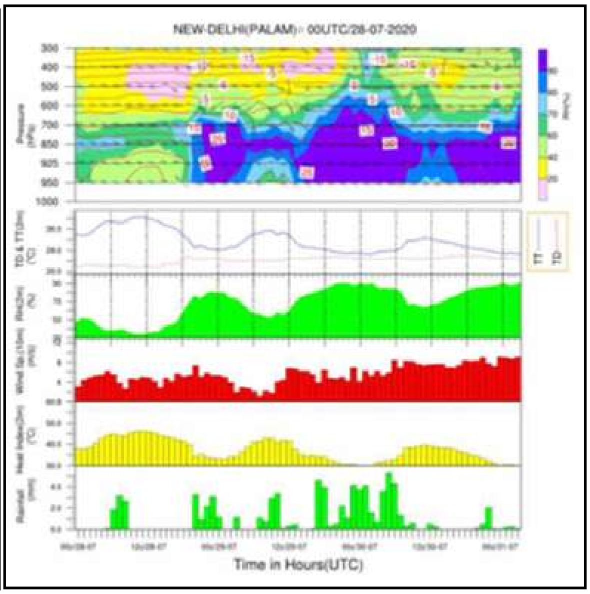


Figure 8b: WRF Meteogram

Table 4: Sample of Objective Consensus for Location specific rainfall

DATE	METEOGRAMS	RAINFALL	AMOUNT of Rainfall (mm) valid for 15th August			
			0_6 UTC	6_12 UTC	12_18 UTC	18_24 UTC
15-08-2020	ECMWF	YES	1.5 (Max=3)	4.5 (Max=10)	1 (Max=11)	3 (Max=7)
	GEFS	YES	8 (Max=19)	0 (Max=1)	2 (Max=4)	3 (Max=12)
	GFS	--				
	UKMO	YES	4 (Max=6)	2 (Max=4)	1 (Max=3)	4.5 (Max=12)

	NCUM	YES	3	0	0	1
	NCUM-EPS	YES	5 (Max=8)	4 (Max=7)	0 (Max=2)	3 (Max=13)
	Mean Rainfall		4 (Max=19)	2 (Max =10)	1 (Max =11)	3 (Max =13)

3.3.3.3. Threshold based IBF and RBW, validity, update timings and contests of Warning symbols and Colour codes.

As per latest Forecasting Circular (01/2024) issued by IMD dated 20/08/2024

1. Bulletins issued by NWFC and all MCs/RMCs (viz. State daily weather report and warning bulletins issued twice a day) should be complete in all respects including all relevant information in a single document. The MC/RMC bulletin should include the following:

a) main weather systems, b) observed significant weather, c) forecast for seven days and warning for next 5 days at district level with IBF up to 5 days, in colour codes d) impacts expected, e) action suggested, f) flash flood guidance (FFG), and associated graphics and legends.

2. The Orange and Red colour warnings will be issued upto 3 days. The impact expected & action suggested will be included for Orange and Red colour warning only.

3. MC/RMCs and NWFC may consider giving orange colour warnings for day 4 and 5 in following cases:

a) If heavy rainfall event is expected to continue over the same area (district/subdivision) upto day 4/day 5.

b) If day 4/day 5 prediction is of high-confidence, such as the case with heavy rainfall due to low/depression/cyclones, and heat wave, cold wave etc.

4. District-wise FFG Map is prepared by Hydromet Division. The same should be included if it comes under the area of jurisdiction of concerned MC/RMC. The name of districts under flash flood guidance should be mentioned in text bulletin by Hydromet Division. The Decision Support System (DSS) unit will make provision for the superimposition of this product on the river catchment and district shape files.

5. The Graphics in the bulletin issued by MC/RMC/NWFC will include a) forecast, b) warning, c) flash flood guidance, d) observed weather during the past 24 hrs, e) special maps, if any, e.g. cyclone/depression track/wind distribution, heat wave & cold wave graphics, thunderstorms etc.

6. **The following rainfall thresholds and relevant color codes are to be followed for the vulnerable zones to issue Heavy Rainfall IBF & Risk Based Warning:**

a) For hilly and landslide-vulnerable districts of Sub-Himalayan West Bengal & Sikkim, the Western Himalayan region, Western Ghats, and Northeastern states, rainfall thresholds for issuing IBF are given below:

Rainfall thresholds	Moderate to heavy (≥ 5 cm)	Heavy to very heavy (≥ 10 cm)	Very heavy to extremely heavy (≥ 15 cm)
Colour	Yellow	Orange	Red

Landslide susceptibility information for the districts is available at the link https://www.gsi.gov.in/webcenter/portal/OCBIS/pageQuickLinks/pageNLSM. It should be used while assessing the impact of heavy rainfall leading to landslide/landslip/mudslide/mudslip/mud sink/land sink.

Concerned MC and RMC should identify such landslide prone districts. These districts names should be included in the heavy rainfall warning bulletin as and when there is a warning as per the above threshold.

b) For urban areas (like Delhi, Mumbai, Kolkata, Chennai, Bangalore, Hyderabad, and any other cities), a yellow warning with corresponding IBF (damage expected and action suggested) can be issued when the city is expected to get 24 hrs rainfall of 5 cm or more considering the expected vulnerability and impact expected to the district.

The following color codes with corresponding IBF are to be followed in such cases:

Rainfall thresholds	Moderate rainfall (≥ 5 cm)	Heavy rainfall (≥7 cm)	Very heavy to extremely heavy rainfall (≥12 cm)
Color	Yellow	Orange	Red

The districts covered by the mega cities will have the existing criteria and colour otherwise. The concerned MC/ RMC may consider the rainfall distribution during past 2-3 days as per SOP, soil condition, physiography, rainfall intensity and persistence, vulnerability, and probabilities of predicted rainfall etc. as per SOP, and judiciously decide the above colour coded warnings.

c) Rainfall threshold for issuing IBF for Ladakh (Cold Desert, Hilly Area with loose soil) will be as follow:

Yellow: 15mm, **Orange:**16-30mm, **Red:** > 30mm

7. Archival of all forecast and warning bulletins, special messages, and press releases will be made locally by the MCs/RMCs/NWFC.

8. Maintenance of consistency and coherency: The warnings over a particular area should be both consistent and coherent among the forecasting offices within MCs and among different MCs/RMCs. Hence, it should be cross-checked before issuing the bulletin and product. For example, warnings issued by FMO, MC, and RMC for a river catchment and concerned districts within river catchment should be consistent and coherent.

9. All warnings should be in both the text as well as in graphical format (information redundancy). These should be cross verified. It should be ensured that the impact expected and action suggested are also provided for all warnings in the same bulletin.

10. In the Yellow warning legend “Be updated” will be replaced by “Be Aware”. In the Orange warning legend “Be prepared” will be replaced by “Be prepared to take action”.

11. Extended Range Forecast Bulletin will be issued on every Thursday along with the expected impact and action suggested by NWFC/CWD/MCs and RMCs for the vulnerable areas of the state/region.

12. Agro-met advisories issued by MCs, RMCs, AMFUs, & CRS-Pune on Tuesday and Friday should incorporate heavy rainfall warnings & their impact and action suggested. The daily heavy rainfall warning issued by MCs/RMCs/NWFC and cyclone warnings/low pressure systems should also be communicated to farmers.

13. Flood Meteorological Office (FMO) bulletins should also include heavy rainfall warning, flash flood guidance, impact expected and action suggested.

14. The Validity period of quantitative precipitation forecast and Hydromet bulletins issued by FMO will be extended up to 7 days.

15. All MCs/RMCs should mandatorily disseminate Forecasts/ Nowcasts/ Warnings:
    - Through social media platforms (such as WhatsApp groups of respective State/UTs, Facebook, and Twitter etc.).
    - Redundancy in dissemination must be ensured.

16. The concerned authorities (such as Heads of SDMA/SEOC, Relief/Revenue secretaries etc.) should be orally briefed and such interactions should be recorded in a register by the Head of the office.

Four colour codes green, yellow, orange and red are in use **(Fig. 9)**. It is recommended to use different symbols for heavy rainfall categories of heavy rainfall with same colour codes for better understanding.

WARNING (TAKE ACTION)
ALERT (BE PREPARED)
WATCH (BE UPDATED)
NO WARNING (NO ACTION)

Fig. 9: Heavy rainfall symbol and colour codes

3.3.3.4. Product generation and Dissemination Heavy rainfall warning bulletins along with other warnings are being issued four times a day based on (00UTC, 0300 UTC, 0900 UTC, 1200 UTC). Warnings are being disseminated through all latest means including webpage, email, social media, common alert protocol, Mobile apps etc.

Presently heavy rainfall warnings are being issued for five days in addition to other weather events like thunderstorm etc. at district levels and up to 7 days at meteorological subdivision levels. Sample heavy rainfall warnings which include other warnings for Day 1 are given at **Fig. 10.** Similar maps are being disseminated for D1-D5. District wise heavy rainfall warnings for 5 days are being disseminated by MCs (**Fig. 11**).

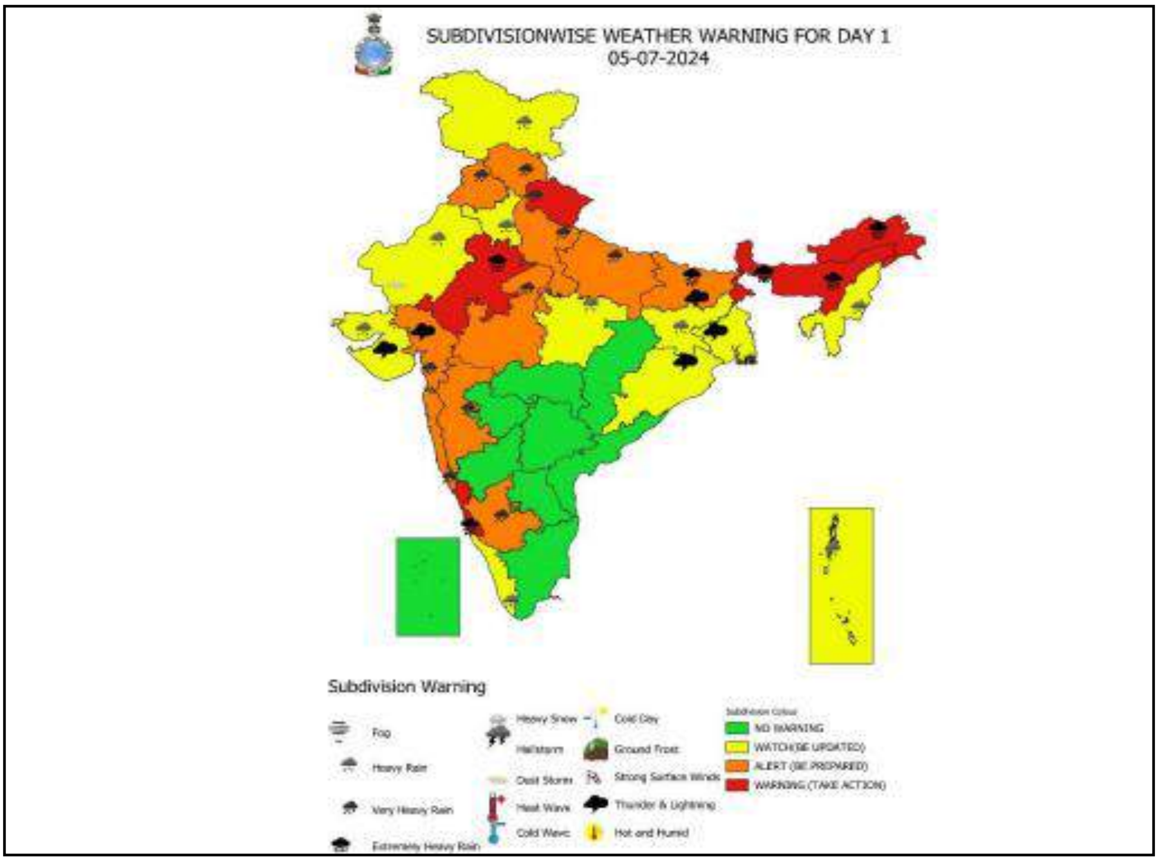


Fig. 10 Weather Warning Map issued by IMD on 05th July 2024 based on 03 UTC valid for next 24 hours till 03 UTC of 06th July 2024.

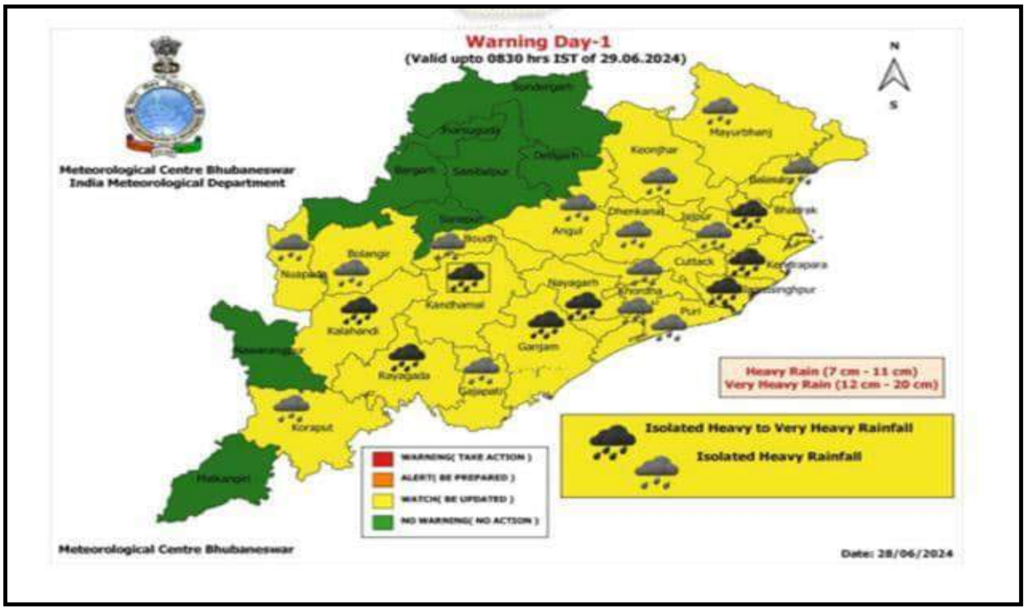


Fig.11. District wise Weather Warning Map issued on 28th June, 2024 based on 03 UTC by MC Bhubaneswar valid for next 24 hours till 03 UTC of 29th July, 2024.

The following are the dissemination modules:

- IMD Website (IMD https://mausam.imd.gov.in/, https://www.imdpune.gov.in/, Website of state MC/RMC), E-Mail
- RSMC website (https://rsmcnewdelhi.imd.gov.in/) for tropical cyclones over north Indian Ocean
- WhatsApp group and Special WhatsApp group for Extreme severe Weather
- SMS and emails: In case of severe weather, warning dissemination is done via email and SMS to registered users and stake holders.
- Mobile Apps: IMD has mobile applications Mausam/ Meghdoot/ DAMINI/ RAIN ALARM/ UMANG for weather information and warning dissemination.
- CAP alerts: IMD has started CAP (Common Alerting Protocol) alerts to disseminate timely and meaningful warning information about the possible severe weather like heavy rainfall, lightning, Thunderstorm, Dust Storm etc.
- VHF/HFRT/Police Wireless, Aeronautical Fixed Terminal Network, Global telecommunication system (GTS), NAVTEX , Internet (e-mail), ftp
- Mass Media: PB & AIR, DD Kisan, other TV, RADIO (AM, FM, Community Radio, Private TV), News Papers,
- **Social Media and YouTube- Facebook, Twitter, Instagram, BLOG-Link and ID**
- ✓ **Twitter: https://twitter.com/Indiametdept**
- ✓ **X::https://www.facebook.com/India.Meteorological.Department/**
- ✓ **Blog: https://imdweather1875.wordpress.com/**

- ✓ **Instagram:https://www.instagram.com/mausam_nwfc**
- ✓ **YouTube:https://www.youtube.com/channel/UC_qxTReoq07UVARm87CuyQw**

At Nowcasts scale, IMD is issuing warnings for heavy rainfall with validity of 3 hours **(Fig 12).** The same is available at mausam.imd.gov.in. Skill of heavy rainfall forecasts recent years and past years in terms of Probability of Detection (POD) since 2002 are given in **Fig. 13.** It shows:

- Forecast issued 24 hrs ahead of occurrence has a skill (Probability of Detection 80%
- Day 5 skill in 2023 (53%) is better than Day 1 skill in 2016 (52%) and all proceeding years.
- Hence, there is improvement in lead period of forecast by 4 days

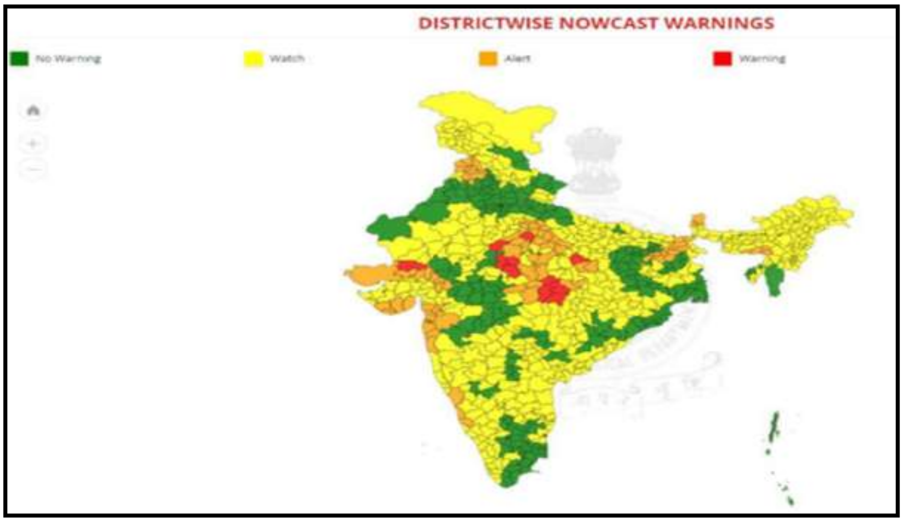


Fig. 12. Warning Map issued at mid night on 05th July 2024 with validity 3 hours.

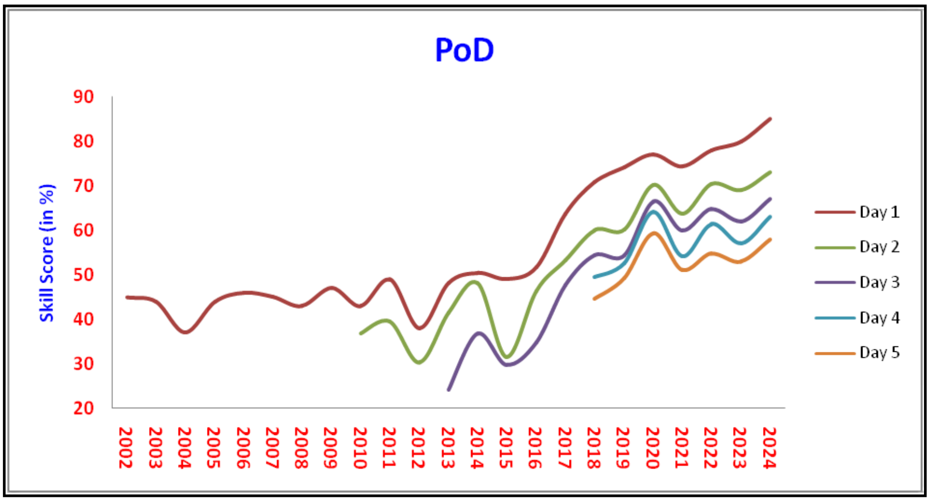


Fig. 13. Probability of detection (POD)) of heavy rainfall warning at met. subdivision level issued by IMD during monsoon season (2002-2024)

Heavy rainfall forecast and warning and IBF-Collaborating decision making:

Currently IMD considers all rainfall products and all model forecasts to arrive at a consensus-based decision and daily a National VC is conducted to discuss it and for value addition. In this CVC, FFGS products are also discussed for providing Hazard based IBF. Following are some of the products referred daily for heavy rainfall warnings at Very Short Range to Short Range scale. Fig 14 to 19b shows various products currently in use by IMD.

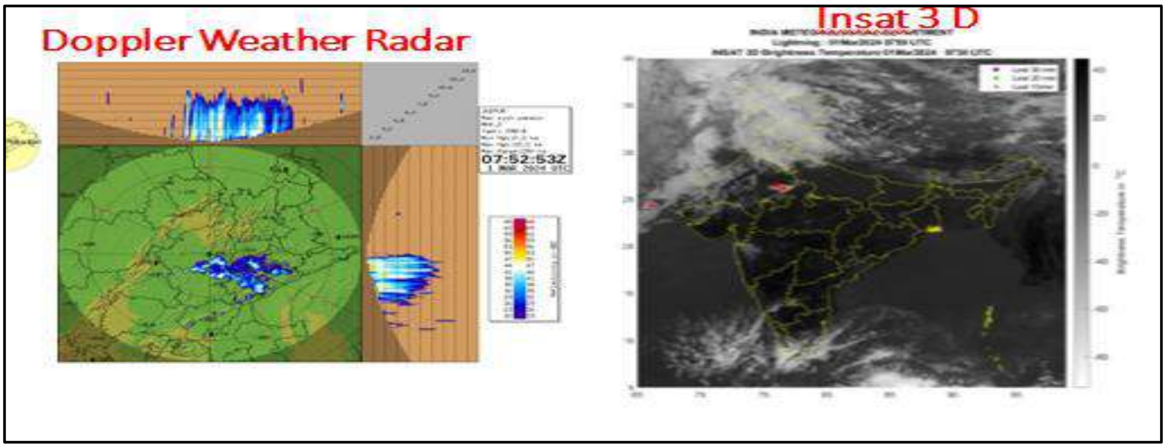


Fig 14: Radar and Satellite

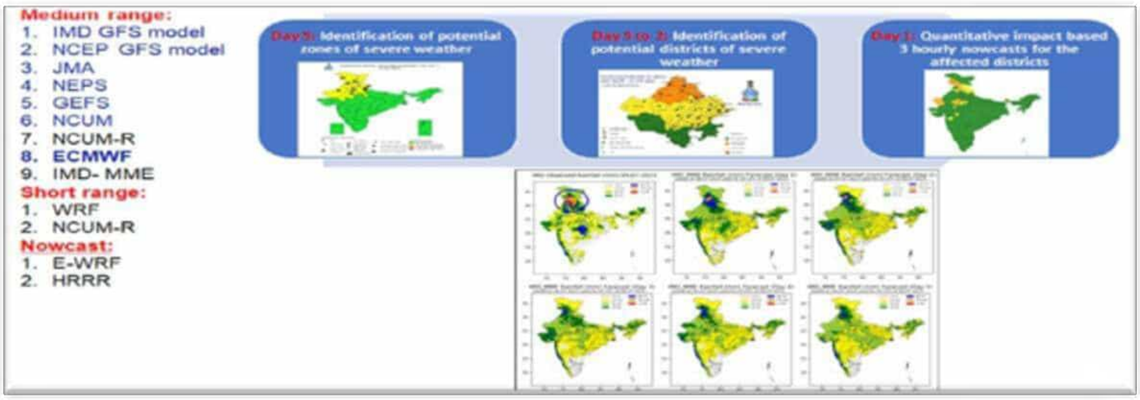


Fig 15: NWP models

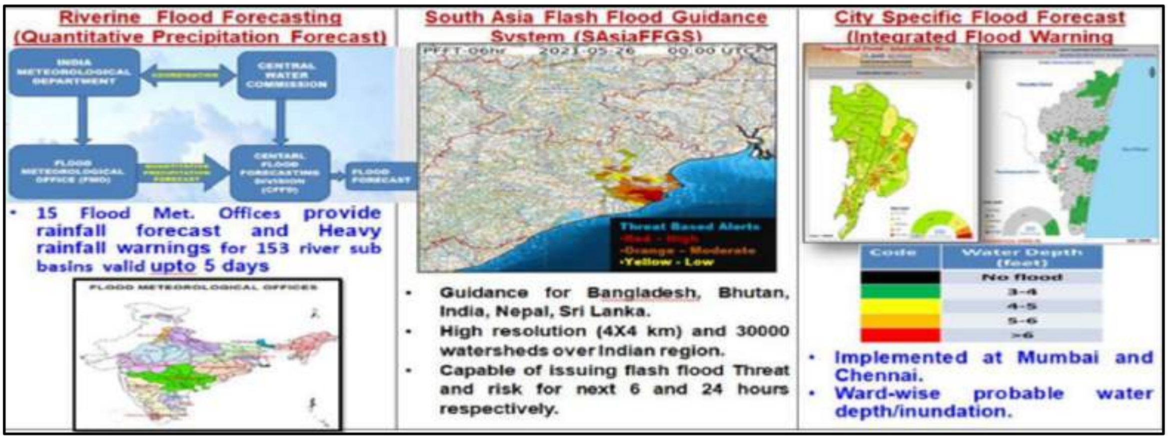


Fig 16: Hydrological DSS and FFGS, I-flows

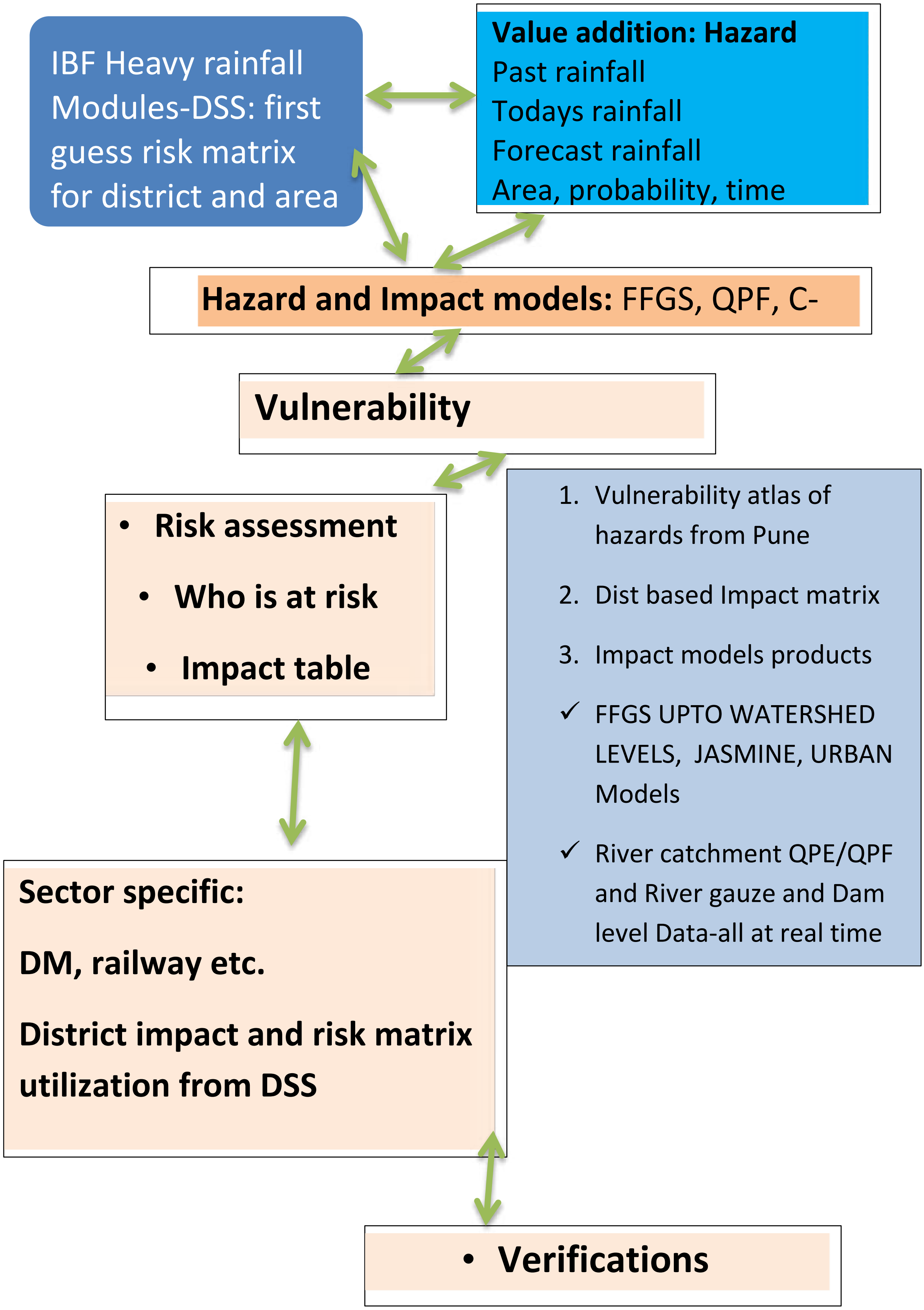


Fig 17. Block diagram of IMD Heavy rainfall DSS-IBF

District level IBF- Flow Chart of IBF Impact/Risk Matrix Formulation

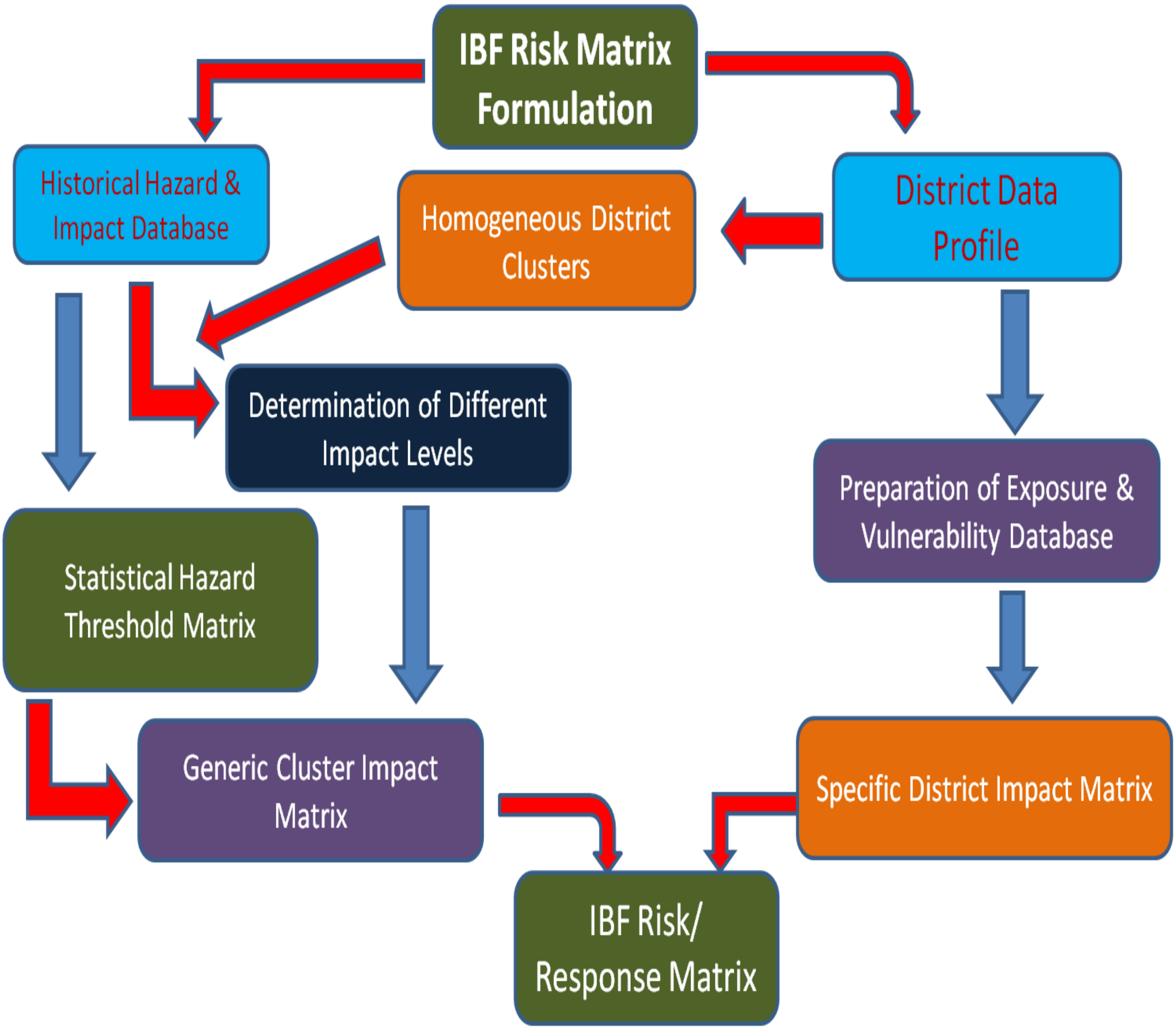


Fig 18: Block diagram of state IBF

Effective utilisation of IMD-GIS Decision Support System

1. **Observational Part:**
   i. Climatological Extreme Data (CRS, Pune)
   ii. DRMS Point & Analysed Raster Rainfall Data (Cumulative Upto 5 Days Lag)
   iii. 15 Minute Real Time AWS/ARG Rainfall & 3 Hourly SYNOP Rainfall Data
   iv. GPM real-time 3 hourly cumulative rainfall data
   v. Synoptic, RSRW, PBO, METAR, Radar & Satellite Data
   vi. Various Synoptic Charts, Prognostics & Diagnostic Parameters

2. NWP Part:

i. 5 Day Model (GFS/GEFS/NCUM/WRF/NEPS/JMA/ECMWF/MME) Forecast Products

ii. SAFFGS data (HydroMet. Division)

iii. Various Model Prognostic & Diagnostic Products

3. Decision Part:

i. Exposure Data

ii. Vulnerability Data (BMTPC/CRS Pune/Local Data)

iii. NWP & Conventional Impact Matrix

4. Bulletin Generation:

i. GIS Polygon maps to be included for a selected domain in Nowcast Mode.

ii. SOP Document/Manual for IBF using GIS Heavy Rainfall Module.

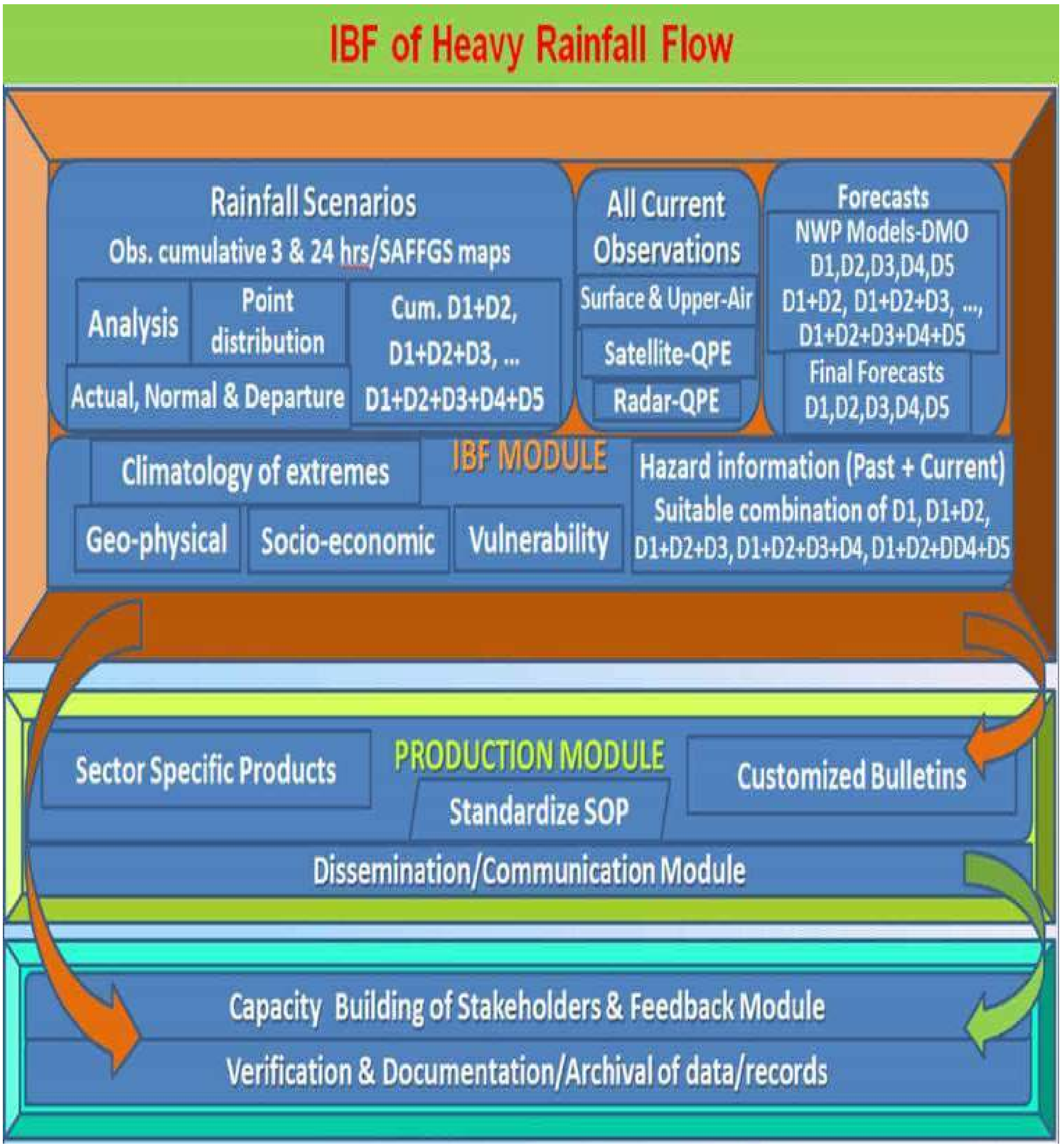
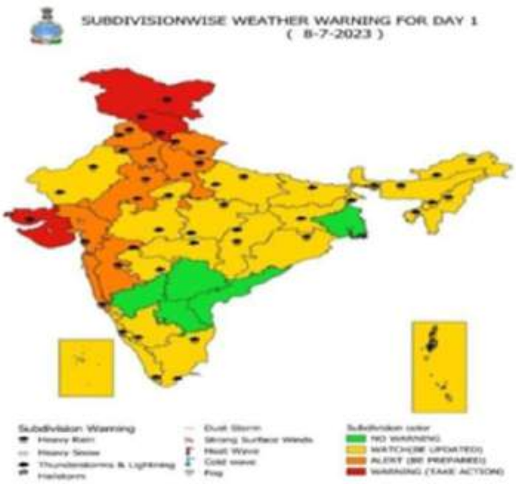


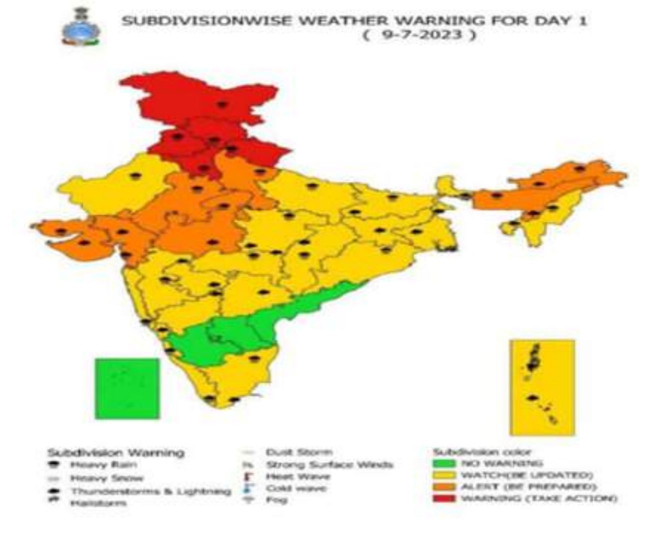
Fig 19a: Heavy Rainfall IBF: Decision Support System (DSS)

Fig 19b Climate vulnerability risk atlas for IBF for different hazards including heavy rainfall related flood hazards

An example of Real time IBF at Met sub-division levels by NWFC IMD new Delhi and district based for next 5 days issued by MC during extremely heavy rainfall episodes in the region for the period 8-10 July 2023 noted in Fig 20 and 21 :

<table>
<tr>
<td>Colour code warning for northwest India and Gujarat state on 08th & 09th July, 2023.</td>
<td>Impact & Action Suggested due to very heavy/extremely heavy rainfall over Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Haryana-Chandigarh-Delhi, Punjab, West Uttar Pradesh, East Rajasthan and Gujarat state on 08th & 09th July, 2023.</td>
</tr>
<tr>
<td>


</td>
<td><u>A. Impact Expected</u>
□ Localized Flooding of roads, water logging in low lying areas and closure of underpasses mainly in urban areas of the above region.
□ Occasional reduction in visibility due to heavy rainfall.
□ Disruption of traffic in major cities due to water logging in roads leading to increased travel time.
□ Minor damage to kutcha roads.
□ Possibilities of damage to vulnerable structure.</td>
</tr>
</table>

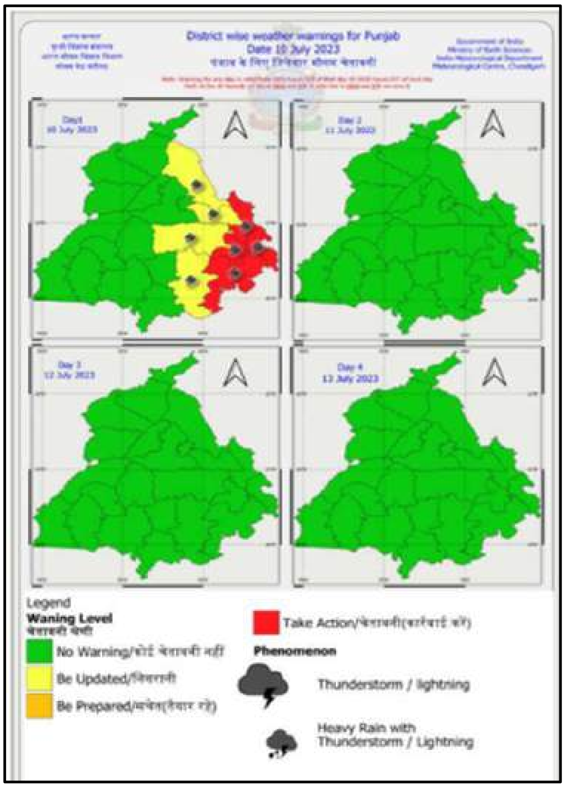


- **Localized Landslides/Mudslides**
- **Damage to horticulture and standing crops in some areas due to inundation.**
- **It may lead to riverine flooding in some river catchments (for riverine flooding please visit Web page of CWC).**

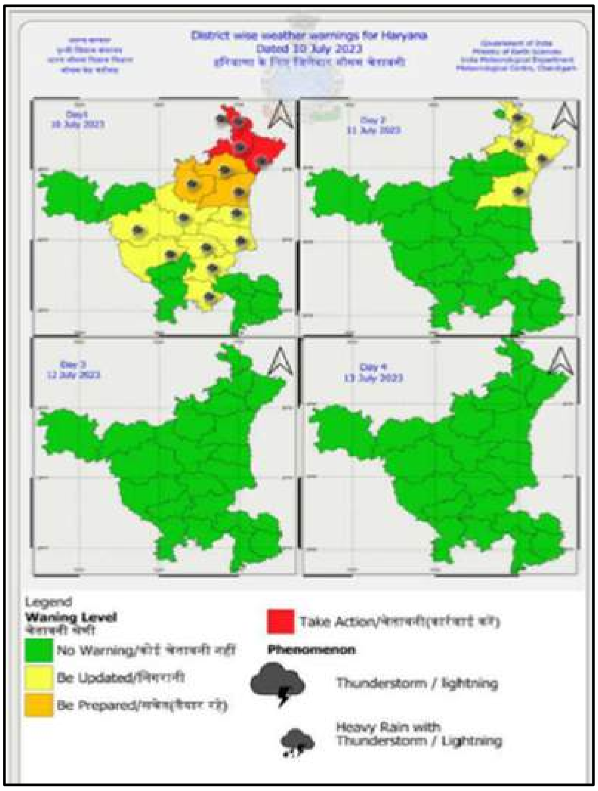
B. Action Suggested

- **Check for traffic congestion on your route before leaving for your destination.**
- **Follow any traffic advisories that are issued in this regard.**
- **Avoid going to areas that face the water logging problems often.**
- **Avoid staying in vulnerable structure.**

Fig 20. District wise weather warnings issued for haryana (including Chandigarh) and Punjab dated 05.07.2023



21(a) Punjab



21 (b) Haryana & Chandigarh

Fig 21 District wise rainfall warning for Punjab, Haryana & Chandigarh issued on 10th July 2023

3.3.3.5. Review of Current Capability (Global status)

We have referred current status of developed countries like Japan, USA and also China for completing the vision document in heavy rainfall forecast and warning.

- **The observational Network:**

  Japan has a total of 1460 rainfall stations with about 160 Surface Observatory with a total of 1,300 AMeDS (Automatic Meteorological Data Acquisition System) (refer Fig 22). It has also around 10000 telemetric rainfall monitoring networks in collaboration with river authority. The country has rainfall station at each about 260 sq km. The real time rainfall map generated at each 15 to 3-h gap with combination from radar, satellite and gauge data at real time.

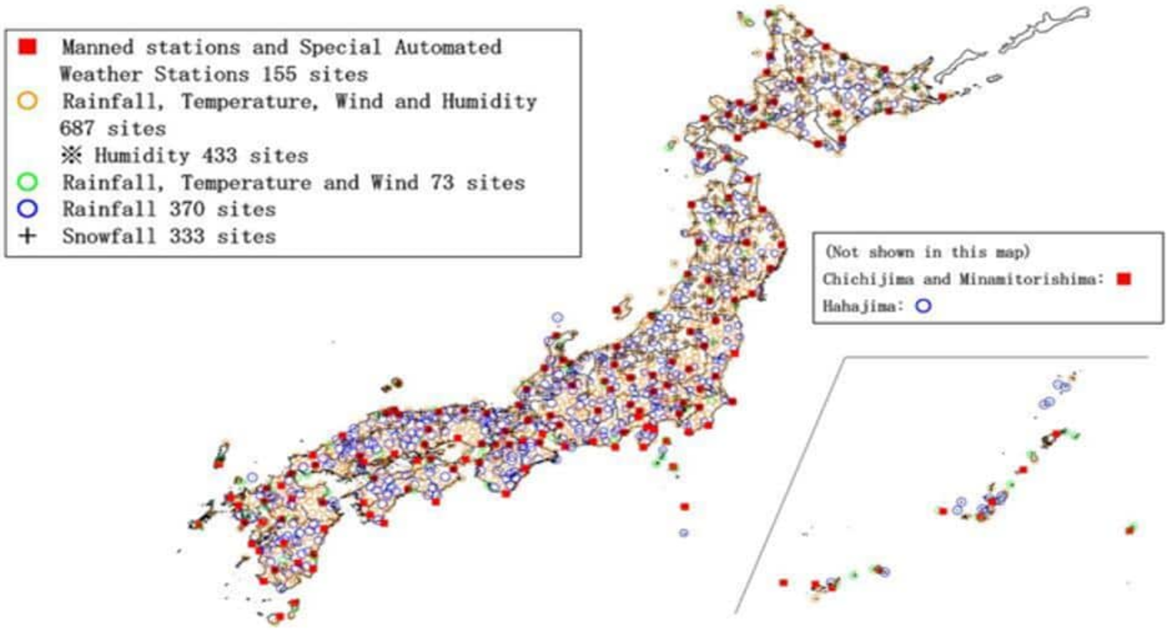


Fig 22: Japan rainfall station by JMA

For USA, there is no such observational density available for the country as whole while documenting this, However, when it comes to network density of weather stations, all data -- especially networks of data available with all states and private agencies. We tried to refer such sources. **Fig 23** show weather station networks and climate monitoring networks over USA. It shows the NWS uses data from following networks which have been installed and maintained through coloration PPP model, to fulfil its mission of protection of life and property and enhancement of the national economy:

- ASOS (Automated Surface Observation System): NWS and FAA observations from airports across the nation, taken continuously by automated instrumentation and, at some locations, augmented by human observers. ASOS is the backbone of the U.S. surface weather observation system. There are 9 ASOS units in Kentucky and 12 in Indiana (over 900 nationwide).
- AWOS (Automated Weather Observation Systems): Similar to ASOS and complementary to the ASOS network but generally at smaller airports. There are 11 in Kentucky and 15 in Indiana (over 1100 nationwide).

- NWS Cooperative Observers: Volunteers who report daily weather such as high/low temperatures, the number of observers nationwide, currently around 33,000, has been on the decline for several years.
- CoCoRaHS (Community Collaborative Rain, Hail, and Snow Network: A network of thousands of volunteers who measure rain and snow each day, usually around 7am local time.
- Kentucky Mesonet: Established by Western Kentucky University in 2007, this is a high-quality local network of automated weather observing equipment at more than 70 sites across Kentucky, with future expansion planned. The equipment is sited to best represent the average weather and climate of the area it serves and provides the NWS with near real-time monitoring (every 5 minutes) via the network's website. Kentucky is very fortunate to be one of a handful of states to possess such a network**.**
- Consumer-grade weather stations: Though not part of an "official" network, the NWS does use personal weather station data as one of the arrows in our weather monitoring quiver. These stations, such as the Davis Instruments equipment used by WKU's White Squirrel Weather, can provide high-resolution data to assist the NWS in monitoring meso- and micro-scale weather variations that may be too small in size to be captured by one of the other networks. When transmitted online via sites such as the Citizens Weather Observation Program and Weather Underground, NWS meteorologists can use the data either in near real-time and when reviewing past weather events.

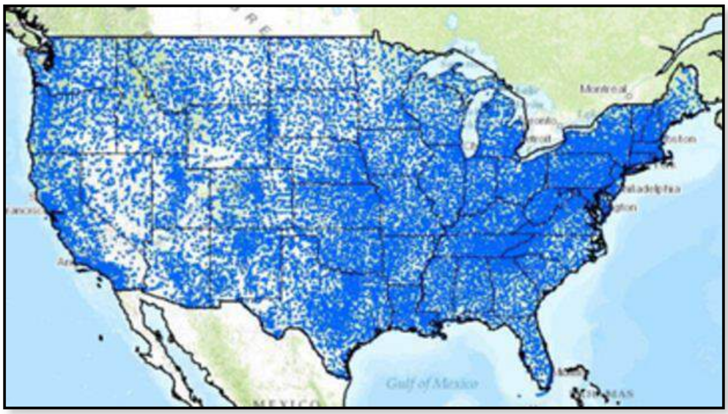


Fig. 23 (a): weather station networks over USA

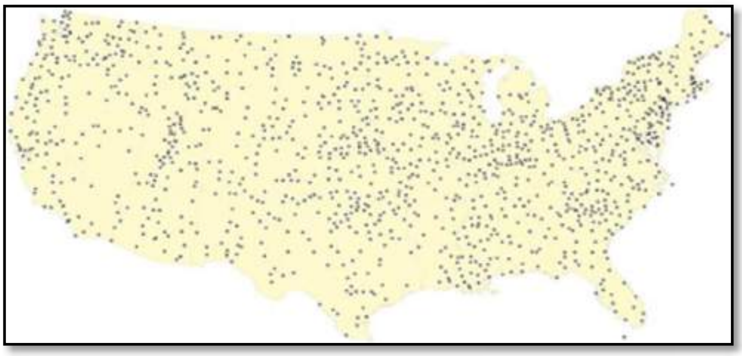


Fig 23 (b): climate monitoring networks over USA

Fig 23: weather station networks and climate monitoring networks over USA

China has set up an observation system composed of 34000 automatic weather stations, 164 new-generation weather radars, 260 isolated warning radars, 8 sets of airborne detection system. At present, ground-based meteorological observation stations have achieved full coverage of towns and villages nationwide, with all stations fully automated, and the transmission efficiency of observation data has been increased from minutes to seconds. Initially, full coverage of the observation of key elements of basic climate variables in 65 climate zones nationwide has been made possible. The AWS measures the hourly precipitation from May–September and ceases measurements from October to the following April over Northern and Western China due to low temperatures. However, the spatial distribution of the gauges is still highly inhomogeneous, as shown in **Fig 24** Below. In Southeastern China, the gauge density is high with the mean distance between a gauge and its nearest gauge 9.6 km, compared to more than 500 km over Northwestern China, especially over the Tibetan Plateau. The quality-controlled procedure in the real-time basis has been developed and applied for hourly precipitation observations since 2010. Overall, the density of these stations varies by region. For example, in urban areas, the density can be as high as 1 station per 30 km², while rural areas may have lower densities depending on geographic and climatic conditions

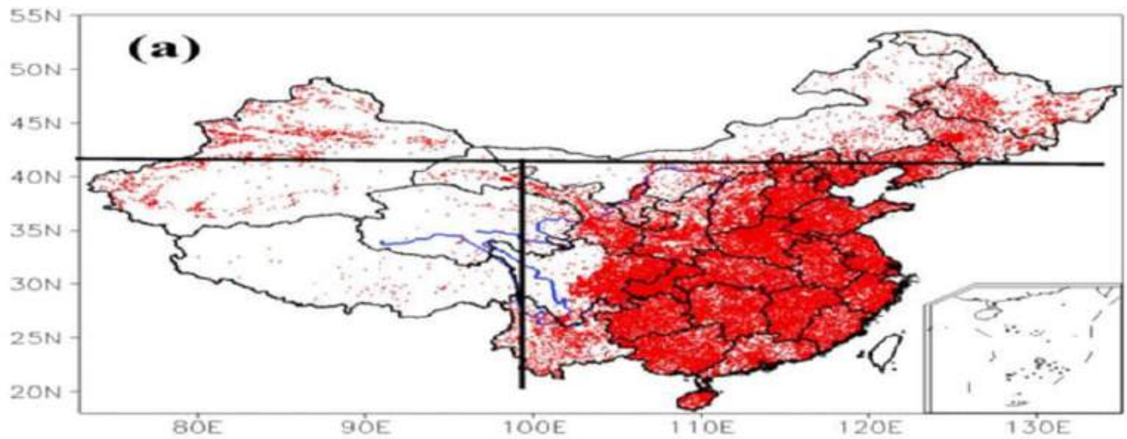


Fig 24: Rainfall monitoring station over China

For UK, the Met Office operates a diverse network of weather stations across the UK, which can be categorized into several types based on their functionality and data collection methods:

1. Automatic Weather Stations (AWS): The Met Office has over 200 automatic weather stations that continuously monitor various meteorological parameters such as air temperature, atmospheric pressure, rainfall, wind speed and direction, humidity, cloud height, and visibility. These stations are typically located about 40 km apart to effectively capture weather patterns across the UK.

2. Manual Weather Stations:

- In addition to automatic stations, there are manual weather stations where observations are recorded by human operators. These stations primarily focus on climate observations, including daily maximum and minimum temperatures and rainfall amounts. Manual observations are often made at specific times, such as 0900 UTC.

3. Synoptic Weather Stations:

- These stations provide synoptic observations at regular intervals (hourly) and are crucial for real-time weather monitoring. They report data such as temperature and cloud cover, which is essential for short-term forecasting.

5. Enhanced SAWS (Synoptic Automatic Weather Station):

This system is an advanced version of the original AWS, capable of producing detailed climate messages in addition to standard synoptic data. It is especially useful in remote locations and has been upgraded to operate effectively in severe weather conditions.

Observations from around 260 UK automatic (synoptic) stations are collected in real time; climate data from these stations also comes in straight after readings are taken. Climate observations from around 140 co-operating observers at manual climate stations are also received in slower time.

All climate stations record daily maximum and minimum air temperature and rainfall amount, recorded over the period 0900-0900UTC (1000-1000BST in summer).

Many stations observe additional elements. The representativity of urban observations to the surrounding urban area can be difficult to judge, and so their data need to be used with caution. Some observations are made from non-standard stations (e.g. located on roof tops) and these are generally not used for routine climate monitoring.

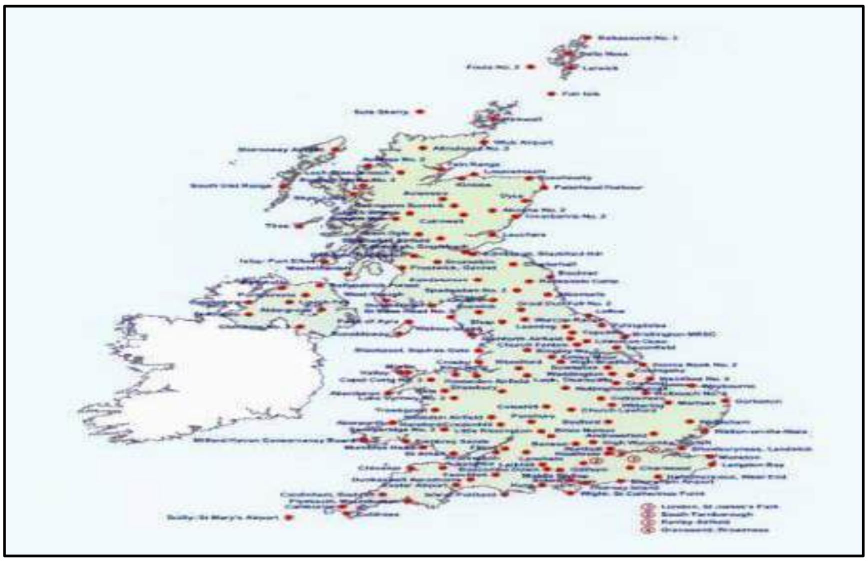


Fig 25: UK observational Network

(Source: https://www.metoffice.gov.uk/weather/guides/observations/uk-observations-network)

❖ **The Forecast:**

For real time warnings and IBF, JMA provides probability information on the risk of severe weather phenomena expected to exceed the warning criteria within the **next five days**. Probability is expressed as "**High" or "Mid**."

Weather Warnings/Advisories	Alert Level	Action to be taken by municipalities	Action to be taken by residents
•Heavy rain emergency warning	5 eq.	Emergency Safety Measures	Evacuate before Alert Level 5 is issued. (A life-threatening situation in which safe evacuation is no longer possible.)
~~ Be sure to evacuate by Alert Level 4 ! ~~~~~~~~~~			
•Landslide alert information •Storm surge emergency warning •Storm surge warning	4 eq.	Evacuation Instruction	All residents should evacuate from affected areas when or before Evacuation Instruction is issued.
•Heavy rain warning (landslide) •Flood warning •Storm surge advisory (when possibility to become warning is high)	3 eq.	Evacuation of the Elderly, Etc.	Elderly people, those with disabilities, and others who may need more time to evacuate should evacuate from affected areas when Evacuation of the Elderly, Etc. is issued.
•Heavy rain advisory •Flood advisory •Storm surge advisory (when possibility to become warning is not referred)	2	Prepare for emergency response	Check evacuation action with a hazard map etc.
•Probability of warnings	1	Prepare for disaster	Prepare for disaster

Fig 26: Sample of Advisory issued by JMA

(Source: https://www.jma.go.jp/jma/en/Emergency_Warning/examples_of_responses.png)

WARNING	A warning is issued when a hazardous weather or hydrologic event is occurring, imminent or likely. A warning means weather conditions pose a threat to life or property. People in the path of the storm need to take protective action.
ADVISORY	An advisory is issued when a hazardous weather or hydrologic event is occurring, imminent or likely. Advisories are for less serious conditions than warnings, that cause significant inconvenience and if caution is not exercised, could lead to situations that may threaten life or property.
WATCH	A watch is used when the risk of a hazardous weather or hydrologic event has increased significantly, but its occurrence, location or timing is still uncertain. It is intended to provide enough lead time so those who need to set their plans in motion can do so. A watch means that hazardous weather is possible. People should have a plan of action in case a storm threatens and they should listen for later information and possible warnings especially when planning travel or outdoor activities.

Fig 27: Sample of Advisory issued in USA
(Source: https://www.weather.gov/sjt/WatchWarningAdvisoryExplained)

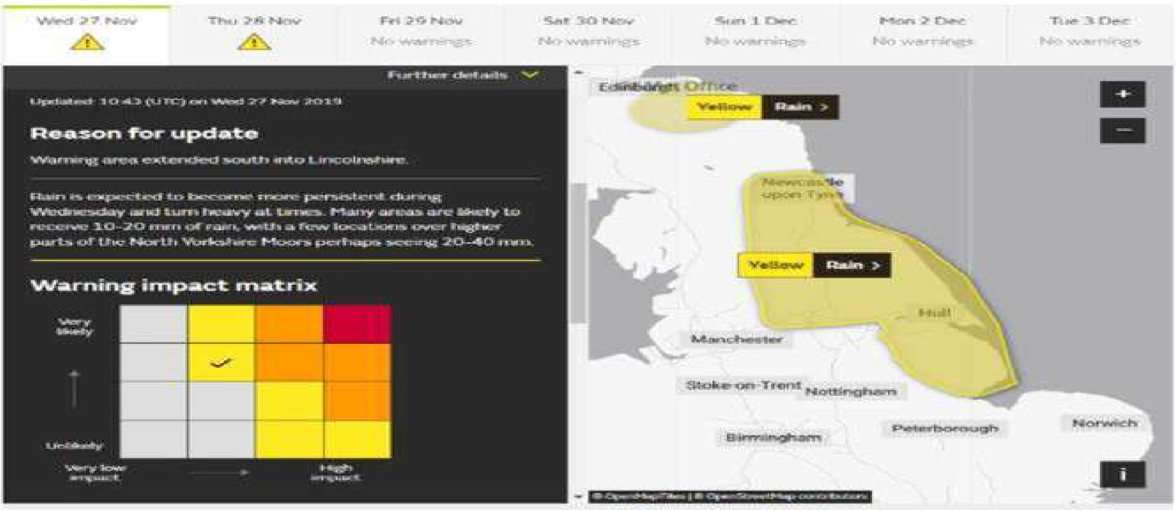


Fig 28: Sample of Advisory issued in UK
(Source: https://www.metoffice.gov.uk/weather/guides/warnings/)

❖ **The Forecast Accuracy:**

The accuracy of weather forecasts in the United States varies significantly depending on the forecast duration **(Table 5).** Beyond Day 7: Forecast accuracy diminishes significantly, with predictions for 10 days or more typically having an accuracy rate of around 50%. Overall, while short-term forecasts (1-3 days) are highly accurate, longer-term forecasts (beyond 5 days) become increasingly uncertain due to the chaotic nature of weather systems and varying regional influences. The accuracy of weather forecasts in the United States varies significantly based on geographic location and the time frame of the forecast. Here are some key findings regarding forecast accuracy:

Table 5: Accuracy of Weather forecasts in USA

Lead Period	Accuracy
Day 1	Accuracy is approximately 96-98%. Forecasts for the same day are highly reliable,
Day 2	Forecast accuracy remains high, around 90%. Predictions for the next day are still quite dependable.
Day 3	Accuracy continues at about 90%, with slight variations depending on geographical factors.
Day 4	The accuracy drops slightly, generally around 80-85%, as weather patterns become more unpredictable.
Day 5	Forecasts are accurate approximately 80-85% of the time, but this can vary significantly by region
Days 6-7	Accuracy decreases further to about 70-80%, particularly in regions with complex weather patterns like the Great Plains, where forecasts may only be reliable for up to 1-2 days.

3.3.4 Challenges and gap areas

As discussed, IMD has various weather forecast models currently running at Indian Institute of Tropical Meteorology (IITM), Pune and National Centre for Medium Range Weather Forecasting (NCMRWF), Noida (Refer Fig 29 for details). Now, anyone can explore the IMD's forecast via modern technologies of communications like the web page, social media platforms i.e. WhatsApp, X, Facebook, Instagram, YouTube handle. Gone, the days when forecast were prepared once for a large–spatial scale and 2 times disseminated on TV. Presently, forecast spatial scale reduced to city & Block levels and temporal scale enhanced to hours. Now, the farmers of our country are directly using the weather and climate services which are helping in the reduction of loss due to severe weather. It has boosted up their yield. Today, IMD is giving a 7 days' city forecast, 5 days' districts and block level forecast and planning for the point specific forecast which earlier just started with monsoon forecast in its initial phase. For IBF and RBW, a SOP is in place to follow by all.

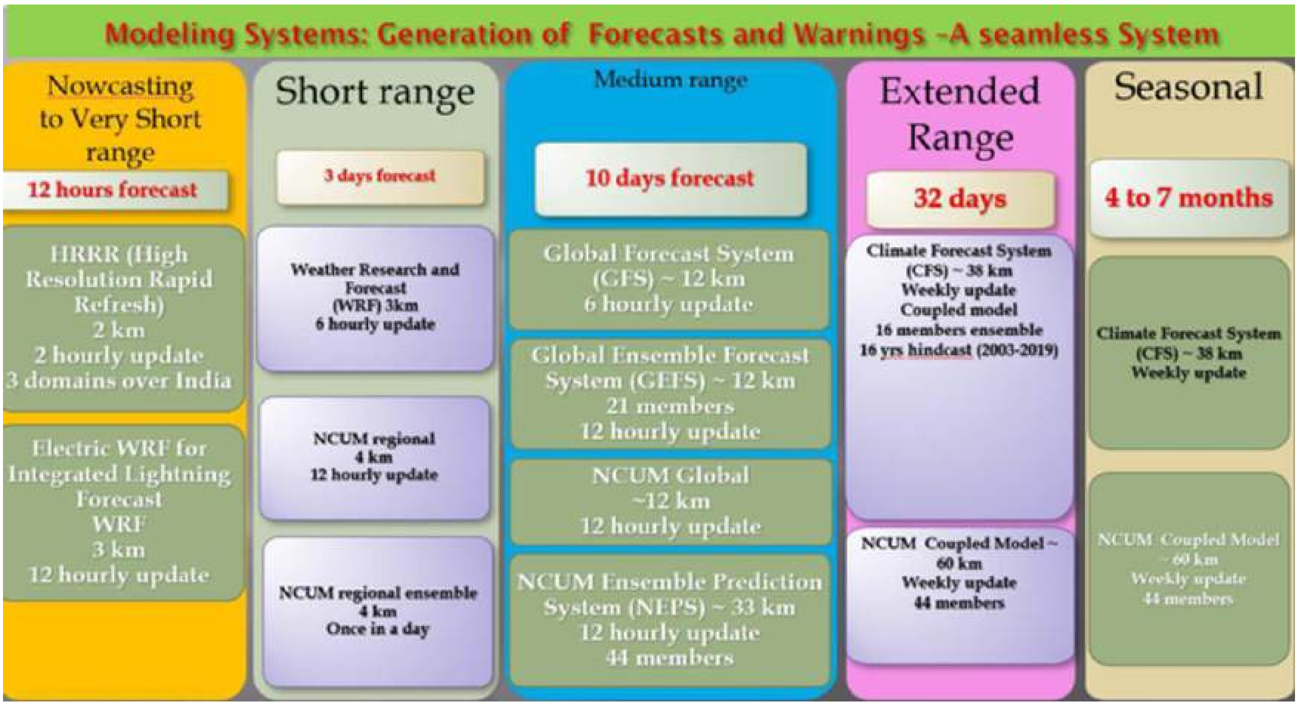


Fig 29: NWP Models support by MoES -IITM, IMD-NCMRWF

IMD's forecast plays a major role from a small farmer's life to a big entrepreneur's life. Government policies are also based on the seasonal forecast. IMD has been more accurate in cyclone intensity and track forecast in the past decade. There has been an increase in validity of forecasts from 2 days in 2006 to 7 days in 2024 and also spatial resolution from meteorological subdivision to block level. Some of the recent achievements are mentioned below:

✓ Augmentation of DWR network, upper air network, GPS Radiosonde, surface observational network, AWS & ARG network cover all the districts of the country.
✓ INSAT-3D or 3DR, Oceansat3 Satellite along with foreign satellites are giving top view of atmosphere.
✓ Enhanced computation power and modelling
✓ Trained Scientists/Meteorologists and Capacity Building

❖ **Gap in observational Network and Reporting frequencies:** The observation density is still lacking in a major portion of the country especially over hilly regions. Ideal observational network for accurate rainfall monitoring needs 1 station at each 10X10 km area. Hence, to scale up this gap, it may be increased upto Gram panchayat/village levels in rural and upto block levels in urban areas. Also, out of current 6600 stations, around 2000 number stations report at 15-minute to 12-hr gap cumulative location based rainfall and rest are 24-hr basis. Hence, it also needs more number of ARG/AWS based rainfall stations across India to capture localized heavy rainfall events which realize at few minutes to 1-hour duration.

❖ **Gap in monitoring and analysis process:** Automatic plotting of rainfall maps at each 30-minute to 1-hr gap. For this Radar and Satellite rain estimates and Gauge based rainfall to be suitably mapped. Though, currently such merged rainfall data are available only using Satellite and gauge data and at real time, it is available for 24-hr scale. Hence all these data need to be automatized and Auto alarm system exceeding some threshold rainfall e.g.- >4 cm/hour may be implemented in DSS/AWS/ARG websites. Based on the synoptic analysis, the weather forecasting for 3 to 6 hours can be made accurate. **Frequent validation and calibration of technical tools** There must be frequent validation and calibration of sensors, AWS, ARGS and other technical tools.

❖ **Gap in modeling:** The gap in Modelling for local convection events involves challenges related to parameterization methods, sub-grid processes, and the high computational requirements for regional models. Localized heavy rainfall in a short time scale is a challenge for models. Hence specific heavy rainfall models to be run with special NWP customized domain-based Models to address orography. IMD currently using Risk matrix based on past impacts and hazards. It needs hazard and impact modelling products to shift to dynamical IBF and RBW system. I-FLOW and C-FLOW are some of the attempt in this direction to address Urban heavy rainfall IBF and flash flood. However, for addressing different regions coastal, hills, main land, specific Hazard and Impact model are need of the hours to include impact of landslide, flood over hilly region and coastal cities.

❖ **Gap in real time forecasting:** Presently, IMD uses both Climatological, synoptic and NWP based products and guidance before issuing rainfall forecast and heavy rainfall warnings. Synoptic methods are available for rainfall for major synoptic systems like LPS, MTC, WD etc, but mapping of rainfall in terms of intensity and areas needs further study and synoptic-climatology maps with respect to location and movements across each area to be prepared. NWP based post processing, customization and validations using longer period hindcasts for each models need to be carried out upto dist. levels across India. This will help to keep the model skill status specific to region or areas and then weight factors and higher priority can be given to a particular model while doing real time forecasting. Over hilly region and also for coastal region, rainfall products from models to be customized by considering topography corrections and by considering sharp terrain and altitude. The forecasting consensus among various models remains a significant challenge for heavy rainfall guidance. While meteorological models have made substantial advancements in recent years, the inherent complexity of heavy rainfall events and the limitations of current models contribute to ongoing uncertainty in rainfall predictions. However, continued improvements in model resolution, ensemble forecasting, and communication strategies are helping forecasters address these challenges more effectively, even though differences in model output and expert interpretation will likely continue to exist.

❖ **Gap areas in Risk and Vulnerability analysis:** For IBF and RBW to be more appropriate, the risk and vulnerability studies based on impacts and hazards to be conducted upto village and block levels and this will be possible if collaboration works conducted with fixed target in coming year.

❖ **Gap in warning bulletins, its generation and dissemination: Currently most of these products are available in static format as PDF and it has limited inter-operability with stakeholders.** The major gap is in the dissemination. The forecast is reaching the state authorities. Many states are actively processing the alerts via SMS too. Sometimes, at village level farmers do not receive the rainfall warnings. Nowcasts for some events like extreme rain is taking a long time to process. Now on many occasions, our scientists are preparing the best forecast but the forecast is unable to reach the public Also, there are many other challenges as documented below which needs to be address earliest:

i. Preparation of Seamless bulletins and warnings in html format, with link to various products and updates

ii. All warnings to be made available in various vernacular/local language as per area or domain it has been issued

iii. IMD must operates its own studio and Digital weather channel at 24X7

iv. Regular Awareness program must be time bound upto school and panchayat level in a planned as per local severe weather and hazards.

v. Directly involving and engaging different sectors in extreme weather events warning systems, active citizen participation during the events, etc. on the ground level.

3.3.5. Vision 2047: Short, Medium and Long

In view of IMDs existing operational real time heavy rainfall forecasting and warning, SOP has considered lead period and spatial coverage as key parameters for integrating with supporting infrastructures such as observations, modeling and DSS accordingly, so any projection or vision have to consider primarily strengthening of all these components accordingly. All these parameters have been while framing the vision for 2047. Further the Vison 2047 has been bifurcated into short, medium and long visions corresponding to next 2-years 2025-2027, subsequent next 10-years 2027-2037 and then last 10 years of the complete period i.e. 2037-2047. By looking at the spatial coverage of current rainfall forecast and heavy rainfall warning services and its temporal available upto district and 5-10 days, the vision has been scaled proportionally by considering both methodology such as business as usual and introduction of special project through fixed period target for improvement of observational and modeling capacity like Mission Mausam 2025-2026. **The targets and vision are given in Table 6 and Table 7 below.**

Table 6: Short to Medium range: Heavy rainfall forecast accuracy improvement with respect to lead time in terms of Day and also areas in terms of Met sub-division-wise, District-wise, Block-wise and Village-wise levels

Parameter	Status in 2024	Goal for 2027	Goal for 2037	Goal for 2047
Heavy rainfall forecast accuracy improvement	**24hrs:** 82%:met. Sub-division 70%:river catchment, district **48hrs:** 75% at	**24hrs:** 90%:met. Sub-division, 80%:river catchment, district , 70%: Block **48hrs:** 85% at	**24hrs:** 95%:met. Sub-division, 85%:river catchment, district , 80%: Block & 50%: village **48hrs:** 90% at met.	**24hrs:** 100%:met. Sub-division, 90%:river catchment, district , 85%: Block & 60%: village **48hrs:**95% at met. Sub-

	met. Sub-division 65%: river catchment, district	met. Sub-division 75%: river catchment, district , 65%: Block	Sub-division 80%: river catchment, district, 75%: Block & 45%: village	division 85%: river catchment, district , 80%: Block & village
	72hrs: 70%: met. Sub-division 60%: river catchment, district	**72hrs:** 80%: met. Sub-division 70%: river catchment, district , 60%: Block	**72hrs:** 85%: met. Sub-division 75%: river catchment, district , 70%: Block	**72hrs:** 90%: met. Sub-division 80%: river catchment, district , 75% Block & 60% village
	96hrs: 65% met. Sub-division 55% : river catchment, district	**96hrs:** 75% met. Sub-division 65% : river catchment, district, 55%: Block	**96hrs:** 80% met. Sub-division 70% : river catchment, district, 60%: Block	**96hrs:** 85% met. Sub-division 75% : river catchment, district, 70% Block & 50% village
	120hrs: 60%:met. Sub-division 50%: river catchment, district	**120hrs:** 70%:met. Sub-division 60%: river catchment, district , 50%: Block	**120hrs:** 75%:met. Sub-division 65%: river catchment, district , 55%: Block	**120hrs:** 80%: met. Sub-division 70%: river catchment, district , 65% Block & 50% village

Table 7: Same as Table 2 but for short to medium range with increasing spatio-temporal scale upto Extended Range scale and upto village levels

Spatial Scale/Temporal Scale	**Status in 2024**	**Goal for 2027**	**Goal for 2037**	**Goal for 2047**
Met Sub-Divisional level	**Forecast upto 10 days with warning upto 7 days**	**Forecast upto 14 days with warning upto 10 days**	**Forecast upto 21 days with warning upto 14 days**	**Forecast upto 35 days with warning upto 28 days**
District/Block/ Panchayat/Village levels	Forecast and Warning at District level upto 5 days	Forecast at District level upto 10 days 5 days upto block levels	Forecast at District level upto 14 days 10 days upto block levels	Forecast at District level upto 21 days 15 days upto block levels and

		3 days upto panchayat levels Warning at District level upto 7 days 3 days upto block levels 2 days upto panchayat levels	and 7 days upto panchayat level 3days upto village levels Warning at District level upto 10 days 5 days upto block levels 4 days upto panchayat levels 2 days upto Village levels	10 days upto panchayat level 7 days upto village levels Warning at District level upto 15 days 7days upto block levels 5 days upto panchayat levels 3 days upto Village levels

3.3.6 Short term vision for next 2 years

- **Develop a heavy rainfall information system** mobile application for general public, media, disaster manager, state authorities and other users to minimize the loss of property, life & environment.
- **Revision of Definition of heavy rainfall** for Hills, Cities and plains. The same may be defined based on impact as well as climatological information.
- **Readily available climatological information of past heavy rainfall data** for easy comparison of current heavy rainfall events with past cases so as to provide real time information like a live cricket match commentary.
- **Short range warning (Lead time upto 48hrs):**

✓ Up gradation of observational network for real-time monitoring of rainfall to panchayat level from existing district level.

✓ Location specific heavy rainfall Impact based warning with high accuracy (POD>0.85) at met subdivision level and at >70.6 at district level.

✓ Dissemination of warning through CAP SACHET SMS, mobile App, social media platforms, website and a dash board etc.

✓ Development of weighted MME technique for heavy rainfall forecasting

- **Medium Range warning (Lead time 02 days to 10 days):**

✓ Development of sector specific Impact based warning at district level with a reasonable lead time & accuracy.

✓ Dissemination of warning through mobile App, social media platforms, website etc.

✓ Development of weighted MME technique for heavy rainfall forecasting

✓ Development of application of AI/ML technique for creation of interactive video, maps etc. for automatic updates on social media channels.

✓ The bulletins in all regional Indian languages.

✓ Auto-generation and dissemination of heavy rainfall warnings with the least human intervention.

- **Extended range outlook (Lead Time upto two weeks):**

✓ More reliable extended range outlook for heavy rainfall at subdivision level with a lead time up to two weeks.

- **Heavy Rainfall Warnings at Nowcasting Scale**

✓ Most accurate heavy rainfall detection and warnings issued at the nowcasting scales (lead time up to 3 hours) at each city level with accuracy of POD>0.7.

3.3.7 Medium term Vision (next 10 years)

Mission:

- The rain gauge density will increase form one in 45km now to one in 10km.
- IMD will provide block level rainfall monitoring from the existing district level monitoring
- **Prediction of heavy rainfall events with accuracy greater than 80% at Taluka/ block level:** Currently IMD is providing heavy rainfall information at the district level. In the medium-term goal, efforts will be made to provide block level heavy rainfall information.
- **Prediction of Extreme and Exceptional heavy rainfall events**: Forecasting extreme and exceptional heavy rainfall events is a complex task that requires advanced meteorological tools and methods. With the help of advanced and high resolution simulating the atmosphere and predict extreme rainfall events with greater accuracy will be aimed.
- Considering long-term climate data and trends to identify regions and seasons that are historically more prone to extreme rainfall events.
- In urban areas (mega-cities), it will increase to one in 5km
- There will be a research test bed to understand the heavy rainfall process
- **Categorization and prediction of catastrophic heavy rainfall events:** At present IMD is giving colour coded district level warnings in different categories like yellow, orange and red depending on the severity of the event. Rainfall >20 cm is categorized as extremely heavy rainfall events. Due to climate change, the number of extremely rainfall events is on a rise and unprecedented exceptional heavy rainfall events, greater than 50-60 cms cannot also be ruled out. Our medium-term vision should stress upon to predict how intense an extremely heavy rainfall event would be. Rainfall of a catastrophic nature that can lead to life-threatening flooding, widespread destruction, and loss of life. Such events are rare but extremely severe. It's important to note that the exact threshold for each category may vary from region to region, as it is often based on local climatology and infrastructure capabilities. Categories with specific rainfall amounts or rates to be introduced to ensure clarity in their warnings.
- **Providing information about the expected duration and intensity of a heavy rainfall event:** The categorization of heavy rainfall events should be combined with other relevant information, such as expected duration, spatial distribution, and the potential for other hazards like landslides, flash floods, and river flooding. The goal is to provide a comprehensive understanding of the potential impacts of heavy rainfall, helping communities and authorities make informed decisions and take appropriate actions to mitigate risks.
- **Use of Machine Learning and Artificial Intelligence:** Utilize machine learning and AI algorithms to analyze large datasets and identify patterns that may precede extreme rainfall

events. AI models will be vastly more sophisticated, capable of analyzing complex patterns in real-time. They will be able to predict not only basic weather patterns but also minute specifications like the exact location and time of a downpour, with the help of dynamic observations from surface observatories, pilot balloons, AWS, radars and satellites. Use of regional models and incorporation of local expertise will be done to understand microclimates and topographical factors that influence rainfall patterns

- **Development of flood warning systems for all major cities in India:** At present we have flood warning systems working for Mumbai and Chennai under the project IFLOWS and CFLOWS respectively. Efforts will be made to develop flood warning systems for all the major cities in a phase wise manner by combining meteorological forecasts with hydrological models to predict urban flooding.

3.3.8 Vision - 2047

"Leader in the globe with the vision 'early warning for all' with the goal to reach out with weather information in each household to enable no loss of life and property due to heavy rainfall in India and the region."

By 2047, we dream a nation where every citizen, be it rural or urban, and each community, and industry will be empowered with trustful, accessible, and actionable early weather information including heavy rainfall warnings. Through latest available technology, relentless innovation, and highly scientific and professional human resource, IMD will lead India to a weather-resilient Society. In the era of climate change, IMD will continue to improve spatial-temporal resolution of early warning at Panchayat and Village level with 3-4 weeks lead time.

3.3.9 Mission

- **Detection of each heavy rainfall event with enhanced observational network**

IMD will be the world class weather observing agency with dense rainfall observational network including AWS and ARG and other digital and automatic rainfall observation instruments. With the dense network, each heavy rainfall will be recorded. There will be at least one raingauge for every one Kilometer. Accordingly, we may be in position to record the heavy rainfall at each village level.

- **Advanced Technological Leadership in weather forecasting:**

By 2047, the technological advancement may open new window to the application and launching of new kinds of Satellite (nano or micro satellite) and RADARs (with low weight and antenna less, micro-Radars). The practical application of these remote sensing tools may be visible in the field of heavy rainfall warning.

The network of such nano or micro satellite and RADARS and their integration with the other observational network including AWSs/ARGs etc. will lead to real time observation and dissemination to the end user through latest dissemination tools like Apps.

- **Accurate and Timely Early Warning of Heavy Rainfall events:**

To deliver world-class, highly accurate forecast with 100% POD at Met subdivision level, >90% POD at district level, >80% POD at Block level, >70% POD at Village level in 24 hours lead period. The timely weather warnings of heavy rainfall including extreme and exceptional events will ensure the safety and well-being of every Indian. IMD will maintain scientific and technological temperament by continuous advancement of modeling, data assimilation, and observational capabilities. Accordingly, we may be in position to offer weather warnings in respect of the heavy rainfall at each village/household level.

- **Automation of generation and dissemination of heavy rainfall warnings**

With advent of emerging tools & technologies including Artificial Intelligence and Machine Learning (AL/ML) in weather forecasting, IMD might be in a position to offer the heavy rainfall warning on real time basis not only for each household for our country but also for the region by 2047.

- **Crowd Sourcing**

As of now IMD is hosting the Crowd Sourcing at official website mausam.imd.gov.in. and mobile app. There could be inbuilt server in mobile phone, wrist watch, vehicle etc. to collect crowd sourcing data.

- **Customized heavy rain warnings and end user Services**

As of now IMD is providing customized location specific heavy rainfall forecast to selected users including Govt. Authorities and other agencies and on specific events like celebration of Independence Day, Republic Day etc. By 2047, IMD may be in position to offer location specific customized weather bulletin to general public at village and household level.

- **Capacity Building and Collaboration**

At present, the IMD Pune is serving as a WMO nodal center for imparting training to scientists. Forge international partnerships and leadership in meteorological research, data sharing, and technology transfer, to strengthen our position in the global meteorological community. The scientists working in IMD will be smarter to act as per the requirement of the society.

- The special bulletins for all strata of society including differently abled persons
- Bulletins in all Indian languages and Dialects so as to ensure early warning for all will be generated and disseminated.

3.3.10 Strategy

To achieve the vision and mission as proposed above, we have to follow a comprehensive strategy for achieving the missions of Heavy rainfall warning by IMD. It requires a multifaceted approach that includes extensive use of technology, innovation, collaboration at national and international levels, and last but not least a strong forecasting and modeling team with high spirit. Some of the tentative strategic frameworks outlining the key components are given below for achieving the missions of IMD in 2047:

Technological Development, Sensor part and dissemination

- **AI/ML laboratory** More and more focus will be required for establishing an AI/ML laboratory in IMD to explore the optimum use of latest tools and techniques to increase the accuracy and spatial coverage with more and more lead time.
- **Establishment of center of excellence:** To meet the demand of the long terms planning, the research centers and innovation hubs in the form of center of excellence to be established to promote and cater ongoing R & D in meteorology and allied fields. Accordingly applied R & D is much needed.

- **Capacity Building for heavy rainfall detection using RADAR and Satellite and on Utility of rainfall forecast products from NWP:** Offer training programs and capacity-building initiatives for government agencies, emergency responders, and local communities to improve preparedness and response.
- **Awareness Programs for End Users:** The understanding of meaning of warnings issued by IMD at the grass-root level is again an issue of concern. Awareness programs through local Government bodies including Primary Health Centers (PHC), Anganwadi Centers, Primary Schools, Gram and Block Panchayat, NGOs, Self Help Groups etc. Local groups may also help to disseminating the warnings at end user levels. Accordingly, the training/awareness posters and templates may be prepared in local and simple languages preferably with the involvement of NDMA/SDMAs.

3.3.11 Outcome

"By 2047, IMD's heavy rainfall warnings, whether it is due to monsoon flow, low pressure systems or due to intense spells of thunderstorms/ Western disturbances must be detected in longer lead time and accuracy at village level. Accordingly, the following outcomes are expected by 2047:

i. **Significant reduction in loss of Life and Property:** Timely and accurate heavy rainfall warnings issued by IMD will help in achieving the goal of zero loss of life and property.

ii. **Global Leadership:** IMD's leadership in the early warning for heavy rainfall will be established in coming years.

iii. **Wellbeing of each Citizen:** IMD's early warning for heavy rainfall will help in wellbeing of each citizen to improve socio-economic conditions.

iv. **Disaster Safe Society** IMD's early warnings for heavy rainfall will enable flood warnings. IMD's early warnings will be trusted by common man and they will feel safe from uncertainty of heavy rainfall.

v. **Enhanced Agriculture Production, water and power management as well as drinking water and sanitation:** Again, the timely and accurate dissemination of early warnings will be helpful in the increase of agricultural production, water and power management as well as drinking water and sanitation.

vi. **Infrastructural Development** Early warnings issued by IMD will help in all kinds of infrastructural development in the Nation.

In summary,

1. Optimum use of technology including AL/ML or any other technology at that time with the motto 'No heavy rain goes undetected and unpredicted at village/Panchayat levels.

2. Heavy rainfall forecast will be issued 3-4 weeks in advance and warnings 10-15 days in advance with high accuracy.

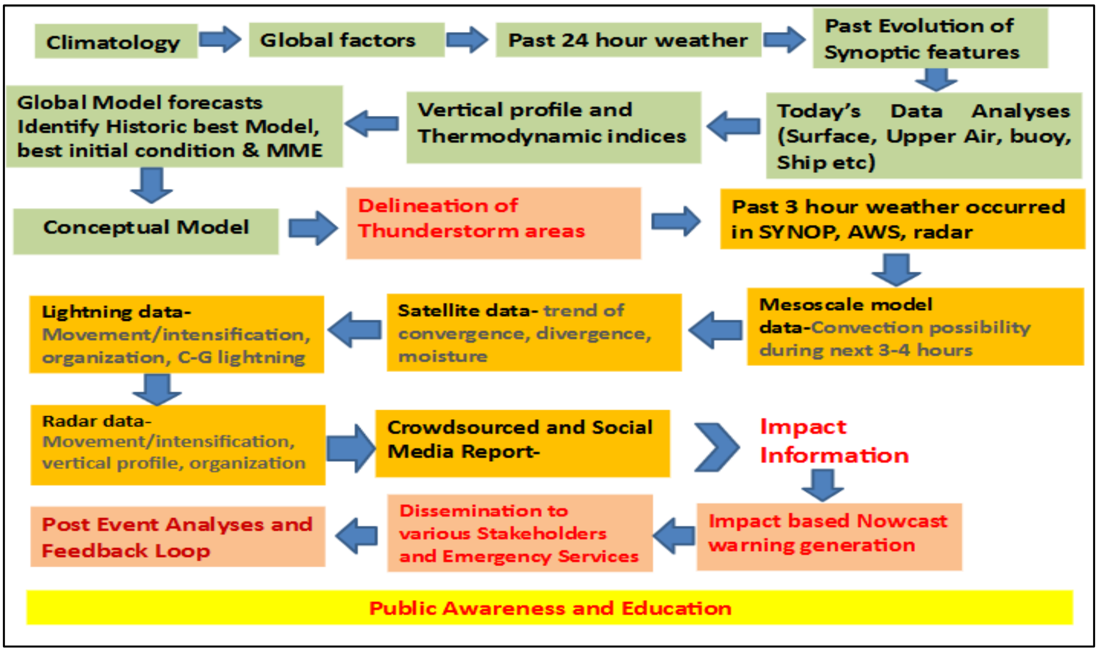
3. **Auto-generation and dissemination of heavy rainfall warnings with the least human intervention and maximum outreach as per request of each person and household.**

3.4 THUNDERSTORM FORECASTING AND WARNING SERVICES

3.4.1 Current status and major achievements during the past 10 years

a) Flowchart of Thunderstorm Forecast/Nowcast Process

This flowchart illustrates a sophisticated weather forecasting and warning system that primarily focuses on thunderstorm prediction and public safety. The process begins by gathering fundamental weather inputs, including climatology, global factors, and recent weather data along with analysis of weather patterns, combining global model forecasts, vertical atmospheric profiles, and current weather data from multiple sources. The system then moves into specialized thunderstorm prediction using a combination of mesoscale model data, satellite imagery, lightning detection, and radar observations including social media and crowdsourced reports, which help verify and enhance the technical observations. The final phase focuses on public safety and communication. This includes gathering impact information, generating appropriate warnings, and disseminating this information to stakeholders and emergency services. The system maintains a feedback loop through post-event analysis, allowing for continuous improvement of the forecasting and warning process. Importantly, the entire system is built on a foundation of public awareness and education, emphasizing the critical role of keeping communities informed and prepared for severe weather events.



b) The nowcast of Thunderstorm commenced in 2012 with 120 stations. At present, IMD issues district & station level nowcasts for severe weather for 1206 stations & all districts of India round the clock at three hour intervals. All these nowcasts are generally updated every three hours on the IMD website (https://mausam.imd.gov.in/responsive/districtWiseNowcast.php).

When severe weather is expected, for maximum effectiveness of the warning, detailed SMS/Whatsapp messages and e-mails are issued to all concerned stakeholders e.g. district collectors, State Disaster Management Authorities and local administration of the district concerned apart from print and electronic media. The impact expected due to the severe weather and suggested actions have also been added to the nowcast warnings in terms of colour codes following WMO Technical Note, 2015 (WMO. 2015) and National Disaster Management Authority (NDMA) guidelines.

c) **Augmentation of Doppler Weather Radar (DWR) Networks:** Doppler Weather Radar (DWR) Networks is augmented from 15 in 2014 to 39 DWRs in 2024.

d) The New Earth stations and Multi-Mission Meteorological Data Receiving and Processing System (MMDRPS) was installed for INSAT-3D, INSAT-3DR and upcoming INSAT-3DS satellite for data processing and product generation. A GIS based rapid analyses tool (RAPID) has been developed jointly by ISRO and IMD. It is operational since 2014

e) **Ground Based Lightning Detection Networks:** Presently, the Ministry of Earth Sciences has a ground based Lightning detection network with 100 sensors working 24X7 to provide lightning location information along with other related variables like the polarity, peak current, height etc since 2019 for entire country. There is also a network of Lightning Detection System (LDS) established by IAF, another network by ISRO. There are satellite based lightning detector is also available in GOES-16, FENGYUN-5 and Meteosat 3rd Gen covering USA, China and Europe respectively.

f) Crowd Source Platform has been launched since 2021 through website and mobile app for collecting various weather observations from common people for six weather events initially, viz., Rain, Hail, Duststorm, Wind Speed, Thunderstorm/Lightning & Fog. The interface has following features: (i) The reporting interface is without login requirement. (ii) The time of submission will be automatically recorded. (iii) The user machine address and time is automatically recorded. (iv) The user has the facility to record the Location, State, District of observation. There is also the facility to add photo or video proof of the event.

g) **Thunderstorm Decision Support System:** IMD has prepared an in-house GIS based thunderstorm decision support system, where data from various observational networks, Satellite, Radar, Global & Mesoscale model etc. has been integrated into the GIS platform.

h) **Short-range Warning of Intense Rainstorms in Localised Systems (SWIRLS) was adopted in 2018.The** SWIRLS is based on the extrapolation of radar echoes using the TREC (Tracking Radar Echoes by Correlation) technique. With a suitable choice of pixel array size on the radar reflectivity maps, the TREC vectors derived can be used to monitor and extrapolate echo motion right across the mesoscale spectrum, from individual convective cells, to super cells and clusters, and to groups of rain bands or squall lines. On the basis of TREC, Quantitative Precipitation Forecast (QPF) algorithms have been developed to produce high resolution forecast rainfall distribution maps over the local area. These maps provide useful objective guidance for forecasters to assess the likely rain scenario in the next 30, 60 & 120 minutes along with analysis and to facilitate decision-making in operating the Rainstorm Warning System. The first SWIRLS was installed and made operational at Delhi in October, 2018. However, this system is not operational currently.

i) Mesoscale Modeling for Thunderstorm Nowcast:

The High Resolution Rapid Refresh (HRRR) model implemented for three domains (north-west, east & north-east & south peninsular) with radar data assimilation & forecast various products update at every two hours valid upto next 12 hrs is operational for nowcast since 2021**.**

E-WRF model with 3 km spatial resolution has also been implemented along with ground based lightning data assimilation for providing lightning forecast and along with other related parameters since 2022. Presently, the model is running two times a day based on 00 and 12 UTC (with latest lightning data assimilation) and provides forecasts for next 72 hours.

A comparison among various leading meteorological agencies has been depicted below in terms of NWP modelling system for thunderstorm nowcasting:

Aspect	**National Oceanic and Atmospheric Administration (NOAA)**	**UK Met Office**	**Bureau of Meteorology (BOM), Australia**	**Japan Meteorological Agency (JMA)**	**European Centre for Medium Range Weather Forecasts (ECMWF)**	**India Meteorological Department (IMD)**
Geographic Focus	United States and region	United Kingdom & Republic of Ireland	Australia and Neighbouring areas	Japan and neighbouring areas	Europe and global	India and Global
Thunderstorm Research	High Focus on Forecasting	Convective weather	Thunderstorms and cyclones	Thunderstorms and typhoons	Medium term severe weather	Thunderstorm, Lightning forecast
Notable Model Names	HRRR, NAM, GFS	Unified Model	ACCESS,AWAP, POAMA	JMA models	Integrated Forecasting System (IFS)	HRRR, NCUM-R EWRF, WRF

Model Lead Times	Short to medium-term	Short to medium-term	Short to medium-term	Short to medium-term	Short to medium-term	Short to medium-term
Model Resolution	Varies (less than 1 km-10 km typical)	Variable grid,1.5 km over UK and Republic of Ireland surrounded by a coarser resolution of 4 km with a variable resolution in the transition zone in between	Varies (less than 1km-10 km typical)	Varies (1-10 km typical)	09Km to 40 Km	02-12 Km

When it comes to the spatial resolution of our models, we are trailing behind other prominent meteorological agencies. They have progressed to sub-km levels, whereas we have not yet reached that level of detail. Additionally, there is room for improvement in optimizing and adapting model physics specifically for the unique conditions of India.

Furthermore, we have an opportunity to enhance our forecasting capabilities by adopting innovative data assimilation and ensemble techniques for better thunderstorm prediction. These advancements are possibilities for the coming years.

j) Forecast Demonstration Program (FDP) is conducted to improve the forecast. FDP Bulletins is issued on daily basis (updated in the afternoon if needed) throughout the year. At the end of every FDP programme, an Annual STORM Report is compiled and published. It contains region wise detailed analysis of observed significant weather events, case studies, verification of Intensive Observation Periods (IOPs) issued during the FDP, as well as verification of 3 hourly Nowcast issued round the clock throughout the season.

- There is a 183% improvement in 24 hr forecast performance (POD) of Thunderstorm events with POD 0.88 during 2024 and 28% (POD) improvement in 3 hour Thunderstorm forecast since 2016 to till 2024 with POD 0.91 during 2024.
- All the eleven categories of Nowcast for thunderstorms and associated weather are considered for automatic verification.

k) **Common Alert Protocol (CAP)** has been implemented as per WMO standard for Thunderstorm warning. It is being used for the Global Multi-Hazard Alert System (GMAS) of WMO and also in India. Google International is also using CAP for Google Alert.

l) **Dedicated app for lightning alert:** Damini app has been launched by the Ministry of Earth Science for providing the thunderstorm/lightning alert to the public, the app is available in both Android and iOS platforms.

m) **Dissemination channels:** Significant improvement has occured in forecast dissemination during the last decade. At present multiple channels e.g. email, WhatsApp, website, TV, Radioare used for timely and large scale dissemination to various stakeholders.IMD has facebook, instagram, X (former name was Twitter), youtube etc. which handle to disseminate the weather bulletin and forecast to the public in a timely manner.

3.4.2 Challenges and Gap Areas

Thunderstorm forecasting and timely dissemination of weather information have significantly improved over the years, thanks to advances in technology and meteorological science. However, there are still some gaps and challenges in these areas:

- The Thunderstorm still goes undetected as entire country is not covered by Radar.
- The structure & dynamics of thunderstorm in different land, surface and synoptic environment in India is least understood as there is lack of meso-scale network of observatories and research Testbed.
- India currently lacks a dedicated Research Test Bed for detailed studies on thunderstorm systems. However, the India Meteorological Department (IMD) is in the process of finalizing the establishment of a Thunderstorm Research Test Bed in Eastern India.
- **Microscale Variability:** Thunderstorms can exhibit microscale variability, making it difficult to predict their exact location, intensity and time of occurrence. While radar and satellite technologies have improved, predicting the exact path and intensity of individual storms remains a challenge.
- **Limited Observations:** Accurate thunderstorm forecasting depends on real-time weather observations. Gaps in the observation network e.g. surface, upper air, Radar etc. can hinder the accuracy of forecasts.
- **Short-Term Predictability:** While meteorologists have made significant progress in short-term weather forecasting, accurately predicting thunderstorms in the very short term (hours or less) remains challenging, especially for isolated, small-scale storms.
- **Complexity of Thunderstorms:** Thunderstorms are complex and can exhibit a wide range of behaviors, from isolated cells to organized supercells. Predicting their development, intensity, and movement is challenging due to the interplay of numerous atmospheric factors.
- **Urban vs. Rural Forecasting:** Thunderstorms can have vastly different impacts in urban and rural areas. Urban heat islands can influence storm development and intensity, which may not be adequately accounted for forecasts.
- **False Alarms:** Over-warning or issuing false alarms for thunderstorms can lead to complacency among the public and emergency responders. Balancing the need to warn for safety with avoiding unnecessary panic is a continual challenge.

- **Lead Time:** Lead time of 1-3 hours may not be adequate for all the stakeholders to prepare for mitigation.
- **Severity of severe Weather:** Prior and accurate estimation of severity of lightning, squall, hail, rain, gust is challenging.
- **Data Assimilation and Models:** Improving the accuracy of thunderstorm forecasts requires better assimilation of observational data into numerical weather prediction models. Advances in data assimilation techniques are ongoing.
- **Timely Dissemination:** Ensuring that accurate weather information reaches the public and relevant authorities in a timely manner can be challenging, particularly in areas with limited access to communication infrastructure or for individuals with disabilities who may rely on alternative means of receiving alerts.
- **Limited Impact Assessment:** In recent times, impact based forecasts are issued i.e. thunderstorm forecast alongwith the expected severity, impact and appropriate advisories for the stakeholders. However, there is very limited scope of estimating/quantifying the observed impact after occurrence of the event.
- **Behavioural Factors:** Even when accurate forecasts are available, people may not always take appropriate precautions or respond to warnings. Understanding human behaviour in response to severe weather warnings is a complex issue.
- **Climate Change Impacts:** Climate change can alter the frequency and intensity of thunderstorms, introducing new challenges for forecasting. Long-term climate models are being used to understand these changes.
- **Resource Allocation:** Effective thunderstorm forecasting and response require adequate resources for meteorological agencies and emergency management. Resource limitations can impact the quality and timeliness of forecasts and warnings.

Efforts to address these gaps in thunderstorm forecasting and timely dissemination continue through ongoing research, technological advancements, and improved collaboration between meteorological agencies, researchers, and emergency management organisations.

3.4.3 Short-term Vision (next two years)

- ❖ **Expansion of Observation Network:** Ongoing improvements in radar and satellite technology, expansion of surface and upper air network will provide meteorologists with more detailed and timely information about the atmosphere. Improvement and coverage of ground based lightning detection networks will provide better lightning detection, which is crucial for predicting thunderstorms.
- ❖ Improved Spatial Resolution in the regional model's (~1km scale) for thunderstorm prediction along with enhanced data assimilation techniques can lead to more accurate short-term forecasts.
- ❖ **Mobile Apps and Warnings:** There will likely be advancements in the delivery of thunderstorm warnings to the public. Mobile apps and other digital platforms will play a crucial role in disseminating timely information to individuals and communities at risk.

- **Public Awareness and Preparedness:** With the increasing frequency and severity of extreme weather events, there will likely be a greater emphasis on public awareness and preparedness for thunderstorms. Educational initiatives and community resilience programs may see growth.
- **Collaborative Research:** Collaborative efforts among meteorological agencies, academic and research institutions will continue to drive progress in thunderstorm nowcasting. Sharing data and expertise can lead to more effective prediction methods.
- The establishment of Research Test Bed in Eastern India will lead to better understanding and prediction of Thunderstorm. It is to be set up over East India with three main nodes Kolkata, Balasore, Ranchi/Rourkella where large instruments related to thunderstorm study are being installed. Thunderstorm Test Bed (TTB) project of MoES for East India has been approved for implementation under the sub-scheme "Upgradation of Forecast System" of the umbrella scheme ACROSS of MoES.

3.4.4 Medium-term Vision (next ten years)

Looking ahead to the next 10 years, the vision for thunderstorm nowcasting is likely to be shaped by significant advancements in technology, data availability, and research. Here are some potential developments and trends to anticipate thunderstorm nowcasting over the next decade:

- **Integrated Sensor Networks:** Improved sensor and dense networks, including ground-based weather stations, upper air observations, drones, and advanced satellites, will provide real-time data for better understanding and prediction of thunderstorms.
- **Citizen Science:** Citizen science initiatives will become more prevalent, with individuals contributing weather data through apps and sensors can create a micro-observational network, helping to improve nowcasting accuracy.
- Depending on season, location, time of development, the movement of the cell and associated intensity (Hail, CG lightning, precipitation) are all compiled and this acts as climatology base for nowcasting.
- Develop GIS based thunderstorm atlas with tracks of thunder cells.
- **Predictive Analytics:** Advanced predictive analytics will be applied to historical weather data to identify long-term trends and patterns related to thunderstorm formation and behavior, helping forecasters anticipate them more accurately.
- **Climate Change Adaptation:** Thunderstorm nowcasting will need to adapt to the changing climate. Models and predictions will incorporate climate change impacts on thunderstorm frequency, intensity, and distribution.
- **Hyper-Resolution Modeling:** Weather models will operate at even higher resolutions (in meter scale), providing more detailed predictions of thunderstorms. This will be facilitated by advances in computing power and numerical modeling techniques. NWP models with higher accuracy.
- **AI-Guided Nowcasting:** Artificial intelligence and machine learning will play an increasingly central role in nowcasting. AI algorithms will become more sophisticated

in processing vast amounts of data to make rapid and accurate thunderstorm predictions.

- **Quantum Computing:** As quantum computing technology matures, it may revolutionize weather forecasting by solving complex atmospheric equations much faster than traditional supercomputers, leading to more precise nowcasting
- **Multi-Model Ensemble and Regional Ensemble Prediction System for Thunderstorm Forecasting:** A combination of various weather models and ensemble forecasting techniques will be used to create more robust and reliable thunderstorm predictions.
- **Customized Forecasts:** Personalized weather forecasts will become more common, with individuals receiving tailored thunderstorm alerts based on their location and preferences.
- **Impact Estimation/Quantification:** Improved and high resolution satellite products, drones etc. for estimating/quantifying the observed impact after the event. Thunderstorm impact modelling and risk based methods will be in place for operational Impact Based Forecast (IBF) and Risk Based Warning (RBW) of Thunderstorm.
- **Faster and More Accessible Alerts:** Thunderstorm warnings will become even faster and more accessible to the public through smartphone apps, social media, and other communication channels including Common Alert Protocol (CAP). Enhanced early warning systems will save lives and reduce property damage.
- **Global Collaboration:** International collaboration among meteorological agencies and research institutions will intensify, leading to the sharing of data, expertise, and resources for more accurate global thunderstorm nowcasting.
- **Green Technology:** Efforts will be made to reduce the environmental impact of weather monitoring and forecasting, including the use of green energy sources and sustainable practices in maintaining weather infrastructure.
- Conduct training workshops and capacity-building programs for farmers, government agencies, emergency responders (NDMA) and local communities to improve their preparedness and response to thunderstorm/Lightning.
- **Capacity Building/Training**: Training of IMD officials at par with international standards to fill the gap area with the best International Centres for weather prediction to improve the operational requirements**.**
- Forecast accuracy is expected to improve and reach upto 96% compared to current levels of 88%, with forecasts available in a customized format tailored to the Panchayat level.
- Establishment of National Thunderstorm Research Laboratory (NTRL) in line with NSSL of USA to conduct research on thunderstorm.

It's important to note that while these developments are anticipated, the exact trajectory of thunderstorm nowcasting over the next 10 years will depend on factors such as funding, research breakthroughs, and global events. Nevertheless, continued innovation in technology and an emphasis on improving our understanding of atmospheric processes will likely lead to more accurate and timely thunderstorm nowcasting in the future.

3.4.5 Vision 2047

a) Improved Data Collection:

- **Advanced weather satellites:** By 2047, we can expect a significant advancement in weather satellite technology, providing more frequent and detailed observations of the Earth's atmosphere. These satellites will offer higher resolution and more frequent updates, improving the accuracy of thunderstorm nowcasts.
- **IoT and sensor networks:** The proliferation of Internet of Things (IoT) devices and sensor networks will lead to more extensive and localized data collection. This will enhance the ability to monitor weather conditions in real-time, including temperature, humidity, wind speed, and atmospheric pressure.
- **Advance Radar:** Radar technology is likely to continue improving in terms of resolution and sensitivity. This means that radar systems will be able to detect smaller and more distant objects, making them more effective in weather monitoring. Machine learning and artificial intelligence (AI) algorithms will play a more significant role in radar data analysis. These technologies can help identify patterns, anomalies, and potential hazards in radar data, such as severe weather conditions.
- **Lightning Detection System from Space and Ground:** Lightning detection from space and ground systems will likely become more sophisticated, providing more detailed information about three dimension lightning channel, including their intensity, location, potential for wildfires, heavy Rain, Cloud Burst etc.
- **Multi-Modal Sensors:** Future radar systems may incorporate multiple sensor modalities, such as radar, lidar, and passive optical sensors, to provide a more comprehensive picture of the environment.
- **Space-Based Radar:** Deploying radar systems in space can provide a global view of the Earth's surface and atmosphere. This could lead to more accurate weather forecasting, improved disaster management, and enhanced monitoring of space debris and near-Earth objects.
- **Quantum Radar:** While still in the experimental stage, quantum radar holds the promise of significantly improved radar capabilities.

b) High-Resolution Modeling:

- **Enhanced numerical weather prediction models:** Meteorological models will become even more sophisticated, incorporating higher resolutions, improved physics, and data assimilation techniques. This will allow for more accurate simulations of thunderstorm development, intensity, and movement.
- **Indigenous NWP model:** Indigenous NWP models with skills at par with best international NWP models' standard.
- **Machine learning and AI:** Machine learning algorithms and artificial intelligence will play a significant role in improving thunderstorm nowcasting. These technologies will help refine predictive models and assimilate real-time data more effectively.

c) **Hyper-localized Predictions:**

- **Micro-scale modeling:** Advances in computing power and modeling techniques will enable thunderstorm nowcasts to become hyper-localized, providing predictions at the neighborhood or even street level. This will be particularly valuable for urban areas and infrastructure planning.
- **Personalized alerts:** Thunderstorm nowcast services may offer personalized alerts and recommendations based on individual user preferences, such as travel plans, outdoor activities, and specific weather sensitivities. Thus these will be impact based forecast and risk based warning at Panchayat Level.

d) **Rapid Communication and Visualization:**

- **6G and communication networks:** Lightning-fast 6G and beyond will enable near-instantaneous communication of thunderstorm warnings and updates to mobile devices and smart infrastructure.
- **Augmented and virtual reality:** Advanced visualization tools, including augmented and virtual reality, could be integrated into thunderstorm nowcast services. This would allow users to immerse themselves in real-time weather data and simulations for better situational awareness.

e) **Climate Change Considerations:**

- **Climate modeling integration:** Thunderstorm nowcast services will incorporate climate change predictions and their impact on weather patterns. This will help communities prepare for more frequent or intense thunderstorms as a result of climate change.

f) **Enhanced User Engagement:**

- **Citizen science and crowd-sourced data:** Citizen science initiatives and crowd-sourced weather data will become more integrated into thunderstorm nowcasting, allowing for a broader and more detailed data collection network.
- **Interactive user interfaces:** Thunderstorm nowcast services will have user-friendly interfaces that allow individuals and communities to actively engage with weather data and forecasts, fostering better understanding and preparedness.

g) **Improved Lightning Protection:** Advances in lightning detection will also lead to better lightning protection systems for infrastructure, reducing the risk of damage from lightning strikes.

h) **Lightning Prediction System:** System for prediction of more accurate lightning current and strike areas on ground.

i) **Thunderstorm Generation/Modification Experiments:** Experiments for artificial generation/modification of thunderstorm/lightning.

j) **Zero Death,Minimum loss of Property with near 100 percent forecast accuracy:**

Achieving zero deaths and minimum property loss due to lightning is a challenging goal, but it's a goal that can be approached through a combination of strategies, technologies, and public awareness efforts. While it may not be possible to completely eliminate lightning-related risks, significant progress can be made in reducing the impact. Here are some key approaches to work toward this goal:

- **Advanced Warning Systems:** Develop and deploy more advanced lightning detection systems that can provide accurate and timely warnings to individuals and communities. This includes improved radar technology, lightning mapping arrays, and early warning apps.
- **Education and Awareness:** Educate the public about the dangers of lightning and the importance of seeking shelter during storms. This includes schools, workplaces, outdoor event organizers, and public awareness campaigns.
- **Building and Infrastructure Safety:** Implement lightning protection systems in high-risk structures, such as tall buildings, communication towers, and critical infrastructure facilities. Encourage the installation of lightning rods and surge protection in homes and businesses to mitigate property damage.
- **Personal Safety Practices:** Promote safe behaviours during thunderstorms, such as staying indoors, avoiding electrical appliances and plumbing fixtures, and not taking shelter under trees. Educate people on the "30-30 rule," which involves seeking shelter if you hear thunder within 30 seconds of seeing lightning and waiting at least 30 minutes after the last clap of thunder before leaving shelter.
- **Emergency Response and Medical Care:** Ensure that emergency services are well-prepared to respond to lightning-related incidents and injuries. Promote prompt medical attention for lightning strike victims to improve survival rates.
- **Climate Change Mitigation:** Work to mitigate climate change, which can potentially alter weather patterns and lead to more frequent or intense lightning storms. Reducing greenhouse gas emissions can play a role in this effort.
- **Research and Technology Development:** Invest in on-going research to better understand lightning behaviour, predictability, and risk factors. Develop advanced lightning protection technologies and materials.
- **Community Planning:** Include lightning safety considerations in urban planning and building codes to reduce the risk of lightning-related fires and accidents.
- **International Collaboration:** Collaborate with neighbouring countries and international organizations to share knowledge and best practices for lightning safety.

It's important to note that while these strategies can significantly reduce lightning-related risks, there may always be situations where lightning strikes occur unexpectedly or in remote areas, making it challenging to achieve zero deaths and zero property loss in every single instance. However, a comprehensive and proactive approach can greatly minimize the overall impact of lightning on lives and property.

Targeted Observation System accuracy for 2035, 2047 is presented in Table below:

Phenomenon	Existing Observation Network (2024)	Accuracy & Capabilities (2024)	Goal for 2035	Goal for 2047
Lightning	Lightning Detection Networks (ILDN, NRSC, WWLLN) Presently covering approx. 20,545 sq Km area of country by 1 Lightning sensor	70-80% detection efficiency; 3 km spatial resolution; 10–15 min delay	95% detection efficiency; 1 km resolution; near real-time (5 min)	99% detection efficiency; 100 m resolution; real-time (under 1 min)
Squalls	AWS/ARG, Doppler Weather Radars (DWR)/Eye Observation /Crownsourcing Presently covering approx. 2739 sq Km area of country by 1 AWS	Moderate accuracy; limited detection and prediction; regional scale	High accuracy; improved detection capability; block-level forecasts	Near-perfect accuracy; hyperlocal detection (village-level); 6–12 hr lead time
Hail	DWR, Satellite Observations, AWS/ARG, Eye Observation /Crowdsourcing Synoptic Obs.: 1 in 100 km Presently covering approx. 10,00,00 sq Km of country by 1 Radar	Low detection accuracy; regional scale; post-event verification	Moderate detection with 40 % improvement in accuracy; block-level detection; pre-event prediction (24 hr lead time)	High accuracy; with 80% improvement in detection accuracy hyperlocal detection; pre-event prediction (24–72 hr lead time)
Heavy Rain	AWS/ARG, Rain Gauges, Satellite Observations	78% accuracy for 24-hr forecasts; regional scale; hourly updates	90% accuracy; block-level forecasts; updates every 15 min	Near 98% accuracy; hyperlocal forecasts; real-time updates

Targeted forecast accuracy for 2035, 2047 is presented in Table below:

Parameter	Status in 2024	Goal for 2035	Goal for 2047
Thunderstorm Forecast Accuracy (24 hr)	88% for 24 Hr 91% for 3 hr	96% for 24 hr 98% for 3 hr	~100% in 3 & 24 hr scale.
Spatial Resolution	District/Regional level	Panchayat level	Hyperlocal (village/block level/Household level)
Lead Time	Short-range (0–5 days)	Medium-range (7–14 days)	Extended-range (up to 30 days)for identification of probability of large thunderstorm systems
Forecast Customization	/Met Subdivision/State/district level	Panchayat level	Individualized (personalized alerts)
Data Sharing Platforms	Limited to static reports	Interactive dashboards/apps	Fully immersive & automated platform

3.4.6 Strategy

Here are the comprehensive mission guidelines outlining key objectives and strategies:

- **Safety First:** Prioritise human safety by delivering timely and reliable warnings and guidance to individuals, communities, and relevant authorities to reduce the risk of injuries, fatalities, and property damage caused by thunderstorms.
- **State-of-the-Art Technology:** Continuously innovate and invest in the development of advanced tools and technologies, including improved weather radar, lightning detection systems, numerical weather prediction models, and real-time data assimilation techniques.
- **AI driven Techniques:** Explore the integration of emerging technologies like artificial intelligence (AI), machine learning, and advanced data analytics to enhance prediction accuracy and lead time.
- **Localized Predictions:** Develop hyper-localized thunderstorm nowcasts, providing specific information about storm paths, intensities, and potential impacts on communities, infrastructure, and critical assets.
- **Public Awareness and Education:** Educate the public about thunderstorm risks and safe practices, including sheltering indoors and avoiding dangerous activities during storms. Promote awareness on the importance of following official warnings and guidance.

- **Interdisciplinary Collaboration:** Collaborate closely with meteorologists, emergency responders, researchers, academic institutions, policymakers to foster a multidisciplinary approach to thunderstorm prediction and mitigation.
- **Climate Adaptation:** Incorporate climate change considerations into thunderstorm nowcasting services to anticipate shifts in thunderstorm patterns and intensities due to global climate changes.
- **Community Resilience:** Work with local communities to develop and implement resilience plans, including building codes, infrastructure upgrades, and emergency response strategies that account for thunderstorm risks.
- **Rapid Communication:** Develop efficient communication channels to disseminate warnings and updates in real time, utilising the latest communication technologies, including 5G, mobile apps, and social media.
- **Research and Development:** Foster a culture of research and development to stay at the forefront of meteorological science and technology, continually improving the accuracy and lead time of thunderstorm predictions.
- **Transportation and Aviation Safety:** Providing real-time information to aviation authorities and transportation agencies to help them make informed decisions about flight operations, road closures, and other safety measures during thunderstorms.
- **Resource Allocation:** Assisting emergency responders and local authorities in allocating resources effectively in response to severe weather events. This may involve pre-positioning personnel and equipment in areas at high risk of thunderstorms.
- **Global Outreach:** Collaborate with international partners to share knowledge, data, and best practices, especially in regions prone to severe thunderstorms.
- **Continuous Improvement:** Regularly evaluate and improve the effectiveness of thunderstorm nowcasting services based on feedback, lessons learned, and advancements in technology and science.

3.4.7 Outcome

We can envision several potential outcomes or goals that the field of thunderstorm nowcasting might aim to achieve by 2047 and beyond:

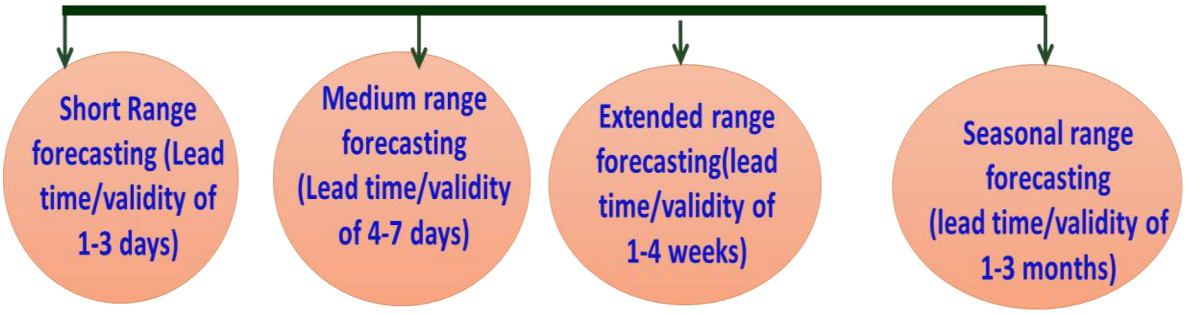
- **Global Coverage:** Thunderstorm nowcasting will aim to provide global coverage, helping regions that currently lack sophisticated weather forecasting capabilities to better prepare for thunderstorms and related hazards.
- **Advanced Data Sharing and Collaboration:** International collaboration will be strengthened, with global sharing of weather data and expertise to ensure accurate predictions regardless of geographical boundaries.
- **Near-Perfect Accuracy:** Thunderstorm nowcasting systems may strive for near-perfect accuracy, with the ability to predict the timing, location, and intensity of thunderstorms with an extremely high level of precision. This could significantly reduce false alarms and improve public safety.

- **Extended Lead Times:** Longer lead times for thunderstorm warnings will be a key goal. By 2047, it may be possible to provide hours or even days of advanced warning for severe thunderstorms, giving people and communities more time to prepare.
- **Seamless Integration with Daily Life:** Thunderstorm nowcasting could seamlessly integrate into everyday life, with automatic alerts sent to personal devices, vehicles, and smart infrastructure to ensure rapid response and safety.
- **High-Resolution Real-Time Visualization:** Advanced technologies like augmented reality (AR) or virtual reality (VR) could provide highly detailed, real-time visualizations of thunderstorms, enabling better situational awareness for both the public and emergency responders.
- **Climate-Resilient Predictions:** With climate change continuing to impact weather patterns, thunderstorm nowcasting will adapt to provide predictions that account for changing climatic conditions and extreme events.
- **Customized Alerts:** Thunderstorm nowcasting systems might offer personalized alerts and recommendations, taking into account individual preferences, needs, and vulnerabilities.
- **Environmental Sustainability:** The technology and infrastructure used in thunderstorm nowcasting will prioritize environmental sustainability, using renewable energy sources and eco-friendly practices.
- **Continuous Improvement:** Research and development will remain ongoing, with a focus on continuous improvement. The field will adapt to emerging technologies, data sources, and scientific discoveries.
- **Resilience and Disaster Preparedness:** Thunderstorm nowcasting will play a central role in building resilience against thunderstorm-related disasters, reducing the economic and human impact of severe storms.
- **Ethical and Privacy Considerations:** Thunderstorm nowcasting will address ethical and privacy concerns related to the collection and use of personal data for weather prediction, ensuring transparency and consent.

3.5 HEAT & COLD WAVE FORECASTING & WARNING SERVICES

3.5.1 Current Status and Major achievements during past 10 years

At present IMD has established a unified forecasting strategy for Heat Waves and Cold Waves starting from short range to seasonal range forecasts and warnings.



Major achievements of IMD during the past 10 years include: -

a) Heat Wave & Cold wave warning services lead time increased from 3 days to 5 days in the year 2015 and further to lead time of 7 days from 2024. The forecast spatial resolution has improved from the meteorological sub-division to the district-level forecast from the year 2020.
b) Heat Wave and Cold Wave forecast & warning guidance for extended range (2 weeks lead time) started from the year 2017.
c) Seasonal Outlook of Temperatures and Heat Waves for the country (sub-division level) started from the year 2016.
d) Heat Wave and Cold Wave services on district level, sub-division, state and region.
e) Impact-based forecast of Heat Wave and Cold Waves over the country at district level since year 2020.
f) Hot Weather hazard Analysis over the country since 2023.
g) Vulnerability Atlas for Heat Wave and Cold Wave since 2021.
h) Heat Wave and Cold Wave Products transitioned to the GIS platform in 2021.
i) New Products for Heat Wave and Cold Wave forecasting services like Heat Index, percentage-based maximum & minimum temperature analysis, Relative Humidity, Winds, etc., along with their coexistence and persistence for impact based forecast started in 2022.
j) Efforts are underway in developing a Decision Support System for Heat Wave & Cold Wave Warning services.

k) Heat Wave forecast accuracy in the form of Probability of Detection (POD) has increased from 68%, 52% & 27 % in 2014 to 95%, 88% & 77% in the year 2024 for 24-hour, 48-hour, and 72-hour lead periods.
l) Heat action plans have been established by the National Disaster Management Authority (NDMA) in collaboration with states & IMD in 23 states and union territories.

3.5.2 Challenges and Gap Areas

a) The Heat Wave & Cold Wave forecasting and Warning services skills deteriorate after 3 days lead time and need to be improved further.
b) The tailored impact-based forecasts and action suggested for all sectoral applications need to be provided, moving ahead from today's generalized impact-based forecast. For this, the past year's authentic impact data would be required for all the sectors.
c) Hot Weather & Cold Weather hazard & vulnerability Analysis over the country considering more socio-economic and high-resolution observation data.
d) Shift from generalized impact-based forecast and warnings to threshold-based forecast and warnings for different use cases.
e) Localized Heat Wave & Cold wave forecasts and warnings should be actionable with considerable skill for at least 5 to 7 days lead time.
f) Dense network of AWS station to map micro-climatic zones of high/low temperatures. Research related to the physical understanding of Urban Heat Island effects. Satellite-based sub-km surface temperature is to be validated for dense coverage of observations.
g) Improvement in the NWP model forecast of temperature and other meteorological parameters using AI/ML, Bias Correction, and MME concepts is required to reduce the forecasting error in Heat and Cold Waves medium-range forecasts.
h) Automation of Forecast/warnings generation and dissemination is required to provide 100% coverage of Early Warning Services for Heat Waves & Cold Waves.
i) Regional disparities need to be properly communicated for the Heat Wave and Cold Wave warning services, such as urban heat island effects, coastal humidity effect, etc.
j) There is a need to shift focus towards user-centric heat wave and cold wave warnings, signifying a shift towards demand-based services.
k) Research and study on the development & Utilization of different indices, their study in the Indian context to provide an impact-based forecast of heat waves and cold waves.
l) Close collaboration with Heat Action Plans and their implementation is needed.
m) Revision of Heat Wave & Cold Wave criteria and modification of the Standard Operating Procedures (SoP) to include the evolved understanding of Meteorological parameters to disseminate respective forecasts and warnings.
n) Though there is a significant improvement in heat wave forecast/warning & action plans, there is a lot to be improved with respect to cold waves.

3.5.3 Short term vision (for next 2 years)

a) Fully Functional Decision Support System to provide sectoral impact-based forecast and warnings of Heat Wave and Cold Wave.

b) Skilled District and Block Level forecast and warnings for Heat Wave and Cold Wave with 7 days lead times.

c) Special emphasis on research and studies to generate effective impact-based forecast and warning considering the impact of heat wave & cold waves on human life and health.

d) Sectoral applications for labour intensive agriculture and allied activities (horticulture, animal husbandry, dairy, fisheries), industries, Tourism, Transport (Aviation, Railways, Highways/Expressways, Inland waterways) and power sector.

e) Effective dissemination strategy to communicate the risk information to all stake holders for timely action using all channels of print, electronic, social media and through public awareness.

f) Gradual shift from generalized impact-based warning to dedicated sectoral threshold-based impact-based warnings.

3.5.4 Medium term vision (for next 10 years)

a) Revision of Heat Wave & Cold Wave criteria and SoP for improved warning services.

b) Automated generation and dissemination of impact-based forecast and warnings for all sectoral applications. Improved NWP models and AI/ML techniques to increase the overall forecast accuracy.

c) Skilled District, Block and Panchayat level forecast and warnings of Heat Waves and Cold Waves for 10 days lead times along with tailored impact information with action suggested. Similarly skilled extended range forecast to be provided for a month (4 weeks). Improved forecast accuracy by 40% from a baseline of 2024 is targeted for all spatial and temporal range of heatwave & cold wave forecasts

d) Special emphasis on research and studies to generate effective impact-based forecast and warning considering the impact of heat wave & cold waves on irrigation, Food Processing Sector, Food & Public Distribution and labor-intensive sectors etc.

e) Hot Weather & Cold Weather Hazard Analysis is to be prepared for the entire country considering different sectoral implications.

f) Dedicated sectoral thresholds for impact-based heat wave & cold wave actionable warning services for extreme temperature resilient socio-economic operations.

g) More involvement in framing and implementation of Heat Action Plans.

h) Urban Heat Island effect to be predicted and communicated to the people with sufficient lead time.

i) Dynamic Meteogram for heat wave and cold wave impact-based forecasts and warnings. Thereby extending them as a platform for on-demand forecasting and warning services.

j) Utilization of dense remote sensing data for Heat & cold wave monitoring and forecasting services.

3.5.5 Vision for 2047

a) Automatic heatwave alerts through automatic weather stations through sign boards/internet of things, etc., to appraise the general public regarding the prevalent situation.

b) Seasonal forecast on smaller spatial dimensions, such as at the district level and smaller for micro-management of different sectoral applications harnessing the projected power of quantum computers.

c) Automated demand-based skilled location-specific forecast and warnings of Heat Waves and Cold Waves for 10 days lead times (at 15-minute intervals) along with tailored impact information with action suggested using new technologies including quantum computing.

d) Internet of things-based application working on the heat wave and cold wave services of IMD to take requisite actions based on the impact and action suggested. Ethical rationing of resources for effective heat wave and cold wave warning services thereby giving more priorities to the most vulnerable sectors.

e) Heat Wave & Cold wave services will be omnipresent covering 100% of sectors in terms of impact based forecast, warnings and public awareness such as Education sector, Defense cantonment boards, Youths, Sports, Water Resource management, Tribal Areas, Textile sector, Heavy Industries, Panchayat level services (temperature impact over small water bodies/ponds etc.), communication, Police and Law Enforcement officials (On field duty officers like Traffic Police) etc.

Vision Heat & Cold Wave Warning Services

Dimensions	Medium Term Vision (Next 10 years)	Vision (2047)
Forecast Accuracy w.r.t. the baseline of 2024	Improvement by 40%	Improvement by 80%
Forecast spatial & temporal resolution	District level, block level & Panchayat Level warnings with 4 weeks lead time provided daily.	Automated location-specific warnings. Seasonal forecasts at district/block/panchayat level for micro-management.
Impact based forecast	Dedicated sectoral thresholds for impact-based heat wave & cold wave actionable warning services for extreme temperature resilient physiological & socio-economic operations.	Heat Wave & Cold wave services will be omnipresent, covering 100% of sectors regarding impact-based forecasts, warnings, action suggested and public awareness.
Decision Support System	GIS-based information platform considering multi-sectoral applications for Impact-based forecast services.	In addition to DSS, the Development of Hazard, impact & risk models for heat and cold waves with higher temporal and spatial resolutions

3.5.6 Strategy

a) Development of Decision Support System (DSS) using GIS, AI/ML and other observation & NWP model datasets.
b) Inclusion of Climatological information and past hazard/impact data into DSS.
c) Sectoral studies to generate thresholds considering different meteorological, socio-economic and exposure dataset to provide impact-based forecast and warning services.
d) Automated warning and forecast generation using the thresholds and scientific understanding to be disseminated to the stake holders.

3.5.7 Outcome

a) Decision Support System.
b) New and evolved Heat Wave & Cold Wave criteria reflecting the evolved understanding of physiology and environmental relationships.
c) AI/ML based applications to support Heat Wave & Cold Wave warning services.
d) Development of Hazard, impact & risk models for heat and cold waves with higher temporal and spatial resolutions.
e) IoT based Heat Wave and Cold Wave services.
f) Improved NWP model output and MME based guidance for forecasters.
g) Research studies with publications with respect to different indices for portraying the impact of extreme temperatures.
h) Research studies to find out synoptic signals & NWP products in conjunction with AI/ML to capture Heat Waves during longer lead times (more than 3 days).
i) Sectoral bulletins (print, electronic, graphical, and Multimedia) are used for different sectors and regions.

3.6 HYDROMETEOROLOGICAL SERVICES

3.6.1 Current status and major achievements during the past 10 years

❖ Current status:

i. Real time Rainfall Monitoring

- Monitoring and compilation of the rainfall observations over the entire country throughout the year and preparing rainfall statistics at the district, meteorological sub-divisions, State, four Homogeneous regions and country as a whole. The Statistics are prepared on daily, weekly, monthly, seasonal and annual basis.
- Automisation of the process for the preparation of statistics and its representation in both Text and Graphical formats through 'Customized Rainfall Information System (CRIS)'.
- Rainfall observation network of 6295 stations used to compile and generate the Rainfall statistics for 729 districts across 36 Met Subdisions.
- Upgrading of the CRIS software to "iRains." with advance features of quality controlled data integration.

ii. Hydro-meteorological Support for flood forecast

- Real time monitoring of the rainfall conditions and synoptic situations , realized rainfall and evolving Flood situation over 157 river sub-basins with central agencies Central Water Commission (CWC), National Disaster Response Force (NDRF).
- During Flood Season (May-December), Hydromet bulletins are issued to CWC by 15 Flood Meteorological Offices. These Bulletins contain QPF & heavy rainfall warnings for a lead time of 168 hours.
- Special Quantitative Precipitation Forecast (QPF) is issued during Cyclone or Heavy Rainfall Spells during non-flood season.
- Numerical models used for generating deterministic QPF are WRF, NCUM-R, GFS, NCUM, MME while Probabilistic QPF (PQPF) is generated using GEFS & NEPS

iii. Hydro-meteorological Design storm studies

- Provides the design storm estimates (Return Period values, iso-pluvial maps, SPS/PMP values and their time distribution) to the Hydrologists and design engineers in estimating design flood for the construction of hydraulic and water management structures for irrigation projects, Dams & hydel projects.
- Short duration Return Period rainfall values, Isopluvial maps, intensity duration frequency (IDF) curve are provided as a tool for construction of minor structures like highways, bridges, railway, airports, metro rail, urban drainage network etc.

iv. South Asia Flash Flood Guidance System

- First of its kind in South Asia to provide guidance on Flash Floods for the countries of South Asia:- Bangladesh, Bhutan, India, Nepal, Sri Lanka
- The Advisories are issued at 00, 06, 12 and 18 UTC with 6 hourly updates.
- Generating flash flood Threat for 06 hours up to the watershed level and Flash Flood Risk with 24 hours validity for the districts of the country

❖ Major Accomplishments/ Achievements during last 10 years:

i. Real time Rainfall Monitoring

- Commissioning of Customized Rainfall Information System (CRIS) for auto-generation of the rainfall statistics summary & maps and graphs on 15 Jan 2015.
- Continuous integration of the new rainfall stations under District Rainfall Monitoring scheme (DRMS) and newly created districts. Increase from 660 to 729 districts & 4359 to 6495 rainfall stations under DRMS
- Calculations of Statistics using new RF Normal (1971-2020) implemented.
- In-house development of "iRains" , an enhanced version of CRIS involving new features like Data Quality control and regional data integration

ii. Hydrometeorological Support for flood forecast

- Enhancement from 121 to 157 river sub basins for providing categorical QPF.
- New FMO activities started at MC, Srinagar (2015); MC Bengaluru (2016) and RMC Chennai (2016), and Thiruvananthapuram (2021).
- Validity period of river sub-basin-wise QPF is enhanced from 5 days to 7 days.
- Improvement in river sub-basin-wise operational QPF by 8% in 2023 in day-1 forecast. It is 6% & 5% for the day 2 & day 3 forecast respectively in 2023.
- Improvement of operational QPF over NWP guidance by 14% in Day1 and 10% in Day2.
- Real-time monitoring of QPF & Flood situation and shared with central agencies CWC, NDRF.

iii. South Asia Flash Flood Guidance System

- Operationalize the South Asia Flash Flood Guidance System for providing Flash Flood Guidance for the country and as well south Asian countries (Bangladesh, Bhutan, Nepal and Sri Lanka) in collaboration with WMO.
- IMD is the WMO designated Regional Centre for providing Flash Flood services to the South Asian Nations.
- Integration more than 5000 rain gauge stations, Rainfall data of 18 IMD Doppler Weather Radars, 03 NWP model rainfall forecast data into the SAFFGS system.
- Enhanced the SAFFGS products generation from 30,000 watersheds to 1 lakh watersheds.

iv. Hydrometeorological Design storm studies

Design storm studies completed for the 227 No. of projects during 2013-2024 and supplied to the project authorities. This service helps in earning revenue.

3.6.2 Challenges and Gap Areas

A. Challenges :

- The efficacy of any Early Warning system significantly depends upon the density of the observational Network and the quality of the forecasting products generated across different Spatial and Temporal domains using this observations.

- Flash Flood advisories being a high intensity event with a short response time is critically dependent upon the ability of the NWP models to forecast extreme events.
- The area of River sub-basins are appreciably small and issuing QPF for such small areas poses a big challenge. Accurate rainfall forecast especially heavy rainfall cases using regional/global models and its application in the river sub-basins for flood forecasting activities.
- Rainfall estimates derived from Radar and Satellites also need to complement the ground observations.
- The ground truthing and the validation of the advisories issued needs to be authenticated through a reliable source. This can be partially achieved through remote sensing and ground observations. Validation of the events would lead to better forecast.
- Application of limited use of extended/climate numerical weather prediction model in the water resource management activities.

B. Gap Areas:

Following points may be as possible Gap Areas in hydrometeorological services;

- **Observation System**
  - Rain gauge network at a high resolution. Robust measuring equipments .
  - Sparse radar network
  - Non-availability of high-resolution Digital Elevation Map (DEM) (<10m resolution) for all flood prone cities and flood plains.
  - Availability of updated soil moisture and land use/cover data. Evapotranspiration, and stream discharge data for validation .
  - Lack of Interoperability hinders the usage of various datasets
- **Modelling**
  - Requirement to predict extreme weather events due to the occurrence of localized rainfall activity with very high intensity leading to urban floods and flash floods, in view of increase in frequency of such events nowadays.
  - Convective scale data assimilation is a need of the hour for predicting the extreme precipitation events with at least 2 days lead time.
  - Downscaling of NWP model output at a high spatial resolution.
- **Application**
  - Customized, bias corrected rainfall forecast for early warning of River flooding, urban flooding with GIS compatibility.
  - Impact based prediction of heavy rainfall and warning on inundation regions due to floods
  - Decision support system for hydro-meteorological support services for floods
  - Limited application of Remote sensing (Satellite/Radar) observation data in Hydrometeorological applications
  - Automatic module for product generation on design storm study values.

- **Management**
  - Better coordination with the stakeholders.
  - Last mile connectivity through the use of latest communication channels.
  - Use of comprehendible and specific action oriented advisories

3.6.3 Short-term Vision (next two years)

- Increase in the network of raingauge stations for improving the representative stations upto block /taluka level
- Application of Extended range/Seasonal model forecast for water resource management purposes
- Use of remote sensing (Radar/Satellite) rainfall and other meteorological parameter after rigorous verification, validation in Hydrometeorological application
- Real time reception of rainfall in standard OGC compliance data
- Minimization of time lag for data collection and its dissemination
- Application of dynamic down scaling/post processed/Bias corrected NWP model-based rainfall forecast for short, medium in the river sub-basins
- Application of ensemble NWP model-based (MME) rainfall forecast in the river sub-basins
- Automation of design storm study analysis which will be a major input for the construction of any hydraulic structures
- Centralized data archival system for seamless data sharing of raw data as well as processed data in the digital format confirming to OGC compliance
- Realtime rainfall monitoring and summary report generation in near realtime basis at block/taluka level
- Query based system for customized location /time specific rainfall report generation
- Integration of Alerts with CAP (Common Alert Protocol) will be pivotal for quick dissemination of alerts. Integration of all radar data to the Flash Flood Guidance system for improving the performance of the system.
- Integration of urban flood module to the FFGS for a pilot city
- Dissemination and coordination with stakeholders will be scaled up utilizing all modern technology
- Application of bias corrected satellite based QPE in the river sub-basin scale
- DSS system for Flood meteorological offices for their hdyromet support for flood forecast activities
- Automation for the development of synoptic model with the updated data for the river sub-basins
- Integration of realtime rainfall observation data to the centralized server for realtime rainfall monitoring services.

3.6.4 Medium-term Vision (next ten years)

Hydro-meteorological modelling framework (Operational coupled (Land and Atmosphere at least) models, dedicated hydrological models for larger basins based on geographical/climatic basis, impact-based flood forecasting and dissemination for selected basins

- Increase in the network of raingauge stations for improving the representative stations upto panchayat/municipality level in the country
- Increase in the network of automatic raingauge stations at the 1kmx1km resolution in the urban areas
- Application of high-resolution Extended range/Seasonal model forecast for water resource management purposes
- Realtime rainfall monitoring and summary report generation in near realtime basis upto Panchayat/municipality level
- Integration of ensemble-based NWP model forecast to the Flash Flood Guidance System (FFGS) for improving the performance of the system
- Integration of urban flood module to the FFGS to major cities of the country
- Automation of DSS for location specific Flash Flood Guidance bulletin generation and its dissemination to the stakeholders
- Generation of high resolution, hourly/3hourly analysis of rainfall on realtime basis from all available raingauges, DWR and satellite derived observed rainfall data.

3.6.5 Vision 2047

- Increase in the network of raingauge stations for improving the representative stations upto village level in the country
- Highly dense automatic rainfall network in the country special emphasis on the flood plain river basins and in the urban areas
- Realtime rainfall monitoring and summary report generation in near realtime basis in the smallest unit upto village level
- Generation of post processed QPF including heavy rainfall which statistically downscaled to the high-resolution grid points and its validation on real time basis
- Comprehensive Query based system for client centric rainfall report generation and on the fly generation of rainfall products at different spatial and temporal domain
- Automation of location specific SMS alerts to public for flash flood
- No Hydro-meteorological hazard due to high QPF specially in respect of floods goes undetected by zeroing down the impacts on life and property
- Sharing the short-term prediction of the heavy rainfall associated urban flood scenarios on web-GIS with one-minute refreshing time
- Impact based full hydro-meteorological services
- Fully automatic operational hydro-meteorological services for river sub-basin scales

3.6.6 Strategy

- Enhance the raingauge network at higher spatial density and temporal (hourly) scale over the region (hotspots of extreme rain) with use of various observational platforms especially river sub-basins/city specific.
- Development of a comprehensive Query based system for client centric rainfall report generation and on the fly generation of rainfall products at different spatial and temporal domain
- Real time data entry by RMCs/MCs to the centralized server via remote logging facility for real-time rainfall monitoring activity. For this a GUI will be developed.
- Coordination with RMCs/MCs for installation of more no. of raingauges and also encourage to them to coordinate other Government agencies to get the additional rainfall data operationally.
- Co-ordination with WMO for enhancement of the SAFFGS services and inclusion of urban flood module for the country. Integration of above into our current set-up of impact-based forecasting and warning system. Integration of Alerts with CAP (Common Alert Protocol) will be started for quick dissemination of FFGS alerts. Integration high resolution bias corrected NWP models and ensemble base NWP model rainfall forecast into the SAFFGS system.
- Development of a module for automation of design storm studies for improving its product accuracy and timely products generation.
- Development of a DSS for Hydromet support for flood forecast in the Flood Meteorological Offices for their hydromet support activities riverine flood forecast and a module for the synoptic analogue model.
- Development of post processing/bias correction/dynamic downscaling technique for the improvement of NWP model forecast at river sub-basin scale and applied for automatic rainfall forecast products generation for river sub-basins.
- Improve in user interaction mechanism and annual user interaction workshop
- A robust data base management system at O/o DGM, HQ and CRS, Pune for hydrometeorological data and products
- Updating the manual of Hydrometeorology for detail technical and operational documentation of Hydrometeorological services
- Data availability (in-situ, RS, and reanalysis) and preparing background or climatological information related to rainfall, evapotranspiration, soil moisture, discharge etc.
- Grid-scale mapping of variables viz. rainfall, evapotranspiration, soil moisture etc. and its validation up to sub-basin scale
- Development of a modules for realtime verification of river sub-basin-wise QPF, flash flood and urban flood forecast/warnings.
- Strategy improvement for Community and Outreach programs
- Collaboration with other allied agencies for all the aspects, participation in all the areas of related stakes
- Setting up a dedicated centre such as NWFC for the hydrological services

- Improvement in developing observational and monitoring aspects
- Active participation in the policy and implementation strategy
- Coordination with Central Water Commission for setting up the Hydrological modelling framework for different basins/sub-basins coupling with IMD NWP model forecasts.

3.6.7 Outcome

- Web application for a comprehensive Query based system for client centric rainfall report generation and on the fly generation of rainfall products at different spatial and temporal domain and also realtime availability of station-wise rainfall data.
- Automatic monitoring and generation of observed rainfall statistics in the smallest unit upto block/ Tehshil/ Panchyat/village level in near realtime mode.
- Generation of NWP model-based bias corrected/post processed/dynamic down scaled QPF for river sub-basins.
- Automation of design storm study in a module for computation of Return period values, SPS, PMP and time distribution of rain storm. Online availability of all design storm study related values for the stakeholders.
- Automated upgraded product generation on flash flood guidance system and development of a city specific urban flood warning system. Integration of Alerts with CAP (Common Alert Protocol) will be pivotal for quick dissemination of FFGS alerts. Integration high resolution bias corrected NWP models and ensemble base NWP model rainfall forecast into the SAFFGS system.
- Setting up a national centre for hydro-meteorological services (monitoring and forecasting)
- Impact based hydro-meteorological forecasts (droughts, floods).
- Realtime verification of river sub-basin-wise QPF, flash flood and urban flood forecast/warnings.
- DSS for Hydromet support for riverine flood forecast mainly for QPF. Module development for automated updated statistical synoptic analogue model at river sub-basin-scale.
- Enhanced raingauge network at higher spatial density and temporal (hourly) scale over the region (hotspots of extreme rain) with use of various observational platforms especially river sub-basins/city specific.
- A robust data base management system at DGM, HQ and CRS, Pune for hydrometeorological data and products.
- Preparation of a manual of Hydrometeorology for detail technical and operational documentation of Hydrometeorological services.

3.7 POLAR METEOROLOGY

3.7.1 Current status and major achievements during the past 10 years:

- **Research Stations:** India's commitment to polar research is evident through the establishment and upgradation of its research stations. Maitri and Bharati Stations in Antarctica have been pivotal for research, while the Himadri Station in the Arctic has played a crucial role since its inception in 2008. As part of the Indian government's initiatives to better study and quantify the Himalayan glacier responses towards the climate change, National Centre for Polar and Ocean Research (NCPOR), Goa, under the Ministry of Earth Sciences has established a high-altitude research station in Himalaya called HIMANSH, at a remote region in Spiti, Himachal Pradesh on October 2016.
- IMD ozone sonde and Brewer data have clearly shown that there is ~~a~~ ozone hole during late winter to early spring (September - November).
- **Integrated Climate Studies:** Comprehensive studies have been conducted to understand the impact of polar climate changes on broader global patterns, notably the Indian monsoon and sea-level variations.
- **Remote Sensing:** India's advancements in space technology have facilitated satellite missions focused on polar observations, significantly enriching meteorological, and oceanographic data.
- **Oceanographic Surveys:** Extensive studies in the Southern Ocean have provided insights into its physical, chemical, and biological properties.
- **Ice Core Analysis:** Extracting and studying ice cores from Antarctica have enabled researchers to reconstruct past climates and greenhouse gas patterns.
- **Technological Innovations:** India's indigenous development and deployment of Automatic Weather Stations (AWS) in Antarctica have been noteworthy.
- **Capacity Building:** Institutions like the National Centre for Polar and Ocean Research (NCPOR) have been at the forefront of training and expeditions to Polar Regions.

3.7.2 Challenges and Gap Areas

While there have been commendable advancements in polar meteorology, there exist following challenges:

- **Limited Temporal and Spatial Data:** Many research expeditions are restricted to milder summer months, leading to gaps in data during harsher seasons.
- **Complex Dynamics:** The interactions between the atmosphere, ocean, and ice in Polar Regions require deeper exploration.
- **Climate Modeling Inaccuracies:** Existing climate models often fall short when applied to the Polar Regions, especially in predicting extreme events like polar cyclones. The study of polar characteristics with respect to large scale features like monsoon needs investigation.

- ❖ The interactions between melting ice, ocean circulation, and atmospheric patterns remain an active area of investigation.
- ❖ While models have improved, predicting precise rates of ice melt and the associated rise in sea levels over decades to centuries remains challenging.
- ❖ **Biogeochemical Cycles:** More research is required on Polar Regions' roles in global carbon and methane cycles.
- ❖ **Human and Ecological Impact:** Anthropogenic activities' effects on polar meteorology and polar ecosystems' responses to meteorological changes are areas demanding further study.
- ❖ **Technology and Methodology:** There's a need for more advanced remote data collection technologies and continuous long-term monitoring systems.
- ❖ **Interdisciplinary Research:** Integrating meteorological data with other fields like biology, oceanography, and geology can provide a more holistic understanding of polar systems.
- ❖ **Policy Implementation:** Research must be better translated into actionable climate adaptation and mitigation policies.

3.7.3 Short-term Vision (next two years)

- ❖ **Data Consolidation**: Create a unified and accessible database consolidating the past decade's polar meteorological data, complemented with user-friendly data visualization tools.
- ❖ **Infrastructure Upgrades**: Modernize research stations with advanced instruments and enhance communication systems for real-time data relay from remote polar areas.
- ❖ **Expedition Increases**: Conduct at least one additional expedition to both the Arctic and Antarctic, targeting previously less explored regions.
- ❖ **Model Refinement**: Target a 10-15% increase in polar climate model prediction accuracy and incorporate real-time data for better forecasting.
- ❖ **Collaborative Initiatives**: Strengthen at least three international research collaborations and facilitate monthly virtual symposiums for global knowledge exchange.
- ❖ **Education and Awareness**: Launch an online portal or app for polar meteorology engagement, aiming for 100,000 active users, and host regional workshops to raise awareness.
- ❖ **Preparatory Measures**: Start preliminary groundwork for future missions and evaluate the introduction of sustainable technologies in research settings.

3.7.4 Medium-term Vision (next ten years)

- ❖ **Advanced Monitoring Systems**: It is aimed at collection of surface and upper air meteorological data by deploying latest state of art equipment. Continuing Radio Sondes and Ozone Sondes and deploying of advanced space Radars. This is necessary to understand how energetic particles and electrical currents from space affect both the upper and the lower atmosphere. Thus providing exceptional details and vast quantities of data and opening the scope of research. Integrate AI and machine learning into polar monitoring and expand satellite coverage with high-precision sensors. Real time data to be made available at IMD, New Delhi for further analysis and forecasting.

- ❖ **Research Facility Expansion**: Establish three new research stations in both the Arctic and Antarctic and make existing stations energy self-sustaining.
- ❖ **Deep Ocean-Ice Interactions**: Intensify study of ocean-ice interactions and utilize advanced AUVs designed for polar research.
- ❖ **Holistic Climate Modeling**: Develop integrated climate models incorporating meteorological, oceanographic, and biogeochemical data, targeting a 30-40% reduction in prediction errors.
- ❖ **Sustainability Focus**: Implement zero-waste policies across polar research and study the feasibility of geo-engineering methods in Polar Regions.
- ❖ Expanding and improving the observational network in Polar Regions including Himalayas is crucial for advancing our understanding of climate change, the environment, and the unique conditions in this remote and critical region.
- ❖ Extension of third pole research and services, India will host Third Pole Regional Centre (TPRCC)

3.7.5 Vision 2047

- ❖ **Pioneering Polar Tech**: Develop fully autonomous, renewable-energy-powered research stations and deploy AI-driven drones and robots.
- ❖ **True Global Collaboration**: Establish a unified global polar research council and create universally accessible data repositories.
- ❖ **Deep Time Climate Understanding**: Retrieve ice cores providing detailed ancient climate records and recreate these epochs with advanced models.
- ❖ **Climate Mitigation and Adaptation**: Showcase sustainable geoengineering projects to restore melting ice and draft strategies for regions impacted by polar melt.
- ❖ **Next-Gen Education and Training**: Build global polar-focused universities and interdisciplinary scientist training programs.
- ❖ **Holistic Ecosystem Understanding**: Conduct detailed biotic surveys in Polar Regions and devise conservation strategies for the ecosystems.

3.7.6 Strategy

- ❖ **Initial Plan:**
  - Enhance existing research infrastructures with modern technology.
  - Initiate extensive year-round data collection from ground stations to drones and satellites.
- ❖ **Subsequent Decade Plan:**
  - Establish advanced, mostly autonomous research hubs.
  - Deepen understanding of interactions between the atmosphere, ocean, ice, and biogeochemical cycles in Polar Regions.
  - Forge international collaborations.

- Emphasis on understanding the Polar Regions' role in the global carbon cycle, particularly methane emissions from permafrost.

❖ **Technological Development:**
  - Collaborate with the tech industry.
  - Deploy AI-driven robots and advanced climate models by mid-term.

❖ **Eco-Footprint Management:**
  - Rigorous measures to reduce environmental impact.
  - Goal to make polar expeditions and research a sustainability benchmark in 30 years, setting a global example.

❖ To establish a widespread global ice core drilling program, targeting previously unexplored icy territories and utilizing advanced technologies. Techniques to extract even more detailed temperature records should also be developed. Increase the resolution of ice core measurements to understand shorter-term variations in gas concentrations and refine lab techniques to detect even lower concentrations of trace gases. Combine ice core data with ocean sediment data to create comprehensive models of past ocean-atmosphere interactions.

❖ Deploy more comprehensive satellite systems, underwater drones, and buoy networks to monitor changes in ice cover, thickness, and volume. Provides richer, high-resolution data to refine and validate models.

❖ Develop and employ machine learning and artificial intelligence tools to process large datasets and refine predictive models.

3.7.7 Outcome

Polar research is more than just understanding the Earth's extremities; it's about recognizing the extensive implications of these dynamics for our global society, environment, and economy. The results of such research offer both tangible and intangible benefits, some immediate and others long-term.

- Comprehensive insights into Earth's climate via polar meteorology, ecology, and geophysics data.
- **Improved Disaster Preparedness**: Enhanced polar meteorology knowledge aids better weather forecasting and reduces losses.
- **Health Benefits**: Recognizing climate change impacts from polar changes helps in mitigating health risks.
- **Job Creation**: Expanding polar research leads to varied employment opportunities.
- **Innovation-driven Growth**: Development of cutting-edge technologies suited for polar studies can boost other industries.
- **Insurance and Risk Management**: Polar data refines risk assessment.
- Real-time data gathering and analysis through autonomous research infrastructures.
- A global alliance addressing polar challenges and sharing resources to streamline research.
- Prototypes of sustainable research stations, offering insights for global sustainable practices.

3.8 IMPACT BASED WEATHER FORECASTING

3.8.1 Current status and major achievements during the past 10 years

Impact Based Forecast (IBF) can be implemented by following the four stages mentioned below:

- Stage I (Threshold Method): Define a forecast threshold at which people or infrastructure in a specific location are expected to be negatively impacted, based on the vulnerability of that location/infrastructure.
- Stage II (Qualitative combination method): Create a composite index that combines relative vulnerability with forecasted hazard magnitude to create a relative priority score, often a qualitative assessment by a group.
- Stage III (Impact Model Method): Combination of Stage I & Stage II.
- Stage IV (Climate Sensitivity Method): Real-time impact-based forecast and risk-based warning using Stage I, II & III and dynamic information on socio-economic sectors, secondary hazards & geospatial data.

In IMD, Stage I, II, and III is completed for most of the hazards and Stage IV is under process. Stage IV has been implemented in case of Tropical Cyclones since 2021 and is partially implemented in case of Heavy Rainfall. Implementation of Stage IV IBF is underway and major challenge for remaining severe weather hazards.

At present IMD is issuing IBF for major cities and at the district level in colour-coded format. Currently, there are four stages of forecast/warning dissemination in connection with IBF.

- Stage -1: Heavy rainfall Advisory (Watch)-(5 days lead time with 6-hrly updates)
- Stage-2: Heavy rainfall Alert (48 hours prior to the occurrence of the event at 12 hourly updates)
- Stage-3: Heavy rainfall Warning (24 hours prior to the occurrence of the event at 06/12-hourly updates)
- Stage-4: 12 hours prior to occurrences of maximum rainfall spell

Recently, IMD has implemented a Decision Support System, in which a color-coded impact matrix is generated based on observations & model guidance for determining the warning level for all the districts of the country.

3.8.2 Challenges and Gap Areas

Impact-based forecasting is an essential approach in meteorology and climate science, but it is not without its challenges and gap areas. Identifying and addressing these gaps is crucial for improving the accuracy and effectiveness of impact-based forecasts. Here are some common gap areas in IBF.

❖ **Hazard and Impact Forecasting Scenario:**

- For most hazard types, impact forecasting is in its infancy, while operational impact forecasting systems exist for a few hazard types only, for instance, heat waves and earthquakes. Hazard modelling is more advanced compared to impact modelling. Enhanced and more systematic efforts are recommended to move impact modelling to a comparable level.
- Impact forecasting needs to consider social systems and the structures that support them. Although this environment has been largely created and shaped by human intervention, our knowledge of it is surprisingly weak, therefore resulting in highly uncertain impact models.
- A closer collaboration of natural sciences, engineering, and social sciences is required to understand the role of the human factor and its influence on the transformation of a hazard forecast into an impact forecast.
- Quantifying the uncertainties of forecasts is important as it provides an honest and fuller picture for informed decision-making. The state of the art uncertainty quantification is very different between hazard and impact modelling. Whereas uncertainties are often provided for hazard modelling, this is hardly the case for impact modelling.
- Impact forecasting is expected to offer new possibilities for emergency management and disaster risk reduction, as it provides richer information to manage crisis situations. This is of great importance as extreme events are expected to increase in the future due to climate change and economic and population growth, while simultaneously the complexity of our society is also growing.
- Impact forecasting is associated with new challenges for communication and decision-making, as (uncertain) impact information may lead to different responses from warned people. Not only are there more studies needed to better understand the effect of impact forecasts, but novel approaches need to develop and tailor impact forecasts according to the operational contests.

❖ **Data Quality and Availability:**

Limited access to high-quality, real-time meteorological and environmental data can hinder the accuracy of impact-based forecasts. Gaps in data coverage, particularly in remote or less developed regions, can make it challenging to provide comprehensive forecasts.

❖ **Spatial and Temporal Resolution:**

Fine-scale spatial and temporal resolution is often necessary to accurately predict local impacts, such as flash floods or small-scale weather phenomena. Many forecasting models and systems may not provide adequate resolution for certain impact assessments.

❖ **Data Assimilation:**

Integrating observational data into forecasting models (data assimilation) can be complex and may introduce uncertainties. Accurately assimilating diverse data sources, including satellite, radar, and ground-based observations, remains a challenge.

- **Modeling Capabilities:**

Numerical weather prediction models have limitations, especially in simulating extreme events or complex atmospheric phenomena. Improvements in model physics and computational power are needed to enhance forecast accuracy.

- **Hydro-Meteorological Coupling:**

Forecasting the impact of rainfall on river discharges, flooding, and water resource management requires a strong coupling between meteorological and hydrological models. Inconsistencies or mismatches between these models can result in inaccurate flood forecasts.

- **Communication and Decision Support:**

Ensuring that forecasts are effectively communicated to decision-makers and the public is a challenge. Tailoring forecasts for specific user needs and providing clear guidance on actions to take during extreme events is essential.

- **Uncertainty Quantification:**

Communicating forecast uncertainty is critical for decision-making, but it can be challenging to quantify and convey uncertainties accurately. Probabilistic forecasts and uncertainty estimates need further development.

- **User Engagement and Training:**

Many users, especially in vulnerable or less developed regions, may lack the training and capacity to interpret and act on complex forecasts. Providing user-friendly information and training programs is essential.

- **Integration of Climate Change:**

Incorporating the long-term effects of climate change into impact-based forecasts is a growing concern. Models and systems need to account for changing climate patterns.

- **International Collaboration:**

Collaboration between meteorological agencies at the regional and global levels is essential for addressing trans-boundary weather and climate impacts. Gaps in international cooperation can hinder effective forecasting of events like tropical cyclones.

- **Interdisciplinary Research:**

Impact-based forecasting often requires collaboration between meteorologists, hydrologists, climatologists, and social scientists to understand and address societal impacts fully. Interdisciplinary research efforts can be limited.

Addressing these gap areas often involves a combination of research, technological advancements, improved data sharing, capacity building, and collaboration between meteorological agencies, governments, and other stakeholders. It's an ongoing process to enhance the accuracy and usefulness of impact-based forecasts for the benefit of society and environmental-based forecasting.

3.8.3 Short-term Vision (next two years)

The optimistic approach will come up with a provisional qualitative cum quantitative Impact Based Warning products on dynamical zonal/regional/local scale classified on the basis of climatic/hazard/vulnerability profile with specified color codes based upon the scale of exposure & vulnerability pertaining to the specific type of hazard/multi-hazard in this region depending upon the spatial & temporal scale of the hazard, which may ultimately result in better contingency planning with community centric bottom-up approach.

The impact based forecast and risk based warning in a dynamic platform based on hazard & impact modeling and risk assessment with a lead period of 3 days for heat/cold wave and heavy rainfall will be in place with accuracy of 80% one day and 60% by 3 days ahead.

Short-term missions in connection with Impact-Based Forecasting (IBF) by the India Meteorological Department (IMD) can help set the stage for the long-term vision while addressing immediate needs and challenges. Here are some short-term missions that IMD can consider:

❖ **Synergy of GIS and IoT for Weather Disasters Monitoring and Management:**

Information technology plays a significant role in attaining safety from natural disasters through providing predictions and early warnings to minimize the degree of danger and the damage due to the severe weather conditions. We can integrate GIS and the Internet of Things (IoT) technologies in the detection and alerting processes in disaster management of severe weather conditions. A multi-layered geo-database is developed with the integration of the IoT data. Spatial analysis is carried out to identify the vulnerable areas to disasters due to the severe weather conditions.(M. Nabil et. al, 2019)

❖ **Real-Time Monitoring and Alerts (Use of IoT):**

Advances in sensor technology and communication infrastructure will enable real-time monitoring of hazards and immediate dissemination of alerts to affected populations through various channels, including mobile apps and social media.

❖ **Artificial Intelligence and Early Warning Systems:**

- Early warning systems (EWSs) are designed to effectively and efficiently disseminate appropriate information related to disaster events, in the form of alarms or warnings, to vulnerable communities before or during a disaster so that proactive and preventive measures can be taken to minimize the loss and damage associated with such events. With the advent of the Internet of Things and the advanced technology driven sensor devices, large amounts of data are getting generated at a rapid speed. This data needs to be captured, stored and analyzed by EWS, since it possesses useful indicators and could provide enormous opportunities for monitoring and managing both natural and man-made disasters.
- The use of artificial intelligence (AI) can enable EWS to mine early warning signals from this data, so that proactive and preventive measures for disaster mitigation, preparedness, response and recovery can be planned leading to timely alerts and warnings being disseminated to the relevant stakeholders.

❖ **Use of Xtended Reality (XR) for public awareness:**

- Augmented Reality (AR), Virtual Reality (VR) and Mixed Reality (MR), collectively called Xtended Reality (XR), are the application areas of computer graphics that allow the user to interact with the computer-generated imagery in both real and virtual environment scenarios. VR scenes consist of a fully virtual environment with virtual elements that obscure the physical environment, and simulate the physical objects whereas an AR scene consists of a real environment with integrated but non - dominating virtual objects that can react to the user and/or the scene.

- It was found that the XR technology is applied extensively in computer simulation modeling, interaction techniques, training, infrastructure assessment and reconnaissance, and can be used for public awareness areas of disaster management.(Khanal S et. al, 2022)

❖ **Integration of AI and Machine Learning for Hazard Analysis:**

Artificial intelligence (AI) and machine learning (ML) algorithms will play a significant role in hazard analysis. These technologies will help process vast amounts of data, identify patterns, and make real-time predictions, improving early warning systems and decision support.

❖ **Development of an IBF Quality Assurance Framework:**

Develop an IBF Quality Assurance Framework that ensures the accuracy, precision, and timeliness of IMD's IBF services.

❖ **Use of Predictive Analytics:**

Predictive analytics can be used to forecast the likelihood and impact of hazards. Probabilistic modeling will provide decision-makers with a range of scenarios to prepare for different outcomes.

❖ **Data Fusion and Remote Sensing:**

Advances in remote sensing technologies, including satellites, drones, and ground-based sensors, will provide a wealth of data for hazard analysis. Data fusion techniques will combine data from multiple sources for more comprehensive hazard assessments.Unmanned Aerial vehicles (UAVs) equipped with sensors will be routinely used for atmospheric profiling, especially in regions with challenging terrain or inadequate ground-based observations.

❖ **Localized Impact Assessment:**

Pilot localized impact assessment models for specific regions or states to understand and communicate the potential impacts of weather events on agriculture, infrastructure, and public safety. It is needed to assess not only the primary impacts but the secondary impacts also. The health sector is falling under the secondary impacts after most of the severe weather events and this part needs to be analyzed seriously.

❖ **Capacity Building:**

Conduct training workshops and capacity-building programs for government agencies, emergency responders, and local communities to improve their preparedness and response to extreme weather events.

- **User Engagement:**

Engage with key user groups, such as farmers, fishermen, and disaster management authorities, to understand their specific needs and incorporate their feedback into forecast products. We need to develop some mobile apps so that these communities can easily communicate the real-time scenario over some region which in turn can be utilized for improving the IBF for that region.

- **Research and Innovation:**

Invest in research initiatives to improve weather modeling, data assimilation, and forecasting accuracy, especially for localized events like thunderstorms and flash floods.

- **Data Integration and Observation Network:**

With speeding technological advances, we foresee state of art automated network of meteorological observational system with very high resolution (~5 km^2 grid box in case of Rainfall & ~100 km^2 grid box in case of other meteorological parameters). Also, there will be need to integrate data from diverse sources, including citizen science initiatives and private weather stations, to enhance real-time monitoring and forecasting capabilities. We can think of some mobile apps for collecting information from the general public. Even the information from social media can also be utilized but we need to verify the integrity of this information before utilizing the same.

- **Probabilistic Forecasting:**

Develop and provide probabilistic forecasts to convey the likelihood of different weather scenarios, enabling better decision-making by stakeholders.

- **Enhanced Communication:**

Implement a robust communication strategy to effectively convey forecast information to the public, including the use of mobile apps, social media, and local radio. An interactive web page may be designed through which block level IBF can be issued in near real-time for all the regions of India. Also, an effective Public Address/Alert System may be in place to address the vulnerable sections of society at places under threat.

- **Community Resilience:**

Collaborate with local governments and communities to identify and implement community-based resilience measures, such as flood-resistant infrastructure and early warning systems.

- **Public Awareness Campaigns:**

Launch public awareness campaigns to educate citizens about the importance of weather preparedness and the actions they can take to protect themselves during extreme events.

- **Multi-Agency Collaboration:**

Foster collaboration with other government agencies, research institutions, and regional meteorological organizations to leverage expertise and resources for more accurate forecasts.

- **Feedback Mechanism:**

Establish a feedback mechanism to receive input from users and stakeholders on the usefulness and effectiveness of forecast products and services.

- ❖ **Disaster Risk Reduction:**

Collaborate with disaster management authorities to integrate IBF into disaster risk reduction strategies and response plans.

- ❖ **Impact Outlooks using Seasonal Forecasts:**

Strategic use of seasonal weather and climate forecasts to inform early action that can address the impacts of potential hazards.

- ❖ **User-Centric Services:**

Tailor forecasting services to meet the specific needs of various user groups, including farmers, fishermen, urban planners, and healthcare professionals, with a focus on delivering actionable information.

- ❖ **Data Sharing and Open Access:**

Promote data sharing and open access to weather and climate information to facilitate research, decision-making, and innovation.

- ❖ **Hazard-Impact real time atlas:**

Collaboration between IMD-NDMA for preparation of hazard-impact data base on a GIS platform which is available at state level with limited data available from state authorities, currently only the hazard and vulnerability atlas are available.

- ❖ **Citizen Science Initiatives:**

Launching an initiative involving High school and undergraduate science students who can volunteer and contribute in micro-observational network similar to NASA's Globe observer project.

3.8.4 Medium-term Vision (next ten years)

Medium-term missions for Impact-Based Forecasting (IBF) by the India Meteorological Department (IMD) should align with the overarching vision of building a weather-resilient nation. These missions are designed to achieve sustained progress in enhancing the accuracy and effectiveness of weather and climate forecasts while reducing the impacts of extreme events on society, the economy, and the environment. The impact based forecast and risk based warning of district and block level for all types of severe weather based on hazard & impact modeling and risk assessment will be in place with a lead period of 5 days and accuracy of at least 70%. Here are some medium-term missions in connection with IBF by IMD:

- **High-Resolution Regional Models:**
  Develop and maintain high-resolution regional weather and climate models that can accurately predict localized weather phenomena, enabling precise impact assessments and forecasts.

- **Integrated Data and Observations:**
  Continue to integrate data from various sources, including satellites, radar, ground-based stations, and citizen science initiatives, to enhance the accuracy and timeliness of forecasts.

- **Advanced-Data Assimilation:**
  Invest in advanced data assimilation techniques to assimilate a wide range of observational data into forecasting models, improving the initialization of weather simulations.

- **Multi-Hazard Early Warning Systems:**
  Expand and enhance early warning systems to cover a wide range of hazards, including cyclones, floods, droughts, heat waves, and air quality issues, ensuring timely alerts and advisories.

- **Localized Impact Assessment Tools:**
  Develop sophisticated impact assessment models that can provide detailed and context-specific information on the potential impacts of weather events on sectors like agriculture, water resources, transportation, and public health.

- **Research and Innovation:**
  Foster a culture of continuous innovation and research in meteorology and climatology, encouraging the development of cutting-edge forecasting technologies and methodologies.

- **Climate Change Integration:**
  Incorporate climate change considerations into impact forecasting models and assessments to address the long-term shifts in weather patterns and their impacts.

- **International Collaboration:**
  Strengthen collaborations with international meteorological organizations, research institutions, and neighboring countries to share expertise, data, and best practices for addressing trans-boundary impacts.

- **Continuous Monitoring and Evaluation:**
  Establish a robust system for monitoring, evaluating, and improving IBF processes and services, incorporating feedback from users and stakeholders.

These long-term missions aim to position IMD as a leader in IBF, ensuring that India is better prepared to cope with the impacts of extreme weather and climate events, promote sustainable development, and safeguard the well-being of its citizens for generations to come.

3.8.5 Vision 2047

"Empowering India with Impact-Based Forecasting Excellence- Pioneering a Weather-Resilient India"

In 2047, we envision a nation where every citizen, community, and industry is empowered with precise, accessible, and actionable weather and climate information. Through cutting-edge technology, relentless innovation, and unwavering commitment, IMD leads India in building a weather-resilient future. Our foresight protects lives, sustains economies, and nurtures a thriving environment, ensuring a harmonious balance between nature and progress.

The impact based forecast and risk based warning will be made available at each household level utilizing dynamic hazard & impact modeling and risk assessment with 90% accuracy and lead period of 7 days.

Mission

Our mission, as we approach India's centenary of independence, is to fortify our nation's resilience to the diverse challenges of weather and climate. We pledge to:

- **Accurate and Timely Forecasts:**
  Deliver world-class, highly accurate, and timely weather and climate forecasts, including extreme events, ensuring the safety and well-being of every Indian.
- **Tailored Impact Assessment:**
  Foster an impact-centric approach, precisely assessing and transparently communicating the potential impacts of weather and climate events on every sector of society, economy, and environment.

- **A Comprehensive IBF System:**
  Establish a comprehensive IBF system that covers both medium-range and extended-range weather and climate risks for all regions of India. Even we need to plan for an IBF system that can be used in the seasonal-level forecast.

- **Advanced Technological Leadership:**
  Maintain our technological leadership by continuously advancing modeling, data assimilation, and observational capabilities, propelling our forecasting accuracy to new heights.

  With advent of emerging tools & technologies in this developing field we might be in position to have a real time gridded dynamic impact database at very high resolution (~sub-km scale) with exact geo-tagged information to be assimilated in regional/local sectoral impact/vulnerability model to implement realistic sector specific IBF module at sub-km scale by 2047.

- **Early Warning and Preparedness:**
  Enhance early warning systems to provide robust alerts and advisories, fortifying our nation's preparedness and reducing vulnerabilities to extreme events.

- **User-Centric Services:**
  Engage with our diverse user groups through user-centric services, equipping them with information that empowers informed decisions and fosters resilience.

- **Education and Capacity Building:**
  Invest in education and capacity building, nurturing a generation of meteorologists, climate scientists, and informed citizens who champion weather resilience.

- **Global Leadership and Collaboration:**
  Forge international partnerships and leadership in meteorological research, data sharing, and technology transfer, strengthening our position in the global meteorological community.

- **Climate Resilience Integration:**
  Integrate climate change considerations into our forecasts and assessments, anticipating and adapting to long-term shifts in weather patterns and their impacts.

- **Continuous Innovation:**
  Embrace a culture of relentless innovation, research, and development to continuously improve our forecasting capabilities.

- **Transparency and Public Trust:**
  Uphold transparency in forecasting processes, ensuring public trust by providing clear communication of forecasts, uncertainties, and their potential impacts.

- **Resilient India:**
  Align with India's broader goals of building resilience to extreme weather and climate events, supporting sustainable development, and safeguarding the well-being of our nation's diverse communities.

By 2047, we commit to realizing this vision—a weather-resilient India where IMD is a global leader in impact-based forecasting, enabling progress, protecting lives, and nurturing a sustainable environment for generations to come. Together, we shape a resilient, harmonious future for India.

3.8.6 Strategy

Developing a comprehensive strategy for achieving the missions of Impact-Based Forecasting (IBF) by the India Meteorological Department (IMD) in 2047 requires a multifaceted approach that encompasses technology, research, education, collaboration, and more. Below is a strategic framework outlining the key components for achieving the missions of IMD in 2047:

Technological Advancements:

- **High-Resolution Models:** Invest in the development and utilization of high-resolution numerical weather prediction models capable of accurately forecasting local-scale weather and climate events.

- **Data Assimilation:** Continue to improve data assimilation techniques to integrate diverse data sources, including satellite, radar, and ground-based observations, for enhanced forecasting accuracy.
- **Advanced Observation Networks:** Establish and maintain an extensive network of weather and climate observation stations, including automated weather stations, to capture real-time data across the country. We need to establish more ground-based radars and IoT-enabled sensors for getting real-time hazard as well as impact information. Space-borne radars and images, drones, etc. can also be utilized for this purpose.
- **Supercomputing Infrastructure:** Invest in state-of-the-art supercomputing infrastructure to run complex modeling simulations and handle big data processing efficiently. Artificial Intelligence (AI)/ Machine Learning (ML)/ Big Data Analytics are the future of data analytics and can be utilized for data analysis.

Impact-Centric Forecasting:

- **Impact Assessment Tools:** Develop sophisticated impact assessment models that evaluate the potential consequences of weather and climate events on various sectors, taking into account local vulnerabilities and sensitivities. We need to update the impacts created by the hazards after each event and accordingly need to modify the meteorological thresholds to improve the IBF.
- **Sector-Specific Forecasts:** Tailor forecasts and warnings to meet the specific needs of different user groups, including agriculture, disaster management, transportation, and public health.
- **Probabilistic Forecasting:** Provide probabilistic forecasts to communicate uncertainty effectively and help decision-makers make informed choices.

Early Warning and Preparedness:

- **Early Warning Systems:** Strengthen early warning systems for extreme events, ensuring that alerts and advisories reach the public and relevant authorities promptly.
- **Capacity Building:** Offer training programs and capacity-building initiatives for government agencies, emergency responders, and local communities to improve preparedness and response.

Research and Innovation:

- **Interdisciplinary Research:** Foster collaboration between meteorologists, climatologists, hydrologists, and social scientists to advance research on the impacts of weather and climate events.
- **Climate Change Integration:** Incorporate climate change considerations into forecasting models and assessments, allowing for long-term planning and adaptation.

- **Innovation Incubators:** Establish research centers and innovation hubs to encourage ongoing research, development, and experimentation in meteorology and related fields.

Collaboration and Partnerships:

- **National Collaborations:** Strengthen partnerships with government agencies, research institutions, and regional meteorological organizations within India.
- **International Engagement:** Actively participate in international collaborations, sharing expertise, data, and best practices with global meteorological agencies and organizations.

User Engagement and Education:

- **User-Centric Approach:** Continuously engage with diverse user groups to understand their needs and preferences for forecast information.
- **Education and Awareness:** Develop educational programs and campaigns to promote weather and climate literacy among the general public and decision-makers.

Climate Resilience Integration:

- **Long-Term Planning:** Collaborate with government agencies and planners to integrate weather and climate considerations into long-term infrastructure and development plans.

This strategic framework outlines the essential components and actions required for IMD to achieve its missions in connection with IBF by 2047. It emphasizes the importance of technology, research, education, collaboration, and transparency in enhancing the accuracy and impact of weather and climate forecasts in India.

3.8.7 Outcome

"By 2047, IMD's Impact-Based Forecasting (IBF) initiatives have revolutionized weather and climate services in India, resulting in a weather-resilient nation where the devastating impacts of extreme events are significantly reduced, and sustainable development thrives."

This outcome statement reflects the envisioned success of IMD's IBF efforts by 2047, emphasizing the following key outcomes:

vii. **Significant Impact Reduction:** IMD's IBF initiatives have successfully reduced the adverse impacts of extreme weather and climate events on various sectors, safeguarding lives, property, and the environment.

viii. **Enhanced Resilience:** The nation has become more resilient to weather-related challenges, with communities, industries, and infrastructure better prepared and equipped to withstand and recover from extreme events.

ix. **Sustainable Development:** IMD's IBF contributions have facilitated sustainable development by supporting informed decision-making, protecting economic activities, and ensuring the well-being of citizens across India.
x. **Cutting-Edge Services:** IMD's IBF services have set new standards in meteorology, offering cutting-edge technology, highly accurate forecasts, and tailored impact assessments for diverse user groups.
xi. **Global Recognition:** IMD's leadership in IBF has garnered international recognition, positioning India as a leader in meteorology, climate resilience, and global meteorological collaborations.

Benefit to the Society

The vision statement of Impact-Based Forecasting (IBF) for 2047 by the India Meteorological Department (IMD) should aim to deliver significant benefits to the nation, society, and economy. Here are the potential benefits that can be realized through the successful implementation of the vision:

a) **Enhanced Public Safety:** IBF will lead to more accurate and timely weather and climate forecasts, resulting in improved early warnings for extreme events such as cyclones, floods, and heatwaves. This will significantly reduce the loss of life and property, enhancing public safety.
b) **Reduced Economic Losses:** By minimizing disruptions caused by extreme weather events, businesses and industries will experience fewer interruptions, leading to reduced economic losses. Agriculture, transportation, and infrastructure sectors will become more resilient, fostering economic stability and growth.
c) **Sustainable Agriculture:** Farmers will receive tailored weather forecasts and impact assessments, allowing them to make informed decisions about crop planting, irrigation, and harvesting. This will enhance agricultural productivity and food security.
d) **Improved Disaster Management:** Government agencies responsible for disaster management will have access to accurate and impact-based forecasts, enabling better preparedness, response, and recovery efforts in the face of disasters.
e) **Climate-Resilient Infrastructure:** Infrastructure planning and development will incorporate IBF data, resulting in more climate-resilient infrastructure that can withstand extreme weather events, reducing infrastructure damage and repair costs.
f) **Informed Urban Planning:** Urban planners will use IBF information to design and implement climate-resilient cities, reducing the vulnerability of urban areas to flooding, heat stress, and other climate-related challenges.
g) **Efficient Transportation:** IBF will improve transportation safety and efficiency by providing real-time information about weather-related hazards, reducing accidents and disruptions in road, rail, and air travel.
h) **Public Health Benefits:** Health authorities will use IBF data to anticipate and respond to health risks associated with extreme weather events, such as heat-related illnesses and disease outbreaks, leading to improved public health outcomes.

i) **Water Resource Management:** Better forecasts will enable effective water resource management, leading to more sustainable use of water for agriculture, industry, and domestic consumption.

j) **Environmental Protection:** IBF will aid in the protection of ecosystems and biodiversity by providing insights into how weather and climate changes affect natural habitats, allowing for conservation efforts and sustainable resource management.

k) **Climate Change Adaptation:** The incorporation of climate change considerations into forecasts and impact assessments will help society adapt to long-term shifts in climate patterns, reducing vulnerabilities.

l) **Global Leadership:** IMD's leadership in IBF will position India as a global leader in meteorological science and disaster risk reduction, fostering international collaborations and knowledge sharing.

m) **Empowered Communities:** By providing accessible and actionable weather information, IBF will empower communities to make informed decisions, enhancing their resilience and self-reliance during extreme events.

n) **Sustainable Development:** The vision of IBF for 2047 aligns with India's broader goals of sustainable development, contributing to a more prosperous, resilient, and environmentally responsible nation.

In summary, the vision statement for IBF for 2047 by IMD envisions a future where the benefits of accurate and impact-based forecasting extend across all sectors of society, the economy, and the environment, resulting in a safer, more resilient, and prosperous India.

Chapter 4 Sector Specific Services

4.1 AGROMETEOROLOGICAL ADVISORY SERVICES

4.1.1 Current status and Major achievements during the past 10 years

- **Establishment of District Agro-Met Units (DAMUs) and Block-Level Extension**

Since 2018, Indian agriculture has witnessed significant advancements with the establishment of District Agro-Met Units (DAMUs) and the introduction of upgraded high-resolution models. The Integrated Agro-Meteorological Advisory Service (IAAS) has been extended to the block level, enhancing the precision and reach of weather-related agricultural guidance.

- **Expansion of Agro-Met Field Units (AMFUs)**

Presently, 130 Agro-Met Field Units (AMFUs) have been established at various State Agricultural Universities (SAUs), institutes of the Indian Council of Agricultural Research (ICAR), and Indian Institutes of Technology (IITs). Additionally, 199 District Agro-Met Units (DAMUs) have been set up at Krishi Vigyan Kendras (KVKs) across the country.

- **Role of AMFUs and DAMUs in Advisory Preparation**

These centers play a crucial role in preparing Agromet Advisories every Tuesday and Friday for the districts and blocks under their jurisdiction. The advisories provide valuable information to farmers, enabling them to make informed decisions for their day-to-day agricultural operations. Bulletins are prepared in English and twelve regional languages (Hindi, Telugu, Assamese, Gujarati, Kannada, Malayalam, Marathi, Odia, Tamil, Mizo, Bengali, and Punjabi).

- **Coordination of State and National Level Bulletins**

The state composite bulletins are prepared by Regional Meteorological Centres (RMCs) and Meteorological Centres (MCs). The national level Agromet Advisory Service (AAS) bulletin is prepared by the Agricultural Meteorology Division, IMD, Pune.

- **Collaborations for Quality Improvement**

To improve the quality of advisory bulletins, Memorandums of Understanding (MoUs) have been signed with national and international research institutes and NGOs. These collaborations aim to utilize advancements in data science, Artificial Intelligence (AI), and Machine Learning (ML) for advisory automation and quality enhancement.

- **Launch of Panchayat Mausam Sewa (PMS)**

To reach farmers with weather forecasts and AAS at the village level, a new initiative, ‘Panchayat Mausam Sewa (PMS),’ was launched on January 15, 2024, by the Honorable Vice President of India, Shri Jagdeep Dhankar. PMS is a joint venture of IMD, Ministry of Earth Sciences, Ministry of Panchayati Raj, and ‘Green Alerts’ under the Public-Private Partnership (PPP) mode. PMS is an open/freely accessible portal and an automatic system to send the real time weather information/alerts on registered mobile numbers of sarpanch and Sachiv of each panchayat. The block wise panchayat mapping of all ~ 269,189 Gram

Panchayat was done to send block specific information to concerned panchayat and further to farmers (https://mausam.imd.gov.in/greenalerts).

Major milestones achieved

- **Creation of Decision support system for Agromet Advisory Services (Agro-DSS)**

IMD in collaboration with Regional Integrated Multi-Hazard Early Warning System (RIMES), Thailand has developed a web based decision support system named Agromet-Decision Support System (Agro-DSS: https://agromet.imd.gov.in/), with the provision for integration of all AAS activities in one platform. A dedicated portal 'Agromet DSS' has been developed to make seamless exchange of data and other information among concerned organizations in more objective, timely, transparent and effective manner leading to improvement in the quality of services. It facilitates the scientists/ institutions with customised tools to integrate weather and crop information to prepare agromet advisories at finer scales in short time to serve farming community at micro level with dynamic feedback.

- **Generation of new products for use in AAS bulletins**

IMD initiated the preparation of new products in collaboration with Space Application Centre (SAC), Ahmedabad using the Normalised Difference Vegetation Index (NDVI) derived from INSAT 3A CCD for framing agromet advisories. A joint initiative has also been taken up by Indian Space Research Organization (ISRO), Indian Council of Agricultural Research (ICAR), India Meteorological Department, National Centre for Medium Range Weather Forecasting (NCMRWF), Noida, Mahalanobis National Crop Forecasting Centre (MNCFC), New Delhi under DAC (Department Agriculture and Cooperation) to prepare satellite derived products and value added products using geospatial data for the use in AAS Besides, started preparing the maps for Standardised Precipitation Index (SPI) on weekly, bi-weekly and seasonal basis and aridity anomaly maps on weekly basis.

In collaboration with International Centre for Radio Science (ICRS), Jodhpur preparation of maps for soil moisture estimation have been started for Gujarat, Madhya Pradesh, Assam, Andhra Pradesh, Kerala, West Bengal, Uttar Pradesh, Rajasthan, and Tamil Nadu. These maps are being generated by using satellite data viz. soil moisture, NDVI and brightness temperature data from SMOS, MODIS and LST values from SSMIS sensors. Besides, based on water balance method and using gridded rainfall data, soil moisture maps at 60 cm depth at district level across the country were also prepared daily and displayed in the division's website

- **Extended range/monthly bulletin**

In collaboration with the Indian Institute of Tropical Meteorology (IITM), Pune initiated the work of preparation of Agromet Advisory bulletins based on extended range forecast in AAS particularly in forecasting of long dry spells and heavy rain on fortnightly basis during present monsoon season. These bulletins, thus prepared were circulated through the network of AMFUs and KVKs for helping the farmers on strategic contingent planning.

- **Dissemination of AAS: Reaching the last mile**

The progression of information and communication technology (ICT) has revolutionized farming practices by providing farmers with easy access to crucial weather updates and agricultural advisories via smartphones. These services are made available through various dissemination channels, including All India Radio (AIR), Doordarshan, private TV and radio channels, newspapers, and the internet, as well as SMS and IVRS under Public-Private Partnership mode. Additionally, agromet advisories are disseminated via SMS through the Kisan Portal launched by the Ministry of Agriculture, alongside a variety of mobile applications. The Indian Meteorological Department (IMD) disseminates forecasts and advisories through platforms like Meghdoot and Kisan Suvidha. Moreover, these services have been integrated into applications owned by state governments in fourteen states, with ongoing efforts aiming to extend this integration to all state government applications. Social media platforms such as WhatsApp play a pivotal role in swiftly disseminating weather forecasts and agricultural advisories, with block-level WhatsApp groups established to ensure even remote areas receive vital information. These groups cater to current and former Panchayat members, Sarpanch, and Secretaries, enhancing the accessibility and reach of these critical services.

Furthermore, the dissemination of agromet advisories has been bolstered by initiatives such as DD KISAN, a dedicated 24-hour channel launched by Hon'ble Prime Minister Shri Narendra Modi, Government of India, exclusively for farmers. Crop-specific weather-based agromet advisories are prepared daily and broadcasted through programs like 'Kisan Samachar' and 'Mausam Khabar' on DD Kisan Channel in New Delhi since May 2015. This concerted effort ensures that farmers across the country receive timely and relevant information to aid in their agricultural decision-making process, ultimately contributing to increased productivity and resilience in the agricultural sector.

Positive impacts of Agromet Advisory Services

- All India AAS bulletins help Central and State Government organizations for taking policy decisions on agriculture.
- Multi-channel dissemination helps the farmers to adopt appropriate weather based farm management at appropriate time and increase crop productivity.
- Advisories during extreme events help farmers to save the crop loss.
- Agromet Advisories based on Extended Range Forecasting System (ERFS) help farmers to select contingency crops during long dry spell.
- Awareness Programme helps to raise awareness about the Agromet Services and also to collect feedback to prepare need based advisories.
- In season yield forecast helps Ministry of Agriculture to prepare advance crop estimate.
- Capacity building programme helps to prepare and disseminate agromet advisories more efficiently.

Economic benefits

The National Council of Applied Economic Research (NCAER) conducted periodic surveys in 2009, 2015, and most recently in 2020 to evaluate the economic impact of weather forecast-based advisories in India. The 2020 study revealed that 98% of surveyed farmers (3,965 farmers from 121 districts across 11 states) made adjustments to at least one of nine agricultural practices based on these advisories. As a result of these modifications, the average annual income of farming households increased significantly. Those who implemented all nine recommended practices saw their annual income rise from Rs. 1.98 Lakh to Rs. 3.02 Lakh. This translated to an additional annual income of Rs. 12,500 for agricultural households classified as Below Poverty Line (BPL) in rain-fed regions. In total, the estimated annual income gain amounted to an impressive Rs. 13,331 crore in rain-fed districts across the country.

4.1.2 Challenges and Gap Areas

❖ Climate Variability and Change

Agriculture in the 21st century faces multiple challenges and has to produce more food and fibre to feed a growing population. The population of the country is expected to stabilise at around 1.6 billion by the year 2030, making food and nutritional security the most important issue. Therefore, food grain production needs to be increased by 50% whereas that of vegetable and fruit production will have to be doubled to meet the needs of this population. This additional food will have to be produced on existing agricultural land that will be around 169 million ha with dwindling soil and water resources coupled with uncertainties of climate change.

Climate variability and extreme weather events present significant challenges to Indian agriculture. Frequent occurrences of cyclones, heat-waves, heavy rains, floods, and droughts disrupt agricultural productivity, necessitating robust adaptation measures. Increasing temperatures and erratic rainfall patterns adversely affect crop yields, soil health, water availability, and pest dynamics, making farming more challenging. Addressing these climate-related issues requires advanced forecasting, real-time data collection, and effective dissemination of information to farmers, enabling them to adapt and respond promptly to changing conditions.

The climate change projections for the Sixth Assessment Report (AR6) of Intergovernmental Panel on Climate Change (IPCC) are made using the Shared Socioeconomic Pathway (SSP) scenarios under the Coupled Model Inter-comparison Project 6 (CMIP6). IPCC has produced scenario narratives and projections from its Third Assessment Report (TAR) till AR6. A compilation of all the scenarios and projections for India captured from peer reviewed literature is presented in the Table I.

Table I. Projected changes in Temperature and rainfall for India

Reference	Scenario	Change in Temperature (°C)	Change in Rainfall (%)
Third Assessment Report (TAR)			
Rupakumar et al., 2006	A2	4.1	23
	B2	2.9	18
Chaturvedi et al., 2012 Bal et al., 2016	A1B	3.19	24
Assessment Report 5 (AR5)			
Chaturvedi et al., 2012	RCP 2.6	1.5	6
	RCP 4.5	2.4	10

	RCP 6.0	2.8	9
	RCP 8.5	4.3	14
Assessment Report 6 (AR6)			
Almazroui, et al., 2020	SSP1-2.6	1.0	9.7
	SSP2-4.5	2.1	14.4
	SSP5-8.5	4.2	27.3

**All the projections are for the 30 year average of 2071–2100 relative to the 1961–1990 baselines. However, CMIP3 projections are for the period 2067–2097, CMIP5 projections are for the period 2070–2099 and CMIP6 projections are for the period 2081-2100.*

All the scenarios and story lines project an increase in temperature and rainfall for India, the most recent CMIP6 models projects increase in temperature between 2.10 °C and 4.20°C through the SSP2-4.5 and SSP5-8.5 scenarios respectively. All the assessments and scenarios showed an increase in rainfall, CMIP6 projections shows an increase of 14.4 to 27.3 % for the SSP2-4.5and SSP5-8.5 scenarios respectively. It is evident from these scenario projections that, in the most preferred business as -usual scenarios (A1B, RCP 4.5 and SSP4.5) temperature is expected to increase 2.1°C or above. Similarly, rainfall is also projected to increase. This increase in temperature and rainfall will impact the agriculture production with varying degrees of magnitude depending on the crop, soil and adaptive capacity.

❖ Extreme events

Globally and more specifically in India, rainfall variability and intensity are increasing, seasons are shifting; sea level is rising, and extreme events such as cyclone, heat wave, heavy rain, flood, and drought are becoming intense and more frequent (MoEFCC, 2021). Extreme weather events (flood, drought, heat and cold waves, flash flood, cyclone, and hail-storms) very severely affect agricultural production (Aggarwal et al., 2021). Also in the IPCC report, it is concluded that intense tropical cyclone activity is likely to increase through the 21st century. Thus, it is reasonable to expect extreme events to occur more often in the future. Findings from Das and Umamahesh (2022), indicate that the TMax anomaly is likely to increase in future causing more intense, high frequency, and long duration heat wave events over India. The study also highlighted that, currently unaffected large regions of southern, northeast, and western parts are expected to be severely affected by heat wave events. These findings reaffirm the paramount necessity for adaptation strategies to address the adverse consequences of foreseen heat wave and extreme rainfall events.

❖ Impacts of Climate Change on Agricultural Systems

The impacts of climate change are expected to be broadly negative including reduced water availability, damage to crops and increased potential for diseases, especially those transmitted by insect vectors. Besides, there is extensive evidence that recent warming is strongly affecting terrestrial biological systems, including such changes as earlier timing of spring events (e.g., leaf unfolding, bird migration and egg laying; and shifts in ranges of plant and animal species Thus,impact of short period climatic variations and long-term climatic change on different production systems should be fully understood in quantitative terms at various spatial scales and at different scenarios.

- **Crop productivity**

Elevated temperature affects most crops and result in early maturity, shortened duration and enhanced respiration, which will cause decline in grain and biomass yields and quality. Rice, wheat and Maize are the major crops of India and are risk-prone as well, productivity of rice and wheat in the Indo-Gangetic Plains (IGP) is projected to reduce and similarly, maize in the mid-IGP and Southern Plateau is also projected to reduce. It is estimated that crop yield in India will be reduced due to climate change by 4.5–9.0% (Naresh Kumar et al., 2020). Impact of climate change on major crops of India viz., rice, wheat and maize revealed varying levels of yield penalty for each degree of increase in temperature. For an increase in temperature less < 2°C rice yield is projected to decrease by 6 % (Saseendran et al., 2000) and wheat yield is projected to decrease by 5.2 % (Gupta et al., 2017). For a projected increase in temperature between 2 – 3°c rice yield was projected to decrease up to 8.4 % (Mathauda et al., 2000) For Maize, the yield decrease for temperature increase of 3°C and is projected to be between 10-30 % (Kalra et al., 2007).

- **Pest dynamics**

An estimated annual loss of 13.6% globally, 17.5% in India is caused by Insect pest (Dhaliwal et al., 2010), climate change is likely to increase the pest associated losses further. Several insect pests, that are the minor pests, are likely to become more devastating with climate change (Sharma 2013). For all the insect species, higher temperatures will result in faster development, resulting in rapid increase of pest populations as reproductive cycle gets shortened. The rising temperature is projected to shift a range of crop pests and diseases to higher latitudes (Rosenzweig et al. 2001).

- **Soil Health**

Elevated temperature is projected to impact soil process, it is anticipated to decline soil organic carbon, Increased nitrogen mineralization in the short-term, Increased de-nitrification, volatilization losses of nitrogen causing negative impacts on soil fertility and ultimately impact the mineral nutrition of crops. St. Clair and Lynch (2010), Chakrabarti et al. (2012a, b). Soil biodiversity is directly and indirectly related to several soil bio-physical processes and properties, any impact of soil biodiversity will impact the fertility. Increase in soil temperature due to climate change will likely alter microbial mediated nitrification and denitrification dynamics in soil environment due to shift of nitrifiers and denitrifies population. This ultimately affects nutrient cycling and organic carbon accumulation (Dijkstra and Cheng, 2007).

- **Water**

In India, the agricultural sector is the largest consumer of water, accounting for approximately 83% of the available water (Gupta et al., 2022). It is crucial to accurately assess future changes in irrigation water usage for effective water and agricultural management (Foster et al., 2020). Predictions suggest that increasing temperatures could result in a reduction in irrigation water availability from both surface sources and groundwater. This decrease is projected to occur in the Indus, Ganges, and Brahmaputra river basins, exacerbating the existing decline in groundwater levels. Therefore, it is essential to implement the "per drop more crop" principle, particularly for water-intensive crops such as rice, wheat, and sugarcane, which collectively contribute to 90% of India's crop production (D'Souza, 2022).

- **Livestock**

The shortage of feed and fodder, including 40 percent dry fodder, 36 percent green fodder, and 52 percent concentrate on a dry matter basis (DAHDF, 2014), along with the poor quality of roughage, primarily crop residues, already poses a major constraint on achieving the full genetic potential in livestock production in India. Considering the current availability of feed and fodder and the adverse impact of climate change on crop production, the gap between the supply and demand for feed and fodder is expected to widen. This situation is further exacerbated. Poultry birds are also highly vulnerable to climate change due to their limited tolerance for temperature fluctuations (Behura and Samal, 2022). Heat stress during the growth period of broilers not only results in lower body weight but also quality losses. In layers, heat stress negatively impacts egg production and quality (Wasti et al., 2020).

❖ Technological and Infrastructure Gaps

The current technological and infrastructure gaps significantly limit the effectiveness of agricultural practices. Real-time weather information and advisories are not reaching all farmers, particularly those in remote areas, due to constrained dissemination systems. Furthermore, the deployment of modern agricultural technologies such as IoT sensors, satellite technology, and precision farming techniques is insufficient, limiting productivity and efficiency. Bridging these gaps requires substantial investment in technology and infrastructure to provide accurate, timely, and actionable information to all farmers.

4.1.3 Short-term Vision (next two years)

❖ Enhanced Weather Forecasting

In the short term, we aim to implement high-resolution weather forecasting models to provide accurate and localized weather advisories to farmers. Expanding the network of Automatic Weather Stations (AWS) and Automatic Rain Gauge Stations (ARG) will significantly improve real-time data collection and dissemination. AI techniques, particularly machine learning and deep learning, are employed to build predictive models that forecast weather conditions with improved accuracy. These models learn from historical weather data, to predict future weather patterns. AI algorithms can continuously learn and adapt as new data becomes available, refining forecasts over time. These advancements will enable farmers to make informed decisions, reduce crop losses, and enhance productivity by anticipating and preparing for adverse weather conditions.

❖ Expanded Outreach

To ensure that all farmers benefit from Agromet Advisories, we will increase the reach of these services through multi-channel, multi-mode dissemination systems. Ensuring that advisories are available in all regional languages will cater to diverse linguistic backgrounds, empowering more farmers with the information they need to optimize their agricultural practices and improve their livelihoods. Presently, IMD has integrated the forecast and advisory dissemination with 14 state governments and in 13 regional languages, and will continue to integrate the forecast and advisory services with all the state governments in their regional language and will collaborate with other private service providers as well to reach each and every farmer in India.

- **Improved Data Collection and Analysis**

Investing in advanced tools such as drones and IoT sensors will enhance data collection capabilities, providing detailed and real-time information on weather conditions, soil moisture, and crop health. Along with the robust network of ground observation network, IMD has installed Agro-AWS equipped with soil temperature and moisture sensors at 4 depths over 200 locations and procurement is slated for 330 more stations to cover all the agriculturally important districts of India to create a benchmark network. IMD currently operates an upper air observational network that includes 56 radiosonde stations and 62 pilot balloon observatories distributed across the country. Radars play a crucial role in IMD's operations by detecting weather phenomena such as thunderstorms, hailstorms, and tracking cyclonic storms. They are also instrumental in estimating rainfall and issuing hail warnings. Radars help estimate a storm's intensity, location, and forecast its future path, ensuring the safe navigation of aircraft and ships.

IMD has taken pro-active steps to increase the Radar Network from mere 15 in 2013 to 39 in 2023 and will add 25 more in next 2-3 years. IMD envisions covering the entire country with a Doppler Weather Radar Network by 2025 to enhance the accuracy of extreme weather event predictions. The existing Doppler weather radars have been networked to provide data for numerical weather prediction models, aiding in nowcasting. Consequently, the radar network is playing a significant role in the modernization of IMD's observational and forecasting systems. Developing integrated systems to combine data from various sources will offer comprehensive and actionable insights to farmers, enabling them to make better-informed decisions and improve crop management practices.

- **Capacity Building**

IMD is also taking continuous efforts to capacitate the farmers in understanding the forecast and update of Agromet advisory services among the farming community by organising Farmers Awareness Programmes (FAPs) through the Agro Meteorological Fiel Units (AMFUs) and District Agromet Units (DAMUs) in various parts of the country. Conducting regular training programs for farmers on climate-resilient agricultural practices and the use of modern technologies is a key short-term goal. These programs will equip farmers with the knowledge and skills needed to adapt to changing climatic conditions, improve productivity, and adopt sustainable farming practices. The number of FAPS will be increased to reach all the farmers in India. This will be achieved through strengthening collaborations with national and international research institutes will further enhance advisory automation and quality improvement.

- **Collaboration and Policy Support**

Strengthening partnerships with research institutes, NGOs, and government bodies will enhance the quality and reach of agromet advisories. Developing and implementing policies that support sustainable agricultural practices and incentivize the adoption of new technologies will be crucial in achieving short-term goals. These collaborative efforts will ensure that farmers receive timely and accurate information, enabling them to optimize their agricultural practices and improve their livelihoods.

4.1.4 Medium-term Vision (next ten years)

- Targeting, tailored crop-specific and location specific hyperlocal advisories by harnessing advanced numerical weather prediction models, IoT-based monitoring systems, and AI-driven analytics to deliver precise and actionable advisories.
- Develop integrated, site-specific decision support tools combining real-time data, historical trends, and predictive analytics to offer comprehensive farm management solutions delivered through mobile apps and other farmer friendly tools for seamless management of weather impacts on agriculture.
- Foster collaboration among Agricultural Extension Services, farmers, seed suppliers, financial institutions, and NGOs to establish a cohesive advisory network for seamless delivery of critical information to all the stakeholders and support agents for effective utilization.
- Provide actionable advisories on precision water management, soil conservation, and integrated nutrient management to maximize productivity while minimizing environmental impact.
- Encourage the adoption of cutting-edge technologies such as GPS, GIS, and Variable-Rate Technology (VRT) to provide advisories to optimize resource utilization, reduce input wastage, and enhance yields.
- Customize and offer advisories on eco-friendly pest and disease management strategies, emphasizing biological control methods, cultural practices, and judicious use of chemicals to reduce crop losses and safeguard environmental health.

This comprehensive vision for the next decade aims to empower farmers with precise, actionable, and sustainable agro-advisories, driving a transformation in agricultural practices and ensuring resilience against climate and resource challenges.

4.1.5 Vision 2047

- Leverage AI, machine learning, and block chain in agromet services to deliver real-time, hyper-local forecasts and actionable insights as agromet advisories, improving decision-making and operational efficiency in farming practices.
- Deliver tailored agromet advisories to support climate-resilient agricultural practices, helping farmers mitigate risks from extreme weather events and maintain productivity in changing climatic conditions.
- Provide precise weather-based advisories and resource management insights to assist smallholders in transitioning from subsistence to commercial farming while optimizing input use for sustainable and profitable agriculture.

- ❖ Disseminate advisories to reach the last mile promoting resource-efficient practices, emphasizing water use efficiency, soil health management, and nutrient optimization to sustainably meet the food demands of the growing population.
- ❖ Position Agromet Advisory Services as a hub for fostering international collaborations, facilitating knowledge exchange, and contributing to global food security and climate change mitigation.
- ❖ To Ensure Agromet Advisory Services play a transformative role in making Indian agriculture resilient, sustainable, and globally competitive by 2047.

4.1.6 Strategy

❖ **Technological Advancements**

Investing in and deploying cutting-edge technologies like satellite imaging, IoT sensors, AI, and machine learning for real-time data and advisory services is a cornerstone of our strategy. Modernizing agromet observatories with advanced sensors and data collection tools will enhance accuracy and reliability. These technological advancements will provide farmers with the information they need to make informed decisions, optimize their practices, and improve productivity.

❖ **Infrastructure Development**

Establishing a comprehensive network of agromet observatories, AWS, and ARG stations across the country will improve data collection and dissemination. Ensuring that all types of agromet data are readily accessible to users will facilitate better decision-making and planning. Infrastructure development will support the implementation of advanced technologies and enhance the effectiveness of agromet advisories.

❖ **Education and Training**

Integrating agriculture and weather subjects into the education system from the elementary level will build a strong foundation of knowledge and skills in future generations. Providing ongoing training programs for farmers will equip them with the knowledge and skills needed for sustainable and efficient farming practices. These educational initiatives will support the adoption of modern technologies and sustainable practices, enhancing the resilience and productivity of Indian agriculture.

❖ **Policy Support**

Developing and implementing farmer-centric policies and subsidies will incentivize the adoption of sustainable farming practices and new technologies. Establishing a regulatory framework that supports the implementation of climate-smart agricultural practices will be crucial for achieving long-term goals. Policy support will create an enabling environment for the growth and development of Indian agriculture, ensuring that farmers have the resources and support they need to thrive.

❖ **Information Sharing**

Creating robust information-sharing systems for effective dissemination of agri-climate information will enhance resilience against climate variability. Ensuring that advisories are tailored to local conditions and needs enabling farmers to make informed decisions and optimize their practices. Information sharing will facilitate knowledge exchange and collaboration, supporting the growth and development of Indian agriculture.

- ❖ **Research and Development**

Focusing on R&D in agro meteorology will drive innovation and improve advisory services. Emphasizing new approaches, simulation models, and value-added services will enhance the effectiveness of agromet advisories. Collaborative efforts between research institutions, government agencies, and the private sector will support the development and implementation of innovative solutions, driving the growth and development of Indian agriculture.

4.1.7 Outcome

- ❖ **Enhanced Agricultural Resilience**

By equipping farmers with precise and timely information, we aim to enhance their ability to adapt to climate variability, reducing crop losses and increasing productivity. Implementing robust adaptation strategies will minimize the impact of extreme weather events on agricultural outcomes, ensuring that farmers can thrive despite changing climatic conditions. Enhanced resilience will support the long-term sustainability and productivity of Indian agriculture.

- ❖ **Sustainable Resource Management**

Improved efficiency in the use of water and soil resources will lead to sustainable agricultural practices. By adopting conservation practices, farmers will ensure the long-term viability of their operations, enhancing sustainability and productivity. Sustainable resource management will support the growth and development of Indian agriculture, ensuring that it can meet the needs of a growing population without depleting natural resources.

- ❖ **Increased Food Security**

Enhanced crop yields and quality will ensure food and nutritional security for a growing population. By providing a stable and reliable food supply, we will contribute to national and global food security. Increased food security will support the health and well-being of the population, promoting sustainable development and economic growth.

- ❖ **Economic Benefits**

Cost savings for farmers through optimized resource use and reduced environmental impact will enhance their profitability and livelihoods. Higher productivity and efficiency will lead to increased profitability, supporting the growth and development of Indian agriculture. Economic benefits will improve the quality of life for farmers and their communities, contributing to sustainable development.

- ❖ **Global Leadership**

India will emerge as a leader in climate-smart agriculture, contributing to global food security and climate change mitigation efforts. Strengthened international collaboration and knowledge sharing will enhance the global impact of India's agricultural advancements. By leading the way in sustainable agricultural practices, India will play a crucial role in addressing global challenges and promoting sustainable development.

- ❖ **Improved Livelihoods**

Empowering farmers to make better decisions through enhanced information and advisory services will lead to improved agricultural outcomes. The adoption of sustainable farming practices will improve the quality of life for farmers and their communities. Improved livelihoods will support the growth and development of Indian agriculture, contributing to sustainable development and economic growth.

4.2. AVIATION METEOROLOGICAL SERVICES

4.2.1. Current status and major Achievements during the past 10 years

Aircrafts fly in the atmosphere where most of the weather systems develop and decay. Information of important meteorological parameters related to the safety of aircraft such as atmospheric Pressure, Temperature, Wind direction and speed, Visibility, Runway Visual Range (RVR) and Cloud Height are needed for smooth operations of an aircraft from take-off to the landing phase. It is therefore very essential that climatology of an airport is available as a ready reckoner to understand mean number of occurrences (frequencies) of various weather elements in different temporal scales which affect aircraft operations round the clock. Aeronautical Climatological Summary (ACS) of an Airport provides this vital information. ACSs for various National and International Airports are being prepared and updated at regular interval. ACSs are being prepared on the pattern of WMO Models and in accordance with the procedures laid down in Technical Regulations as per International Civil Aviation Organization (ICAO) standards. Till now, ACSs of 51 airports have been prepared for various aeronautical applications.

In the past decade, advances in remote-sensing and new observation techniques, including meteorological satellites, weather radars, lightning detection networks, aircraft observations and numerical weather prediction (NWP) have offered great opportunities for enhancing weather services, especially for aviation in India.

Online Briefing System (OLBS), a web based pre-flight information briefing systems, has been implemented for flights originating from FIRs in India. OLBS is being maintained by the AMOs functioning at Chennai and New Delhi. Through this system an authorized stake holder can avail meteorological briefing and download all required documents for flight planning.

India has been contributing significantly in ICAO meetings for the safe and cost effective aviation services to be provided by Member States in Asia pacific (APAC) and taken up cases pertaining to maintenance of service at appropriate level and get the loose ends fixed. India has presented working papers and Information papers under multiple agenda items of various meetings and contributed significantly for the effective and efficient international aviation services. India contributes significantly in revising the various handbook, annexures and reports of various MET subgroups, adhoc and steering sub groups of ICAO APAC. Also, IMD has upgraded its SOP and Forecasters competency document to address the operational requirements. IMD conducts aviation weather forecasting training for India and other countries in regular intervals. The aviation weather services of IMD are ISO certified. The quality system is in conformity with the International Organization for Standardization (ISO) 9000 series of quality assurance standards and is certified by an approved organization.

IMD interacts with its users on various levels. The most common way is through the aviation met offices for the immediate redressal of issues related to meteorological information. Quarterly Regional Operators Committee (ROC) meetings are held regularly by all the stake holders of aviation industry, of which IMD is also a member. Issues related to meteorological services are also discussed at these meetings for the timely and effective disposal, especially when the involvement of many agencies is necessary.

4.2.2. Challenges and gap areas

The world of aviation meteorological service delivery is changing and many of the developing nations are finding it increasingly difficult to keep up with the pace of technology and change. Thus, aviation meteorological services face several challenges and gap areas in both national and international level. These challenges can hinder the ability of IMD to provide high quality internationally recognized aviation meteorological services in a timely and professional manner. Some of the key challenges and gap areas include:

- Forecast of convection and associated hazards (e.g. thunderstorm, lightning, turbulence, wind shear, icing), precipitation types products (e.g. freezing precipitation, hail, super cooled large cloud droplets), volcanic ash cloud, ash concentration etc.
- Aviation specific models for aviation hazards like fog, thunderstorm, heavy rainfall, turbulence, icing, clear air turbulence, low level wind shear etc.
- All in one weather sensing solution for unmanned runways and landing zones
- Ensuring a skilled and knowledgeable workforce requires continuous training and development programs.

4.2.3. Short term vision (next 2 years)

- **Enhancement of Forecasting skill**: IMD to enhance the forecasting and warning systems to support safe and cost-effective flight operations. To develop systematized and advanced core technologies for aeronautical meteorological forecasts and warnings based on decision support system.
- **Improvement in model forecast using data assimilation technique**: Using real time aviation weather observations for data assimilation resulting in improved aviation forecast.

4.2.4. Medium term vision (next 10 years)

- **Integrated framework for efficient coordination between IMD and its stakeholders**: To create an interactive and integrated framework that can be used to access all aviation meteorological data for efficient decision making. This can also be very helpful for the aviation related research activities and for the generation of aerodrome climatological summary.
- **Automated flight briefing**: Development of an automated system with auto-generation of flight folders containing the METARs, TAFs, warnings and weather charts. The data will be selected based on the flight route and departure time. Folders can be viewed, printed, e-mailed or archived: both manually and automatically.

- **Achieving optimum forecast accuracy**: To achieve the optimum forecast accuracy using improved observations from surface as well as airborne equipment including wind Borne. Crowdsourcing weather information by connecting data collected by individual aircraft promises a major leap forward, and several technology companies and meteorology specialists are striving to make such systems available, not just to ground-based operations departments but directly to the flight deck. Increased bandwidth availability provides the opportunity for weather data gathered by individual aircraft-based avionics systems to be shared, so as to provide the most up-to-the-minute information on changes in wind speed or direction, powerful convection, clear air turbulence or other hazard work as an initial condition of models. Drones created specifically for weather purposes will be flown into the boundary layer, which is the lowest part of the Earth's atmosphere. They will have the sensors that can collect data on the temperature, humidity, and wind in the atmosphere, which will help to enhance weather forecasting capability.
- No Aviation hazard should go undetected and unpredicted.
- There will be experiments on weather modifications over the airports especially for rain and fog.
- The aviation forecast accuracy will be improved by 40% by 2023 compared to base year 2024.

4.2.5. Vision for 2047

There is a considerable scope for further accelerating the current initiatives to enable the country to become a world leader in providing high quality aviation meteorological services and contributing to economic and societal benefits. IMD also would like to be a leader in providing the aviation meteorological services The vision document has been prepared for next 24 years (up to 2047) by considering the achievements made during the past years, strength and weakness of our on-going programmes and opportunities for future. Key ingredients for vision 2047 are described below:

- Setting up a comprehensive, long-term research and development program for achieving an appropriate balance between research in support of long-term needs and engineering and technology development in support of near-term acquisition of new operational systems.
- Setting up a Collaborative Decision Making (CDM) process whereby all stakeholders- airports, airlines and air navigation service providers (ANSP) and meteorological service provider can actively and collectively Manages aviation hazards.
- Devising a method of providing meteorological information to pilots while they are in flight would be revolutionary. System should have provision of access to real time data, and to translate data into meaningful conclusion. It should have on board capacity to incorporate data in tactical and strategic flight planning. This system

should have clear thresholds in wind strength or precipitation that can help the users to have understanding of how weather phenomena may evolve.

- The forecast accuracy will be improved by 80% from the base year of 2024 and hence aviation forecast will be near accurate.
- Transition to next-generation aeronautical meteorological services.
- IMD will work on weather modification based on research being conducted during next five years. Especially to ensure safe aviation, there could be modifications of fog and rain over the major airports.

4.2.6. Strategy

Vision for 2047 can be achieved through the implementation of following

a) Education, Training and Competency of Aeronautical Meteorological Personnel

- Education and training curricula
- Qualification requirements
- Competency assessment frameworks and best practice.
- ISO certification

b) Study on Impacts of Climate Change and Variability on Aviation

- Impacts on jet streams and enroute hazards such as turbulence
- Impacts on airport operations
- Impacts on airspace management/optimization and airframe design.

c) Communication and Outreach augmentation

- Newsletters and other such outreach for Members, Stakeholders and partners
- Feedback mechanisms
- Focal point identification and coordination.

4.2.7. Outcome

India Meteorological Department will play a crucial role in providing user centric aviation meteorological services in a timely and professional manner in order to contribute to the safety of aircraft operations and enhance the economic value of aeronautical meteorological services. IMD to secure a leading position in future aeronautical meteorology and accelerate the growth of India in **Amrit kaa**l by strengthening capabilities for sustainable growth and increase the efficiency of agency operation. India would work as an informative aviation weather service hub. No weather related aircraft accidents will be ensured.

4.3 METEOROLOGICAL SERVICES FOR SURFACE TRANSPORT

4.3.1 Current status and major achievements during the past 10 years

Road Transport	Rail Transport
1. IMD issues regular weather forecasts and severe weather warnings for many highways across the country for better efficiency of Road Transport.	**1.** Weather information, weather forecast and warnings provided by India Meteorological Department, plays an important role in the operation of train services by Indian Railways and helps in averting damage to tracks and electric equipment powering the train.
2. Highway forecast provides the information on Temperature, Rainfall/snow, visibility, Fog etc. to optimize traffic flow by anticipating high-impact weather events on the National Highways.	**2.** The India Meteorological Department has played a pivotal role in predicting the heavy to very heavy rainfall in Mumbai and north Konkan areas during the monsoon season that has helped Central and Western Railways to regulate train services in advance during July-October 2017.
3. The Highway Weather Information / Forecast provided by IMD is made available through a special page in IMD website for Highway Forecast.	**3.** Provision of Area Specific Weather Services to Indian Railways.
4. The information, however is made available for few highways generated based on limited user requirement available with IMD field offices.	**4.** On the request of North West Railways Ajmer Division for establishment of Wind Systems on Ajmer- Palanpur section in view of the problem being faced in train operations especially during high winds.
5. IMD is further working to elaborate and extend its highway forecast to other major highways in the country based on user requirements and feedback.	**5.** IMD has made provision for Establishment of Wind Systems enroute of Ajmer - Palanpur Stretch at 19 locations - ABU Road, Kivarli, Madar, Ajmir, Mangliawas, Kharwa, Beawar, New Bar, Chandawal, Sojat Road, Marwar, Binwaliya, Rani, Faina, Jawal Bandh, Nana, Banas, Sarotra Road and Karjoda.

4.3.2 Challenges and Gap Areas

Weather forecasts are crucial for the safety and efficiency of the surface transport sector, which includes road transport, rail transport, and other ground-based transportation modes. Several challenges and gaps exist in providing weather forecasts for this sector:

a) **Accurate Short-Term Forecasting:** Surface transport operators, including drivers and train loco pilots, rely on accurate and timely short-term forecasts for immediate decision-making. This includes anticipating and managing hazards like heavy rain, snow, fog, and ice that can impact road and rail conditions.
b) **Microclimates:** Weather conditions can vary significantly over short distances, especially in urban areas, making it challenging to provide accurate forecasts for localized weather variations.
c) **Seasonal Variability:** Different seasons present distinct challenges. Winter may bring icy roads and rail tracks, while the summer season can lead to heat-related issues such as track buckling or road surface softening.
d) **Extreme Weather Events:** Predicting and preparing for extreme weather events, including hurricanes, tornadoes, and severe thunderstorms, is critical. Such events can lead to severe disruptions and damage to surface transportation infrastructure.
e) **Data Gaps:** Access to real-time and localized weather data is essential for accurate forecasts. Gaps in data coverage, especially in remote or less densely populated areas, can hinder forecast accuracy.
f) **Intermodal Integration:** Many regions rely on a combination of transportation modes (e.g., road and rail). Integrating weather forecasts effectively across different modes of surface transport is essential for efficient intermodal transportation.
g) **Infrastructure Vulnerability:** Weather conditions can impact transportation infrastructure. This includes damage to roads, bridges, rail tracks, and signalling systems. Accurate forecasting can help prevent damage and disruptions.
h) **Safe Operations:** Weather forecasts are vital for ensuring the safe operation of vehicles and trains. Information on wind speed, visibility, precipitation, and temperature is necessary for decision-making related to speed restrictions, route changes, and other safety measures.
i) **Communication and Decision Support:** Effective communication of weather information to transportation operators and travellers is crucial. Decision support systems are needed to translate forecasts into practical actions, such as route changes or detours.
j) **Resource Allocation:** Adequate resources are required for maintaining weather forecasting equipment and infrastructure, as well as for ongoing research to improve forecasting capabilities.

Addressing these challenges and gaps in weather forecasting for the surface transport sector requires investment in research, technology, and infrastructure. Collaboration with surface transport stakeholders, including government transportation departments, railway companies, and road operators, is essential to ensure the effective integration of weather information into planning and operations.

4.3.3 Short-term Vision (next two years)

To advance weather forecasting for the surface transport sector over the next two years, we are planning to provide near real time and accurate weather information with Navigation facility to the users.

a) **Dedicated Application:** Developing a dedicated application for surface transport can provide significant benefits in terms of safety, efficiency, and user experience.

b) **User-Friendly Interface:**
   - An intuitive and user-friendly design to facilitate easy access to information and services.
   - Customizable preferences, such as route preferences, notification settings, and personalization options.

c) **Integrated Route Navigation:** Route selection and navigation facility integrated with weather will be key add-on in making it more users friendly.

d) **Major Routes:** in the phase one development, our focus will be along the major routes in the country for road and rail transport.

e) **Near Real-Time Weather Information:**
   - Integration with meteorological data to provide near real-time weather updates, including temperature, precipitation, wind speed, and visibility.
   - Alerts and notifications for adverse weather conditions, allowing users to adjust travel plans accordingly.

f) **Satellite data:** Integration of satellite layer can make it visually more impactful to understand weather along the route.

g) **7 day Forecast:** Route selection with upcoming 7 days enroute forecast can help users in planning long days of journey.

h) **End User Feedback:** End user feedbacks can play very important in understanding the weak areas for next phase of development.

i) **Public Awareness:** Educating the public and travellers about weather-related risks and precautions, enhancing overall safety and preparedness.

4.3.4 Medium-term Vision (next ten years)

To advance weather forecasting for the surface transport sector over the next ten years, we envision providing real-time, highly accurate, and localized weather information, leveraging cutting-edge technology and fostering collaboration among stakeholders.

a) **Safety First:** Placing a strong emphasis on safety, providing transportation operators with information necessary to avoid hazardous conditions and emergencies.

b) **Feedback Action:** Improvement over weak areas and addition of features as per user's requirement.

c) **Real-Time Weather Information:** upgrade the system from near-real time to real time.

d) **Multi-Modal Transport Integration:** Integration with various modes of surface transportation, including buses, high speed train and metro providing a seamless experience for users switching between different modes.

e) **Radar Mosaic Integration:** Weather radar and satellite imagery for users to visualize current weather conditions.

f) **Safety Alerts and Advisories:**

- Push notifications for safety advisories, such as road closures, accidents, or adverse weather events on the chosen route.
- Emergency contact information and procedures for users to report incidents or request assistance.

g) **Route Planning and Navigation:**

- GPS-based navigation with weather information and dynamic route adjustments to help users avoid congestion and delays. Some form of dynamic adjustments are already done, so specific role of IMD may be highlighted
- Route planning based on weather forecasts to optimize travel times and safety.

h) **Transport Scheduling:**

- Timetables and schedules for public transport, including buses and trains.
- Real-time updates on transportation availability and delays.

i) **Integration with Other Services:** Integration with ride-sharing, parking information and reservations to provide users with a range of transportation options.

j) **Customization:** Customizable preferences, such as route preferences, notification settings, and personalization options.

k) **Community Engagement:** Features that allow users to engage with the transportation community, such as sharing feedback, ratings, and reviews.

l) **Collaboration:** Promoting collaboration among IMD, transportation operators, and government bodies to streamline information sharing and enhance the integration of weather forecasts into planning and operations.

m) **Resource Investment:** Allocating resources for research, infrastructure maintenance, and technology upgrades to continually improve forecasting capabilities.

n) **Short range forecast lead time:**

- Improve from the current 24 to 48 hours to 72 hours for specific surface transport-related hazards like fog, heavy rain, or storms.

o) **Medium forecast lead time:**

- Extend the 7 days lead time for surface transport hazard forecasting, covering 10 to 15 days for more general weather patterns affecting transport (e.g., extended periods of heavy rainfall or temperature extremes).

p) **Real-time warnings:**

- Implement real-time, localized warnings for surface transport with near-instantaneous dissemination via mobile apps, road signs, radio, and highway advisory systems.

- Aim for 24/7 operational capability of forecasting and warning services, ensuring all forms of surface transport receive timely, clear, and actionable alerts.

q) **Decision support tools:**

- Develop an interactive platform for surface transport stakeholders (e.g., transport authorities, logistics companies) offering real-time weather updates with high spatial resolution (sub-kilometre scale).

By working toward this vision, the surface transport sector can become more resilient in the face of changing weather patterns and climate challenges. This will ultimately contribute to safer, more efficient, and environmentally responsible surface transportation over the next ten years.

4.3.5 Vision 2047

Developing a futuristic Weather Application for surface transport involves collaboration among IMD, transportation providers, technology companies, and city planners. Ensuring data privacy and security, especially when using biometrics and block chain, is crucial. The application should focus on delivering transformative and sustainable transportation experiences while enhancing safety and resilience in an era of changing weather patterns and climate challenges.

a) **Hyper-Precise Forecasting:** Integration with advanced weather models, including machine learning and AI, to provide hyper-local and highly accurate weather forecasts, even down to street-level precision.
b) **Predictive Analytics:** Real-time data analytics and machine learning to predict localized weather patterns and their potential impacts on specific routes and transportation schedules.
c) **Environmental Sensing:** Integration with IoT devices and sensors to monitor environmental conditions, such as air quality, temperature, and road surface conditions.
d) **High Resolution Weather Radar and Satellite Imagery:** Real-time access to high-resolution weather radar and satellite imagery to track storms, precipitation, and other weather events.
e) **Augmented Reality (AR) Visualization:** AR overlays that provide real-time weather information on the user's view, helping drivers and passengers make informed decisions while on the move.
f) **Dynamic Route Planning:** AI-driven route planning that takes real-time weather conditions into account, suggesting alternative routes to avoid adverse weather.
g) **Intelligent Traffic Management:** Integration with traffic management systems to adapt traffic signal timings based on current weather conditions, reducing congestion and improving safety.

h) **Emergency Response Coordination:** Integration with emergency services to ensure timely responses to accidents or emergencies resulting from adverse weather conditions.
i) **Multi-Modal Integration:** Integration with various modes of transportation, providing seamless navigation and weather information for users switching between different modes (e.g., walking, cycling, public transport, and driving).
j) **Advanced Alerts and Notifications:** Proactive weather alerts with customized notifications and suggestions for travellers, including recommended departure times and alternate routes.
k) **Quantum Computing for Speed:** Leveraging quantum computing for real-time weather data processing, allowing for faster and more accurate forecasts and route optimization.
l) **Sustainability and Eco-Friendly Options:** Providing information on eco-friendly and sustainable transportation choices, including electric vehicle charging stations, bike-sharing options, and public transport.
m) **Biometric and Health Monitoring:** Integrating biometric sensors to monitor the well-being of passengers, such as air quality, temperature, and humidity levels, to ensure passenger comfort and safety.
n) **Community and Social Features:** Building a community of users to share real-time weather information and travel experiences, fostering collaboration and support.
o) **Space Weather Monitoring:** Real-time monitoring of space weather phenomena, such as solar flares and geomagnetic storms, which can impact GPS and satellite communications.
p) **Holographic Displays:** Integration of holographic displays for interactive, immersive weather visualization and exploration.
q) **Short range forecast lead time:**
    - Achieve a 7-day forecast lead time for specific surface transport hazards (e.g., dense fog, cyclonic storms affecting transport routes).
r) **Medium forecast lead time:**
    - Extend the 7 days lead time for surface transport hazard forecasting, covering 15 to 20 days for more general weather patterns affecting transport (e.g., extended periods of heavy rainfall or temperature extremes).
s) **Global scale and integration:**
    - Provide global or regional surface transport forecast integration, allowing cross-border coordination and predictions for multi-national logistics planning.
    - Achieve fully automated, AI-driven service delivery for all forms of surface transport (e.g., predictive maintenance based on weather, optimized routing recommendations).

t) Comprehensive decision support systems:

- Ensure that weather warnings are integrated into intelligent transportation systems (ITS), with autonomous vehicles receiving direct weather-related guidance.

u) Proactive service delivery:

- Ensure that proactive alerts are delivered based on forecast patterns (e.g., alerting long-distance cargo transport 72 hours in advance of a potential disruption), moving from reactive to predictive and preventative service models.

4.3.6 Strategy

Developing an application for the surface transport sector requires a well-defined strategy to ensure the application's success. Here is a comprehensive strategy for application development in this domain:

a) Define Key Features and Functionalities:

- List the core features and functionalities the transport application will offer. This may include navigation, real-time weather updates, traffic information and route optimization.
- Prioritize features based on user needs and technological feasibility.

b) Technology Stack Selection:

- Choose the appropriate technology stack for development, considering factors like platform (Windows, iOS, Android, etc.), programming languages, and development frameworks.
- Choose the appropriate technology stack for data collection, processing, and dissemination.
- Ensure the technology is scalable, secure, and capable of handling real-time data.

c) Data Sources and APIs:

- Identify and secure access to reliable data sources, including meteorological services, traffic monitoring systems, environmental sensors, and other relevant weather information providers.
- Establish agreements to access real-time weather data, including forecasts, radar, and satellite imagery.

d) Precise Localization:

- Implement precise localization to provide weather information at a granular level, ensuring that users receive information specific to their routes and locations.

e) Safety and Emergency Response:

- Include features for safety advisories and emergency response information, providing real-time alerts related to weather-related emergencies.
- Enable communication with emergency services and authorities.

f) Integration with Traffic Management:

- Collaborate with traffic management systems to adjust signal timings and optimize traffic flow based on real-time weather conditions.
- Provide traffic updates and incident reporting to users.

g) Testing and Quality Assurance:

- Thoroughly test the weather services for functionality, performance, and security.
- Engage users and transportation professionals for beta testing and gather feedback for improvement.

h) Deployment and Marketing:

- Deploy the weather services to relevant platforms, including websites, mobile apps, and information kiosks.
- Develop marketing campaigns and partnerships to promote the services to a wider audience.

i) Scalability and Future-Proofing:

- Design the services with scalability in mind to accommodate a growing user base.
- Stay informed about emerging technologies and trends in weather forecasting to ensure long-term relevance and innovation.

A well-planned and executed strategy is essential for the success of weather services in the surface transport sector. Regular engagement with users, stakeholders, and technology partners, along with adaptability to changing user needs and technological advancements, is key to providing a competitive and user-friendly solution.

4.3.7 Outcome

Developing weather services for the surface transport sector yields a range of significant outcomes. These services enhance safety by providing real-time weather updates and safety advisories to travellers, ensuring informed decision-making and minimizing weather-related accidents. They also improve efficiency by offering traffic data and route planning, helping users avoid congestion and reduce travel times. Moreover, weather services minimize disruptions in transport operations, benefiting transportation providers by optimizing schedules and routes. By encouraging eco-friendly transportation choices, they contribute to environmental sustainability. These services enhance public awareness about the impact of weather on transportation and enable more efficient emergency responses during adverse weather events. Overall, they lead to safer, more efficient, and environmentally responsible surface transport operations, improving the quality of travel for all stakeholders.

4.4 METEOROLOGICAL SERVICES FOR INLAND WATER

4.4.1 Current status and major achievements during the past 10 years

Currently India has a total navigational length of 20,275 km spread across 24 States in the country, out of which 5200 km of river channels and 4000 km of canal networks have been developed as navigational waterways known as 'Inland Waterways. In addition, backwaters and creeks are also used as waterways in many parts. Many states have been using waterways networks as the lifeline of their people that provide cost-effective ways of transportation and generate livelihoods through varied activities. With the growing number of waterways in the country and increasing river transportation, the frequencies and numbers of mechanized and non-mechanized boats have increased exponentially.

In addition, the increased efforts of river conservation by the Government of India have also attracted river tourism in the country. Many people are nowadays using waterways for their recreational activities such as boat/steamer riding, windsurfing, boat racing, etc. As a means of river transportation, both mechanized and non-mechanized boats are being used along waterways across the country; many of them are not having authentic checks on the validity/permit and are over-aged & poorly designed. Whenever any boat accident occurs, overloading, dangerous working practices, poor training, inadequate regulations, near non-existent enforcement, etc., are pointed to as the root cause. After the dreaded Dhubri ferry tragedy of 30th April 2012 on the river Brahmaputra that resulted in the loss of over 250 lives, a need was felt by the Government of India to formulate guidelines on the boat and navigational safety.

Based on the data available on navigable waterways, compiled by the ministry of statistics and programme implementation, by 2015–16 a total of 106 water bodies with a minimum length of 25 km (16 mi) were declared as national waterways. These have been classified into 3 categories based on financial viability and location as well as into 8 clusters based on locations.

The National Waterways Act, 2016 has declared 111 inland waterways as 'National Waterways' (NWs) in the country to promote shipping and navigation on them.

Utilising India's extensive rain-gauge network (6095), the Hydro-meteorological Division of IMD at New Delhi provides real-time monitoring and prepares daily, weekly, monthly, seasonal and annual basis for the 617 districts, 36 States/UTs, 36 Meteorological sub divisions, 4 Homogeneous regions and the country's rainfall products mainly in the form of reports, graphs and maps. All the products are uploaded in the 'Customised Rainfall Information System (CRIS)' (https://hydro.imd.gov.in/hydrometweb/) website portal. IMD renders assistance and advice on the meteorological aspects of hydrology, water management and multipurpose river valley projects management using various available rainfall data products like forecast rainfall data GFS (Global Forecast System) and WRF (Weather Research and Forecasting) to Central Water Commission, Ministry of Agriculture, Ministry of Water Resources, Railways, Damodar Valley Corporation, Flood Control Authorities and the State Governments.

Flood Meteorological Offices (FMOs) have been set up by IMD at fifteen locations viz., Agra, Ahmedabad, Asansol, Bhubaneshwar, Guwahati, Hyderabad, Jalpaiguri, Lucknow, New Delhi, DVC, Srinagar, Chennai, Bengaluru, Thiruvananthapuram and Patna. During the flood season, FMOs provide valuable meteorological support mainly in the form of river sub-basin-wise Quantitative Precipitation Forecast (QPF) to the Central Water Commission/State Irrigation Department for issuing flood warnings especially during the flood season (May to December). Also, Flash Flood Guidance bulletins are issued four times a day (00UTC/6UTC/12UTC/18UTC) during the flood season in the watershed level (~4km/4km) which includes Imminent Flash Flood Threat(IFFT)/Persistent Flash Flood Threat (PFFT) valid for previous/next 6 hours respectively and Flash Flood Risk (FFR) valid for 12/24/36hours.

A World Bank-aided Hydrology Project covering a 6-year period is presently under implementation. This project aims at enhancing the physical infrastructure of hydro-meteorological activities and data processing and management systems resulting in an enhancement of rainfall data quantity and quality. Pan India and ten central agencies including IMD are involved in the project. IMD has an important and active role of providing technical guidance to concerned states/central agencies in procurement and installation of standardised equipment, inspection of existing and new rain-gauge stations, and imparting specialised training to personnel at various levels in the states/agencies.

Weather is an important component in safe boat operations across the world. In India, there are great spatial and temporal variations in climatic characteristics that are reflected in the form of localized weather variations across the country. Whereas, the favourable weather can support boat operators in carrying out safe navigations and organizing pleasure trips, the poor weather can spoil the trip and may cause emergency situations that may eventually lead to major disasters like boat capsizing, collision etc. It is, therefore essential for boat owners and waterways management authorities to pay much attention on weather bulletins and guidelines issued by local meteorological organizations to avert boat tragedies.

Forecast of hydro-meteorological events related to passenger boating suffers from technology and typically short lead-time limitations. However, even with such limitations forecast could be made with a fair degree of accuracy with select technology choices. Meteorological parameter which impact inland waterways and navigations are: -

1. Heavy Rainfall
2. Heat wave
3. Strong Wind
4. Dense Fog
5. Thunderstorm/ Thunder squall/ Dust Storm
6. Tropical Cyclone
7. Lightning
8. Hailstorm

Presently IMD is not issuing any customized bulletin for Inland waterway transport at national level. However, regional offices issue the ferry forecast & warning for ferry route. Climate Change is going to have a huge impact on inland water bodies like rivers & lakes which will make it necessary to have accurate forecast and warnings for safer transportation of cargo and human passengers through the inland waterways. In addition, droughts can also disrupt the inland navigation services by reducing water levels.

4.4.2 Challenges and Gap Areas

Inland water transport has enormous potential in India as a mode of transportation for both passengers and cargo, and it is still under development. The challenges in this sector in terms of providing meteorological information and weather warnings are

- No navigability throughout the year:
- Some rivers are seasonal and do not offer navigability throughout the year. Around 20 out of the 111 identified national waterways have reportedly been found unviable, and as a result, no proper mechanism has been developed for providing meteorological information and weather warnings.
- Issuing forecast and warnings for current operational waterways can be managed easily but as the number of operational waterways increase it will require huge infrastructure for regular forecast for them.
- The inland waterways can play a crucial role in realising Prime Minister's vision of making India a zero-carbon emission country by 2070. In achieving this feat, inland waterways will have to be given utmost priority which will in turn require accurate forecast and warnings on these waterways.
- Sparse Meteorological observation network

4.4.3 Short-term Vision (next two years)

After the road, railways, and aviation sectors, this sector is going to be a vital pillar of mode of transportation in India. Therefore, short-term vision for its safe and efficient operation is:

- Need to increase the observational network (AWS, ARS) along the waterways.
- Customised weather forecasts & warnings for rainfall, thunderstorm, fog, wind & temperature will be issued.
- Like the aviation sector, an online briefing system portal will be developed for waterways transport.
- Increase of observational network (Automatic Weather Station (AWS), Automatic Raingauge (ARG), ARS along the waterways. Application of Doppler weather radar data
- Persons involved in waterways operations will be trained in observing weather situations.
- Dissemination of nowcast warning along the route using suitable technology like radio, TV, GSM, GPRS, social media, mobile app, etc.

- ❖ Installation of a display system for weather forecast and warning at the ferry ghat and fixed port
- ❖ Beginning of forecast & warning for Passenger traffic on all the National Waterways by 2028.
- ❖ Stakeholder interaction through workshop/meeting etc.
- ❖ Coordination with NDMA/ SDMA/ DDM

4.4.4 Medium-term Vision (next ten years)

With passage of time, the sector is likely to grow, and as a result, traffic will grow exponentially; hence, medium-term vision should be

- ❖ Opening of the meteorological office at a fixed inland port
- ❖ Automatic dissemination of forecast & warnings related to cyclone, thunderstorms/lightning, rainfall, hailstorms, fog, gusty wind, temperature etc.
- ❖ Collaboration with national and international organisations is needed for better understanding the need and its resolution.
- ❖ Development of Decision Support System (DSS) for the sector.
- ❖ Beginning of forecast and warning for Passenger as well as Cargo traffic by 2033.
- ❖ Stakeholder interaction through workshop/meeting etc.
- ❖ Coordination with NDMA/SDMA/DDMA
- ❖ The impact based forecast and risk based warning for all the waterways and ports of the country for all types of severe weather based on hazard & impact modelling and risk assessment with a lead period of 5 days and accuracy of at least 60-70%.

4.4.5 Vision 2047

- ❖ Use of AI and ML in weather forecasting with numerical model prediction for short to medium range forecasting for different weather parameters.
- ❖ Automation of forecast & warning generation and dissemination for use as per sector requirements.
- ❖ At present 13 National waterways are in operation, these will increase many folds by 2047. Also the River Linking project is under development which will increase waterways transport many fold including the passenger as well as cargo transport. IMD can plan in advance for all these upcoming waterways growth and their forecast requirement.
- ❖ Developing waterways is a part of the 8.5 Lakh Crore Sagarmala Project which aims at using India's 7500 km coastline for India's economic growth. This project has an aim of developing about 14000 km of inland waterways for port connectivity. Providing Forecast and Warning for this 14000 km of Waterways is IMD's vision for 2047.
- ❖ IMD's vision for 2047 is that we should have a dedicated 'Transport Weather Services' division at IMD HQ as well as at the MCs. This division should be looking after weather services requirements of all types of transport services viz: Railways, Road and Waterways.

- ❖ The impact based forecast and risk based warning for all the waterways and ports of the country for all types of severe weather based on hazard & impact modelling and risk assessment with a lead period of 7 days and accuracy of at least 80-90%.

4.4.6 Strategy

- ❖ Improvement in the meteorological observational network along all the inland waterways, along with a fixed port
- ❖ Automatic dissemination and display of forecasts and warnings adopting new, improved technology
- ❖ Generation of sector-specific and improved forecasts and warnings, adopting and collaborating with new technology like AI and ML
- ❖ Establishment of an office at an important and busy fixed port of Inland Waterways
- ❖ Capacity building and person involved in waterways operation
- ❖ Stakeholder interaction through workshop/meeting etc.

4.4.7 Outcome

In view of India's burgeoning population and increasing traffic, the development of inland waterways will not only reduce travel time and ensure a seamless journey for people and goods, but also be cost-effective and bring down pollution levels. The success of the sector will depend on a holistically designed policy that factor in safety, infrastructure support, inter-state coordination, and integration with other transportation modes. By adopting this strategy, the utmost safety of inland navigation will be achieved due to extreme weather events, which will help minimise the loss of life and property.

4.5 URBAN METEOROLOGICAL SERVICES

4.5.1 Current status and major achievements during past 10 years

The exponential growth of urban populations has become a driving force for human development, particularly in developing countries. It is expected that today's urban population of 3.2 billion will increase to nearly 5 billion by 2030. Although, crowded cities are centers of creativity and economic progress, but face serious challenges on account of polluted air, extreme weather conditions, flooding, and other hazards. Increasingly dense, complex, and interdependent urban fabrics render cities vulnerable: a single extreme event can lead to a widespread breakdown of a city& infrastructure often through cascading downstream or "domino" effects and even loss of human life in large numbers.

The World Meteorological Organization (WMO) recognizes that rapid urbanization necessitates on new types of services which make the best use of science and technology and considers the challenge of delivering these as one of the main priorities for the meteorological community. Urban Services, in the traditional sense, are related to transportation, housing, water management, waste management, public health, electricity, snow clearance, etc. In a rapidly changing urban complexion, there is a need for Urban Integrated Services consisting of observational data and prediction for weather, climate, hydrology, and air quality infrastructure to support traditional (and new) urban services in art-of state manner. Urban Integrated Services typically should include:

i. Observation and Monitoring
ii. Data, databases, and data sharing
iii. Modelling and prediction capability
iv. Tailored urban service applications
v. Decision Support Systems to support decision-making that includes human behavior/response considerations
vi. Products, service delivery, communications and outreach;
vii. Evaluation, assessment, societal impacts
viii. Research and Development.

The vision of India Meteorological Department in urban services involves leveraging meteorological data and expertise to enhance the livability, safety, and sustainability of urban areas. Urban services encompass a wide range of functions and challenges, and the department can play a crucial role in addressing them. Here is a vision for how a Meteorological Department can contribute to urban services:

- **Weather** (especially high-impact weather for nowcast and short-range forecast at the urban and suburban scales, in all conditions, and taking into account the urban influences)
- **Climate** (urban climate, climate extremes, sector-specific climate indices, climate projections, climate risk management and adaptation).
- **Hydrology and water-related hazards** (flash river floods, heavy precipitation, river

water stage, inundation areas, storm tides, sea level rise, urban hydrology)

- **Air Quality** (urban air quality and other larger scale hazards: dust storms, wildfires, smog, etc.)
- **Heat Island Mitigation:** IMD can assist cities in implementing heat island mitigation strategies, such as green roofs, urban forestry, and cool roofing materials, to combat urban heat islands and reduce the health risks associated with extreme heat events.
- **Transportation and Traffic Management:** IMD can provide weather-related information for urban transportation systems to improve safety and efficiency. This includes forecasting weather conditions that affect road conditions, visibility, and public transit operations.
- **Emergency Response and Disaster Management:** IMD can collaborate with emergency response agencies to enhance disaster preparedness and response plans, especially in cases of floods, storms, and other weather-related emergencies. We can ensure effective communication of weather warnings to urban populations.
- **Energy Efficiency:** We can support efforts to optimize energy use in cities by providing data on weather patterns and conditions that affect energy demand and supply, helping cities reduce energy consumption and greenhouse gas emissions.
- **Public Health:** IMD can work with public health agencies to provide early warnings and information related to health risks associated with weather events, such as heat waves and air pollution, to protect vulnerable populations.
- **Water Resource Management:** IMD can also assist cities in managing water resources effectively, including storm water drainage, flood control, and sustainable water supply, considering the impacts of changing weather patterns and climate.
- **Climate Action Planning:** IMD can contribute to developing and implementing urban climate action plans, helping cities reduce carbon emissions and adapt to climate change while promoting sustainable development.

Urban Integrated Services systems need to consider fine-scale urban observations for assimilation and model initialization, urban canopy models, urban vegetation, land use and land cover (to assess both exposure, and vulnerability but also soil permeability, which might affect the hazard in terms of lag time) ensemble prediction, quantification of uncertainties and processes requiring multi-disciplinary approach.

With increasing demand, IMD has already taken Urban Meteorological Services as one of its priority projects to provide city specific single window dissemination system that covers all temporal scales that scale from nowcast to climate projections especially location-specific severe weather warnings for 150+ major cities in the country with the advent of dense observational networks, high-resolution forecasts, multi-hazard early warning systems and climate services promoting the Sustainable Development Goals. However, there are other urban centers with large populations which are tending to become megacities. In view of the expansion of Indian cities, there is an imperative need for strengthening of infrastructure for megacity-oriented weather services.

4.5.2 Specific Gaps

- Integrated Urban Meteorology and Climate Services for Indian Cities need to be developed. Development of programs, tools, and policy recommendations that will improve city's adaptability and build its resilience. Currently the integrated Urban Meteorological Services for 150+ cities over India.
- Integration and agglomeration of various sourced meteorology and air quality observed data networks for urban meteorological Services.
- Adopting modern technological improvements with respect to societal demands dynamically.
- Integration of holistic coupled (land-atmosphere-air quality) modeling framework that advances feedback across scales from all components of the urban ecosystem

4.5.3 Short-term Vision (next two years)

The observational systems will be improved to better understand the physical processes and develop the models for representative cities. The mission is presented below.

Augmentation of cheap meteorological sensors/ instruments in monitoring urban air quality/ meteorological heterogeneity to understand/ forecast at hyper-local levels.

The integration and agglomeration of various sourced meteorological and air quality observed data networks are essential steps in establishing effective urban meteorological services. These services rely on collecting data from multiple sources to provide accurate and localized weather forecasts and air quality information for urban areas. Here's how this integration typically works:

1. **Data Sources**: Meteorological and air quality data can come from various sources, including:

    a. Weather Stations
    b. Satellites.
    c. Ground-Based Sensors
    d. Radar and Lidar
    e. Weather Models

2. **Data Integration**: Data from these diverse sources need to be collected, integrated, and processed into a coherent dataset. This may involve using data fusion techniques to combine information from different sources while accounting for variations in accuracy and reliability.

3. **Quality Control**: Ensuring the quality and accuracy of the collected data is critical. Data quality control measures are applied to identify and correct errors or inconsistencies in the data.

4. **Data Assimilation**: In the case of weather forecasting, data assimilation techniques are used to incorporate observed data into numerical models to initialize and

improve the accuracy of weather forecasts.

5. **Localized Information**: Urban meteorological services require specific data on localized weather conditions within cities, such as urban heat islands, localized rainfall, and air quality variations. This may involve deploying sensors in strategic locations within urban areas.
6. **Communication and Dissemination**: Once the data is processed and quality-assured, it is made available to the public through various channels, including websites, mobile apps, and public alerts. This ensures that residents, businesses, and local authorities can access timely and relevant information.
7. **Continuous Monitoring and Updates**: Urban meteorological services must continuously monitor and update data to provide real-time information and forecasts. This includes monitoring changes in weather conditions, air quality, and other relevant parameters.
8. **Emergency Response**: Integrated urban meteorological services are crucial for disaster preparedness and response. They provide valuable information for managing extreme weather events, such as floods, storms, and heat waves, and can help authorities make informed decisions to protect public safety.

Efforts to integrate and agglomerate data from various sources for urban meteorological services are ongoing, and advances in technology and data science are continually improving the accuracy and timeliness of such services. Local governments, meteorological agencies, and environmental organizations collaborate to make these services more effective and accessible to urban populations

City scale (~300-500 meters) model guidance with multi-layer urban canopy model integration up to 3 days with hourly update for all smart cities over the country.

Creating city-scale meteorological models with high resolution, such as 300-500 meters, and integrating multi-layer urban canopy models is a complex and resource-intensive task. While this level of modeling is highly desirable for providing precise and localized weather forecasts for smart cities, it requires advanced computational capabilities, high-density sensor networks, and access to extensive data. Here's an overview of the steps and challenges involved:

High-Resolution Modeling:

- High-resolution meteorological models use fine grids to represent atmospheric processes in detail.
- These models require significant computational resources and advanced numerical techniques to handle the increased spatial and temporal resolution.

Urban Canopy Models:

- Multi-layer urban canopy models simulate the interactions between the atmosphere and the urban environment, including buildings, roads, and green spaces.
- These models consider factors like heat absorption, reflection, and release from various urban surfaces.

- Implementing urban canopy models adds complexity and computational demands to the simulation.

Data Collection:

- High-resolution models require a vast amount of input data, including atmospheric data (temperature, humidity, wind), land use data, and surface characteristics.
- Access to real-time observations from weather stations, satellites, and ground-based sensors is crucial for model initialization and verification.

Data Assimilation:

- Data assimilation techniques integrate observed data into the model to improve its accuracy and reliability.
- Assimilating data from various sources, including ground-based sensors and satellites, is necessary for urban-scale models.

Computational Resources:

- Running high-resolution urban meteorological models with multi-layer urban canopy models requires powerful supercomputers or high-performance computing clusters.
- Efficient parallelization and computational optimization are necessary for timely updates.

Model Validation and Calibration:

- Urban meteorological models must be validated and calibrated against observed data to ensure accuracy.
- Local variations in topography, urban layout, and land use must be considered during model setup and validation.

Hourly Updates:

- To provide real-time guidance, the model needs to be updated frequently, at least hourly.
- This requires an automated system for data assimilation, model execution, and result dissemination.

Smart City Integration:

- Integration with smart city infrastructure and communication networks allows for real-time data exchange and alerts.
- Smart city sensors and IoT devices can provide valuable data for model initialization and validation.

Public Access:

- The model's output should be made available to the public, local authorities, and emergency services through user-friendly interfaces, apps, and websites.

Cost and Resources:

- Developing and maintaining such a system is resource-intensive, requiring funding, skilled personnel, and ongoing support.

Implementing a high-resolution urban meteorological model with multi-layer urban canopy integration for all smart cities in a country is a long-term and ambitious endeavour. It typically involves collaboration between government agencies, meteorological departments, research institutions, and technology providers. Advances in computational capabilities and data collection methods are continually improving the feasibility of such projects, but they remain challenging to implement on a large scale.

4.5.4 Medium-term Vision (next ten years)

Urban Meteorological Services will be implemented for all the major cities with population of > 10 lakhs with development of meso network and urban modelling at high resolution. The mission is presented below.

Urban networks for hazard preparedness and Response.

Urban networks for hazard preparedness and response are essential components of disaster management and resilience in urban areas. These networks involve the collaboration of various stakeholders, including government agencies, local authorities, emergency services, community organizations, and the public, to effectively prepare for and respond to various hazards and disasters that can affect cities. Here are key aspects of urban networks for hazard preparedness and response:

Multi-Agency Coordination: Effective urban networks bring together multiple agencies and organizations responsible for various aspects of disaster management, such as fire departments, police, medical services, public works, and environmental agencies. Coordination among these entities is vital for a cohesive response.

Emergency Plans and Protocols: Urban networks develop and maintain comprehensive emergency plans and protocols tailored to the specific hazards that a city may face, including natural disasters (e.g., earthquakes, floods, hurricanes) and man-made incidents (e.g., chemical spills, terrorism). These plans outline roles, responsibilities, and actions to be taken during emergencies.

Early Warning Systems: Urban areas often have early warning systems in place to alert residents and authorities about impending hazards. These systems can include sirens, text messages, smartphone apps, and public address systems. Timely warnings are crucial for evacuation and preparedness.

Public Awareness and Education: Urban networks work to educate the public about potential hazards and how to prepare for them. This includes providing information on evacuation routes, shelter locations, emergency contact numbers, and disaster supply kits.

Community Engagement: Engaging local communities and neighbourhoods in disaster preparedness and response efforts is essential. Community-based organizations, neighbourhood associations, and volunteers play a crucial role in helping vulnerable populations during disasters.

Resource Management: Urban networks coordinate the allocation of resources, such as personnel, equipment, and supplies, to respond effectively to emergencies. This includes maintaining stockpiles of essential items like food, water, medical supplies, and emergency response vehicles.

Training and Drills: Regular training exercises and drills are conducted to ensure that emergency responders and the public are prepared to respond effectively during disasters. These exercises simulate real-life scenarios and help identify areas for improvement.
Technological Integration: Urban networks leverage technology for real-time monitoring, data collection, and communication. Geographic Information Systems (GIS), remote sensing, and data analytics are used to assess risks and inform decision-making.
Cross-Border Cooperation: In cases where hazards may affect multiple urban areas or cross international borders, urban networks collaborate with neighbouring cities and regions to ensure a coordinated response.
Post-Disaster Recovery: Urban networks also play a role in long-term recovery efforts, helping communities rebuild infrastructure, provide social support, and restore essential services in the aftermath of disasters.
Continuous Improvement: The effectiveness of urban networks is assessed after each disaster to identify lessons learned and areas for improvement. This process of continuous improvement helps cities become more resilient to future hazards.
Public-Private Partnerships: Collaborations with private-sector organizations, such as utility companies and transportation providers, are critical to maintaining essential services and infrastructure during and after disasters.
Urban networks for hazard preparedness and response are dynamic and adaptive, evolving to meet the specific needs and challenges of urban areas. They are instrumental in reducing the impact of disasters, saving lives, and promoting resilience in cities.

AI-enabled model integration for complex decision-making and disseminating dynamic weather updates for cities.

AI-enabled model integration for complex decision-making and disseminating dynamic weather updates for cities represents a cutting-edge approach to urban meteorological services. Leveraging artificial intelligence (AI) can significantly enhance the accuracy, timeliness, and relevance of weather information for urban areas. Here's how such a system might work:

Data Integration: The system gathers data from various sources, including traditional weather stations, satellites, ground-based sensors, and remote sensing technologies. AI algorithms are used to integrate and harmonize this diverse data, ensuring that it's up-to-date and accurate.

Machine Learning Models: AI models, such as machine learning algorithms and deep learning neural networks, are employed to process and analyze the integrated data. These models can identify patterns, correlations, and trends in the data, allowing for more accurate weather predictions.

High-Resolution Modeling: AI-driven models can achieve high spatial and temporal resolution, enabling city-scale weather forecasts with granular details. This is particularly important for urban areas with microclimates and varying weather conditions.

Urban Canopy Modeling: AI can be used to simulate urban canopy effects, accounting for factors like building heights, road surfaces, and green spaces. This helps in predicting localized weather phenomena, such as urban heat islands.

Real-time Monitoring: The system continuously monitors incoming data in real time, allowing for immediate updates and adjustments to weather forecasts and warnings.

Decision Support: AI algorithms can provide decision support for city officials, emergency services, and the public. They can generate recommendations and alerts based on predicted weather conditions, helping authorities make informed decisions about disaster preparedness and response.

Customized Alerts: AI-powered systems can generate customized weather alerts for different user groups, such as residents, businesses, and emergency responders. Alerts can be disseminated through various channels, including mobile apps, SMS, social media, and public address systems.

User Interaction: The system may feature user-friendly interfaces and mobile apps that allow residents to access real-time weather information, receive alerts, and report local weather conditions. This two-way communication can provide valuable data for model validation.

Dynamic Updates: Weather forecasts and alerts are dynamically updated as new data becomes available. AI models continuously adjust predictions to reflect changing weather patterns and evolving conditions.

Extreme Event Prediction: AI models can identify conditions conducive to extreme weather events, such as heavy rainfall, storms, or heat waves, and issue warnings well in advance.

Resilience Planning: Urban planners can use AI-driven weather data to inform resilience planning, such as designing infrastructure to withstand extreme weather conditions and adapting city layouts for climate resilience.

Post-Disaster Assessment: AI can also assist in post-disaster assessment by analyzing data on the impact of weather events and helping with recovery efforts.

Implementing an AI-enabled model integration system for urban meteorology requires collaboration between meteorological agencies, AI experts, city authorities, and technology providers. It's a powerful tool for improving urban resilience, enhancing public safety, and mitigating the impacts of extreme weather events in cities.

4.5.5 Vision 2047

- Expert System for Integrated Meteorological services for urban and rural areas
- Open street-specific forecasts and warnings for weather, climate, hydrology, and air quality parameters and extremes and impacts.

The vision of the India Meteorological Department in urban services is to be a key partner in creating safer, more resilient, and sustainable cities by providing essential meteorological information and expertise that supports urban planning, infrastructure development, public health, and overall quality of life in urban areas.

4.6 SERVICES FOR CONVENTIONAL POWER, ENERGY AND RENEWABLE ENERGY SECTOR

4.6.1 Current status and major achievements during the past 10 years

- IMD is providing weather forecasting services to power system operators through a dedicated portal, which can be accessed at "**http://14.139.247.5/power/NRLDC/**".
- The portal provides the following services to the power sector:
    - Weather forecasts
    - Nowcast warnings
    - All India Weather forecasts & meteograms
    - Satellite & RADAR information
    - Warnings for severe weather events
- IMD & Grid-India are jointly developing a Weather Based Decision Support System GRID ASTRA (Advance System Tracking And Realtime Analysis) for the Power Sector for Renewable Energy forecasting and Grid Management.
- Collaborative research with private and public organizations such as CEA, Adani Green Energy, Manikaran Analytics, Grid-India, NHPC, and Vayu Power.
- Advisories issued by IMD have helped the power sector in the following ways:
- IMD products are regularly used to take proactive steps for power demand estimation and maintain the system reliability and security of the Indian grid.
- The weather portal also allows in real-time, grid operator to remain more vigilant in case of heavy wind, cyclone, or lightning, which may lead to increased equipment tripping.
- The Weather portal also indicates the Heat/Cold Wave based on which power demand estimation and availability are decided from Grid India throughout India on a real-time basis.
- Based on the IMD weather forecasting portal, Annual Overhaul Maintenance (AOH) of Power Plant and utility network is planned from Regional/ State Load dispatch centres for uninterrupted power supply throughout the year.
- Weather & rainfall forecast to NHPC's hydro-projects at Chenab, Arunachal Pradesh and Assam has helped in effective planning, timely-warning and evacuation of man-machinery.

- Accurate anticipation of extreme weather conditions such as snowstorms, dust storms, high winds, thunderstorms and cyclones helps in advance operational planning, secure system operation and early restoration.
- The warnings of inclement weather help in anticipating sudden unprecedented decrease in demand.
- Advance warning and cyclone tracking by IMD has proved to be very useful for disaster preparedness and mobilizing resources for quick recovery.

4.6.2 Challenges and Gap Areas

a) **High Accuracy of Operational Forecasts at Different Granularity:** To meet the diverse needs of the power sector, including intra-hour, hour-ahead, day-ahead, weekly, and long-term forecasts, IMD faces the challenge of developing highly accurate forecasting models and techniques that operate effectively at various time scales. Achieving this requires specific adaptations of weather forecasting models and data sources.

b) **High-Resolution Solar & Wind Power Forecasts:** Generating high-resolution forecasts for solar and wind power production presents a considerable challenge due to the variability of these renewable energy sources. Accurately converting available weather data into quality solar and wind power forecasts is essential to maximize their utilization. The challenge here lies in refining forecasting techniques to provide high-resolution predictions.

c) **Data Integration and Sharing:** Collaborating with energy authorities, research institutions, and private enterprises to collect relevant data for accurate forecasting requires overcoming data integration and sharing challenges. Data privacy and security concerns must be addressed to ensure seamless information exchange and collaboration.

d) **Resource Allocation for Research and Development:** Allocating resources for advanced research and development, particularly in emerging areas like space-based energy extraction, carbon capture and utilization, and nuclear fusion, poses a challenge. Significant investments are required to explore these technologies while ensuring their integration with weather and meteorological science.

e) **Policy and Regulatory Challenges:** Developing policies and regulations for emerging power technologies and ensuring their sustainability and responsible utilization may face regulatory and policy challenges. IMD must actively participate in policy development, addressing potential obstacles to adopting and growing innovative energy solutions.

f) **Data Accessibility in Remote Areas:** Providing accurate forecasts for offshore projects in India necessitates overcoming the challenges of data accessibility in remote coastal regions. The risk lies in establishing reliable data transmission methods and infrastructure to ensure the availability of timely information for offshore site selection and maintenance.

g) **Environmental and Disaster Resilience:** To secure India's energy future, IMD must address environmental and disaster resilience challenges. As extreme weather events and climate changes become more frequent, developing resilient energy infrastructure and preparedness for disasters is crucial to maintain uninterrupted power supply.

4.6.3 Short-term Vision (next two years) and Strategy to achieve the vision:

Vision statement:

Develop a suitable platform for providing wind and solar power forecasting services to the power sector by IMD and create a Decision Support System for the power sector.

Strategy to Achieve the Vision:

a) **Service Initiation**: Establish a dedicated group within IMD for Power Forecast and Warning Services. Develop and implement a power forecast service for the Indian Power System Operator (POSOCO)/GRID INDIA and other stakeholders in the power sector. Create a centralized forecasting system to support grid managers in effectively managing wind and solar power generation and distribution.

- **Metrics**: Measure the percentage reduction in power sector forecasting errors compared to previous methods.
- **Timeline**: Initiate the service within the first year and complete full implementation within the second year.
- **Risk Assessment**: Potential risks include data security and technical challenges. Mitigation involves robust data encryption and IT support.

b) **Data Integration**: Collaborate with energy authorities, research institutions, and private enterprises to collect relevant data for accurate forecasting.

- **Metrics**: Measure the increase in data sources and the improvement in forecast accuracy.
- **Timeline**: Begin data integration within the first year, with a gradual expansion over the following year.
- **Risk Assessment**: Risks include data sharing concerns. Mitigation includes strict data sharing agreements and privacy protection.

c) **Human Capital Development**: Recruit and train experts in meteorology and energy sector dynamics.

- **Metrics**: Measure the number of experts trained and their contribution to improved forecasts.

- **Timeline**: Recruit experts within the first year and provide training throughout the two-year period.
- **Risk Assessment**: Risks involve recruitment challenges. Mitigation includes effective HR strategies.

d) **Pilot Programs**: Launch pilot projects in select regions to fine-tune services and gather feedback. IMD will serve as the central agency responsible for collecting and storing a comprehensive range of meteorological data, including real-time, forecast, and historical information, as well as data related to wind and solar energy generation.

- **Metrics**: Measure the feedback received and its impact on service improvements.
- **Timeline**: Initiate the pilot programs in the first year and assess feedback for further improvements in the second year.
- **Risk Assessment**: Risks include pilot project scalability. Mitigation involves adaptive project design.

4.6.4 Medium-term Vision (next ten years) and Strategy to achieve the vision:

Vision statement

Seamlessly integrate power sector SCADA data into existing forecasting and data assimilation systems to expand the real-time sensor network and enhance the capture of detailed and accurate weather information. Collaborate with MNRE to find Micro Wind Energy generation potential in India especially in North Eastern States. Promote energy-efficient technologies and offer precise forecasts for renewable energy sectors.

Strategy to Achieve the Vision:

a) Increase NWP update frequency: Enhance the Numerical Weather Prediction (NWP) system by increasing the frequency of weather forecast updates from two times a day to every two hours, ensuring more timely and relevant weather information for the power sector.

❖ **Metrics:**

- Measure the increase in forecast updates per day.
- Assess the impact on forecast accuracy and reliability.
- Evaluate the user satisfaction level with the more frequent updates.

❖ **Timeline:**

- Begin the transition to more frequent NWP updates within the first year.
- Gradually implement the increased frequency over the following two years.

❖ **Risk Assessment:**

- Risks include potential challenges in data processing and computational resources.
- Mitigation involves efficient resource allocation, advanced data processing techniques, and system scalability to handle the increased update frequency.

b) Improve Accuracy of Day-ahead weather forecast: Implement measures to enhance the accuracy of day-ahead weather forecasts, providing better preparedness for weather-related events in the power sector.

❖ **Metrics:**

- Evaluate the reduction in forecast errors for day-ahead weather predictions.
- Measure the impact on decision-making and resource allocation in the power sector.
- Assess the effectiveness of the improved forecast accuracy in minimizing disruptions and losses.

❖ **Timeline:**

- Initiate efforts to improve day-ahead weather forecast accuracy within the first year.
- Continuously refine forecast models and data sources over the following three years to achieve the desired level of accuracy.

❖ **Risk Assessment:**

- Risks may include data quality issues and model complexity.
- Mitigation involves data quality control, continuous model improvement, and regular feedback from end-users in the power sector.

c) Shorten Forecast delivery time: Undertake research and infrastructure improvements to reduce forecast delivery times, providing more real-time weather information to decision-makers and the public.

❖ **Metrics:**

- Measure the time reduction achieved in forecast delivery from data acquisition to dissemination.
- Assess the impact of shorter delivery times on decision-making and public awareness of weather-related events.
- Evaluate user satisfaction with the improved real-time information.

❖ **Timeline:**

- Begin research and infrastructure improvements to shorten forecast delivery time within the first year.
- Continuously optimize the process over the following two years to ensure timely forecast dissemination.

❖ **Risk Assessment:**

- Risks may include technical challenges in hardware upgrades and data processing.
- Mitigation involves efficient hardware and software infrastructure development, rigorous testing, and continuous monitoring to meet delivery time targets

d) **SCADA Data Integration**: Incorporate power sector SCADA data into existing forecasting and data assimilation systems for real-time accuracy. In addition, Increase the density of weather observations near the hub height of wind turbines to improve the accuracy of wind energy forecasts.

❖ **Metrics:**

- Measure the improvement in forecast accuracy and reliability achieved through SCADA data integration.
- Assess the impact of real-time SCADA data on grid management and energy generation.
- Evaluate user satisfaction with the incorporation of SCADA data into forecasts.
- Measure the increase in wind observations at hub height.
- Assess the impact on wind energy generation forecasts.
- Evaluate the improvement in wind energy prediction accuracy.

❖ **Timeline:**

- Initiate the integration of SCADA data and expand observations to hub height within the first year.
- Continuously optimize, increase the observation network, and expand the integration over the following two years to achieve real-time accuracy.

❖ **Risk Assessment:**

- Risks may include data integration complexities and data quality issues.
- Mitigation involves robust data integration frameworks, data quality control, and regular feedback from power sector stakeholders.
- Risks may include data collection challenges and equipment maintenance.

- Mitigation involves strategic deployment and maintenance plans, as well as data quality control procedures.

e) **Energy Efficiency Solutions**: Collaborate with the power sector to advocate and implement climate-informed and weather-sensitive energy-efficient technologies and practices, aligning energy production and consumption with meteorological conditions.

❖ **Metrics:**

- Measure the adoption rate of weather-sensitive technologies in the power sector.
- Assess the reduction in energy wastage and carbon emissions achieved through these technologies.
- Evaluate the impact of weather-sensitive practices on energy efficiency and sustainability.

❖ **Timeline:**

- Start promoting and implementing weather-sensitive technologies within the first year.
- Continuously advocate and expand adoption over the following three years.

❖ **Risk Assessment:**

- Risks may include resistance to technology adoption and the need for financial incentives.
- Mitigation involves creating awareness, providing financial incentives, and demonstrating the economic and environmental benefits of adopting these technologies and practices.

f) **Offshore Forecast**: Provide offshore weather forecasts and oceanographic data for site selection and maintenance planning for developing offshore projects in India.

❖ **Metrics**: Measure the accuracy of offshore weather forecasts and their contribution to project success.

❖ **Timeline**: Begin offshore forecasting in the first year and refine the service in the second year.

❖ **Risk Assessment**: Risks include data access in remote areas. Mitigation involves the use of advanced data transmission technology.

g) **Next-Gen Forecasting**: Develop and deploy advanced AI-based forecasting models tailored to the power and energy sectors' requirements, improving forecast precision and timeliness. Simultaneously, implement 1-minute forecasts to enable precise scheduling and dispatching of energy resources.

- **Metrics:**
  - Measure the improvement in forecast accuracy achieved through AI-based models.
  - Assess the reduction in forecast lead time and the impact on real-time decision-making.
  - Evaluate user satisfaction with the precision and timeliness of AI-enhanced forecasts.
  - Measure the accuracy of 1-minute forecasts in predicting weather conditions and energy production.
  - Assess the reduction in scheduling and dispatching errors and their impact on energy grid management.
- **Timeline:**
  - Commence the development of AI-based forecasting models within the first year.
  - Roll out AI-enhanced forecasts for power and energy sectors over the following two years.
  - Begin offering 1-minute forecasts within the first year.
  - Expand the coverage and accuracy of 1-minute forecasts over the following two years.
- **Risk Assessment:**
  - Risks may include technical challenges in model development and integration, computational requirements, and data access challenges.
  - Mitigation involves comprehensive testing, quality assurance, efficient resource allocation, data-sharing agreements, and continuous model improvement to ensure accurate 1-minute forecasts and AI-based enhancements.

h) **Smart Grid Integration**: Facilitate the integration of smart grid, microgrid, and grid management technologies for effective renewable energy integration and demand management through accurate prediction of meteorology.

4.6.5 Vision 2047 and Strategy to achieve the vision

Vision Statement:

Lead the development of forecasting products for emerging power sector technologies, including space-based energy extraction, hydrogen production, and carbon capture and utilization, to secure India's energy future along with SAARC energy deficient countries.

Strategy to Achieve the Vision:

a) High resolution model: Develop a high-resolution cloud cover prediction model for India to refine solar energy generation forecasts. Simultaneously, increase both the temporal and spatial resolution of weather forecasts to provide more detailed and precise meteorological information. Deliver forecasts at the level of individual Wind Turbine Generators (WTG) and solar panels, elevating accuracy and efficiency in energy generation. Provide intra-hour and hourly forecasts at the farm level to optimize energy production and distribution.

- **Metrics:**
  - Measure the improvement in solar energy generation forecast accuracy achieved through the high-resolution cloud cover prediction model.
  - Assess the enhancement in forecast temporal and spatial resolution and its impact on decision-making in the power sector.
  - Evaluate the accuracy and efficiency gains achieved by delivering forecasts at the individual WTG and solar panel level.
  - Measure the optimization of energy production and distribution based on intra-hour and hourly farm-level forecasts.
- **Timeline:**
  - Commence the development of the high-resolution cloud cover prediction model within the first year.
  - Gradually increase the temporal and spatial resolution of weather forecasts over the following two years.
  - Start delivering forecasts at the individual WTG and solar panel level within the first year.
  - Expand coverage and accuracy in the following two years.
  - Provide intra-hour and hourly forecasts at the farm level within the first year and enhance coverage over the following two years.
- **Risk Assessment:**

- Risks may include data acquisition challenges, computational requirements, and technical complexities in model development.
- Mitigation involves strategic data acquisition, efficient resource allocation, robust testing, and continuous model improvement to ensure the precision of cloud cover predictions, improved resolution, and granular forecasting accuracy.

b) **Advanced Research and Development:** Allocate significant resources to advance research, development, and testing of space-based energy extraction technologies related to weather and meteorology. Collaborate closely with energy companies to create tailored forecasting solutions using Numerical Weather Prediction (NWP) models to optimize energy production.

❖ **Metrics:**

- Measure the progress in space-based energy extraction technology research and development.
- Assess the effectiveness of tailored forecasting solutions in improving energy production and resource utilization.
- Evaluate the integration of space-based energy technologies with meteorological science.
- Measure the impact on reducing greenhouse gas emissions and enhancing energy sustainability.

❖ **Timeline:**

- Initiate research and development efforts for space-based energy extraction technologies within the first year.
- Collaborate with energy companies to create tailored forecasting solutions using NWP models within the first year.
- Continuously enhance and expand these solutions over the following five years.

❖ **Risk Assessment:**

- Risks may include technical challenges in space-based energy extraction and model development, as well as coordination complexities.
- Mitigation involves comprehensive testing, quality assurance, and efficient collaboration frameworks to ensure the success of advanced energy technologies and forecasting solutions.

c) Improvement in Weather forecast: Develop Numerical Weather Prediction (NWP) models that account for specific terrain characteristics, providing location-specific weather forecasts to support renewable energy generation. Focus efforts on improving weather forecasting during the critical monsoon season to enhance preparedness and reduce weather-related risks.

❖ **Metrics:**

- Measure the accuracy of location-specific weather forecasts achieved through tailored NWP models.
- Assess the reduction in forecast errors during the monsoon season.
- Evaluate the impact of improved forecasts on renewable energy generation and risk reduction.

❖ **Timeline:**

- Begin the development of tailored NWP models accounting for terrain characteristics within the first year.
- Focus on enhancing weather forecasting during the monsoon season within the first year.
- Continuously improve and expand these models over the following three years.

❖ **Risk Assessment:**

- Risks may include data availability and complexities in modeling terrain-specific weather patterns.
- Mitigation involves efficient data acquisition, iterative model development, and continuous research to ensure accurate location-specific forecasts and improved monsoon season preparedness.

4.6.6 Monitoring & Forecasting Targets with their possible applications

Prediction horizon	Time ahead	Accuracy target (2035)	Accuracy target (2047)	Applications
Now	0 to 5 min	95%	98%	Managing ramp rates and smart grids, ensuring grid stability
Very short	5 to 30 min	95%	97%	Electricity pricing, control strategies
Short	30 min to 6 h	92%	95%	Economic load dispatching, power scheduling
Medium	6 h to 1 day	90%	92%	Unit commitment, energy storage

				dispatching
Long	More than one day	90%	92%	Maintenance planning, long-term feasibility

4.6.7 Outcome

- **Improved Energy Resilience:** Reduced energy disruptions, enhanced grid management, and efficient energy resource utilization.
- **Sustainable Growth:** Contribution to India's transition to clean and sustainable energy sources, reducing greenhouse gas emissions.
- **Economic Advancement:** Enhanced energy sector productivity, economic growth, and job creation.
- **Global Leadership**: Positioning IMD as a key player in global meteorological and energy services, facilitating international collaborations.
- **Self-Reliance: -** With the development of forecasting models for Demand and RE generation forecasting, IMD may get self-reliance in terms of funds which may be further utilized for other research arm as well.
- **Carbon Market: -** India's Carbon market is likely to be functional in the next 2 to 3 years. So IMD research and modelling for the power sector as well as climate will contribute net Zero target of the Government of India.

4.7 METEOROLOGICAL SERVICES FOR HEALTH SECTOR

4.7.1 Current status and major achievements during the past 10 years

Currently IMD is issuing the forecast in Medium and Extended range time scale for the region that could have malaria transmission suitability. These are based on the WMO-WHO criteria for Malaria and Dengue parasite, based on maximum and minimum temperature is operational in IMD and being practiced. Climate information for coming two weeks is provided for the transmission windows of temperature favourable for development of vector borne diseases like malaria and dengue based on GFS (12 Km resolution) and ERFS (32KM resolution). This has been started in May 2nd week 2017 and is continued on every Friday.

Simultaneously the forecast and warning for temperature tendency, heat wave and cold wave is also being disseminated in short range to extended range time scale. In recent years, Heat index has been prepared and on experimental basis, products are disseminated.

Not just for human health, but also for agricultural health, different products have been developed. Satellite products such as the Normalized Difference Vegetation Index (NDVI), Reference Evapotranspiration and Insolation maps, Vegetation Condition Index (VCI), Vegetation Health Index (VHI), and Temperature Condition Index (TCI) are also produced.

4.7.2 Challenges and Gap Areas

IMD faces various challenges and gaps in its efforts in providing health services. These challenges can hinder its ability to provide timely and effective meteorological support to the health sector. Here are some common challenges and gaps:

- Limited integration of meteorological data with health data and challenges in sharing data between meteorological and health agencies hinders the development of accurate early warning systems.
- Inaccurate or insufficient meteorological data, especially in remote or under-resourced areas, can result in unreliable weather-related health forecasts.
- Limited capacity and expertise within meteorological departments to understand and respond to health-related meteorological challenges.
- Ineffective communication of weather-related health risks to the public can lead to reduced awareness and preparedness.
- Limited financial and human resources hinders the development and maintenance of meteorological services related to health.
- The long-term impacts of climate change on health are complex and require ongoing research and adaptation efforts.
- Ensuring that meteorological information is integrated into the healthcare system's decision-making process can be challenging.
- Engaging communities in weather-related health preparedness and resilience-building can be difficult.

- Collaborating with international organizations and sharing data globally can be hindered by logistical and political challenges.
- Keeping pace with rapidly evolving technology and modeling advancements in meteorology is essential to providing accurate forecasts and warnings.
- Assessing the effectiveness of meteorological services related to health and gathering feedback for continuous improvement can be overlooked.

4.7.3 Short-term Vision (next two years)

- IMD should focus on improving the integration of meteorological data with health data to create more accurate and timely weather-related health forecasts and warnings.
- IMD can launch public awareness campaigns to educate the public, healthcare professionals, and policymakers about the health impacts of weather and climate, including heat stress, air quality, and disease outbreaks.
- IMD can develop and implement heat and cold stress advisories to protect vulnerable populations during extreme temperature events, providing guidance on staying safe in hot summers and cold winters.
- IMD can also invest in strengthening air quality monitoring networks and provide real-time air quality information to healthcare providers and individuals with respiratory conditions.
- IMD can also start to integrate chemical transport model (e.g., SILAM, WRF-Chem) to air quality data with epidemiological models.
- IMD can also invest AI/ML techniques to integrate meteorological/air quality data with epidemiological data.

4.7.4 Medium-term Vision (next ten years)

- IMD should focus on improving the integration of meteorological data with health data to create more accurate and timely weather-related health forecasts and warnings. The forecast accuracy will be improved by 40% for the base year of 2024.
- IMD can develop comprehensive early warning systems that integrate meteorological data with epidemiological models to predict and respond to disease outbreaks influenced by climate factors.
- The augmentation of meteorology and health sector applications involves integrating meteorological data and health information to predict, prevent, and manage health issues influenced by weather and climate. This synergy leverages advanced technologies, such as AI, IoT, and big data, to create solutions that improve public health outcomes.
- IMD can develop and implement of seasonal health trends, climate change and long-term health risks.
- IMD can run GFS and ERFS models at higher resolution (e.g., 6KM for GFS and 12KM for ERFS) to integrate meteorological data with epidemiological models.
- IMD can also run WRF model at higher resolution (e.g., 1KM) to integrate meteorological data with epidemiological models.

- Establishment of strong collaboration with stakeholders (for health) for gaining more information on disease outbreak and simultaneously gathering the line list of data to have better study.
- Creation of health profile based meteorological sub divisions to identify the hotspot region for particular diseases and need for the development of meteorological threshold.
- IMD can enhance the collaboration with the healthcare sector to assess and enhance the resilience of healthcare facilities to extreme weather events, ensuring they can continue to provide critical services during emergencies.
- IMD can invest more in research and innovation projects to better understand the complex relationship between weather and health, leading to the development of new technologies and strategies for health protection.
- IMD can implement community resilience programs that empower local communities to prepare for and respond to weather-related health threats, including training for healthcare workers and first responders.
- IMD can also start to run a global chemical transport model (e.g., GEO-Chem, Global SILAM) at 12 KM resolution to integrate meteorological data with epidemiological models.
- IMD can also start to run chemical transport models (e.g., SILAM, WRF-Chem) at higher resolution (e.g., 1KM for SILAM and WRF) to integrate air quality data with epidemiological models.
- Augmenting meteorology and health sectorial applications, societies can better address the growing challenges posed by climate change, extreme weather, and environment-linked health risks.

4.7.5 Vision 2047

- IMD should focus on improving the integration of meteorological data with health data to create more accurate and timely weather-related health forecasts and warnings. The forecast accuracy will be improved by 80% for the base year of 2024.
- IMD can develop comprehensive long-term strategies to address the health impacts of climate change, including strategies to mitigate the spread of vector-borne diseases, address food and water security, and protect vulnerable populations.
- IMD can forge strong international partnerships to share data, knowledge, and best practices, creating a global network of meteorological and health organizations focused on improving global health resilience.
- IMD can invest more in cutting-edge technology and predictive models that can forecast weather-related health risks with greater accuracy and granularity, allowing for more targeted interventions.
- IMD can establish educational programs and workforce development initiatives to train the next generation of meteorologists and health professionals who can work collaboratively to address weather-related health challenges.

- IMD can also start meteorological/chemical transport models at city level as well as street level to integrate meteorology/air quality data with epidemiological models.
- Better informed decision making with IMD monitoring and predicted data and information could ensure early action leading to reduction of mortality and morbidity, better health for human and live strain, better productivity and economy, sustainable development.

4.7.6 Strategy

This comprehensive strategy aligns the efforts of IMD with the goal of safeguarding public health in the face of weather-related challenges, helping to create a more resilient and informed society. It emphasizes collaboration, data-driven decision-making, and a proactive approach to emerging health threats influenced by meteorology.

4.7.7 Outcome

Overall, the outcomes of IMD involvement in the health sector include improved public health, reduced health risks, and a more resilient healthcare system. These outcomes contribute to a safer and healthier environment for individuals and communities, ultimately enhancing the quality of life for all influenced by meteorology as well as climate change.

4.8 POSITIONAL ASTRONOMICAL SERVICES

4.8.1 Current status and major achievements during the past 10 years

- Playing a successful role as a nodal office in preparing the National Calendar and festival fixing, catering to the plurality and diversity of the country upholding the spirit of the Constitution of India.
- Production of scientific data through in-house codes, liaising of external experts of customs & traditions of the country and publication of Rashtriya Panchang in every year in 14 different languages.
- Computation of data through in-house codes and Publication of yearly Indian Astronomical Ephemeris in English as one of only 8 countries in the world.
- Unhindered, timely Publication of Rashtriya Panchang and Indian Astronomical Ephemeris during unprecedented COVID period successfully.
- Publication of some research papers by some individual.
- An M.Tech. (Astronomical Instrumentation) student of Indian Institute of Astrophysics did a project on variable star and another student did Ph.D. on atmospheric science.

4.8.2 Challenges and Gap Areas

- Regarding Rashtriya Panchang: To streamline each and every element of Rashtriya Panchang conducting workshop/ seminar in every two years with Panchang makers (Pandits) from different parts of the country.
- Regarding Indian Astronomical Ephemeris: Necessary measures will be required to maintain the standard of the Indian Astronomical Ephemeris at per with the International Astronomical union recommendation from time to time.
- Transformation of computer platform and develop programmes for preparing Rashtriya Panchang and Indian Astronomical Ephemeris in more diligent way in phase.
- Take up Astronomy popularization programme.
- Train the young generation in computer and astronomy.
- Involve scientific manpower of PAC for research and development in astronomy-astrophysics and related fields.
- To start collaborative research works with public & private academic institution.

4.8.3 Short-term Vision (next two years)

- To train new scientific officials in work of PAC.
- To train all scientific officials in Linux and suitable computer programming language.
- To train all scientific officials in astronomy & astrophysics at least at basic level.

- To train all scientific officials in astronomical data handling and astronomical observational techniques.
- To start at least basic level research.
- To start public outreach programme again.

4.8.4 Medium-term Vision (next ten years)

- To change all the programmes which will be required for making Panchang and Indian Astronomical Ephemeris in Linux platform and a suitable language.
- To take care of the relativistic corrections which will be required for Indian Astronomical Ephemeris.
- To start research independently/with collaboration in the emerging field of astronomy relativistic astrophysics and astro-meteorology etc.
- To scatter literacy in astronomy all over the Indian subcontinent. In this regard, the target audience will be mainly school & undergraduate students.

4.8.5 Vision 2047

- To set up one or two astronomical observatories in India at suitable places or locations.
- To start observational research work in astronomy.
- Publication of Rashtriya Panchang and Indian Astronomical Ephemeris will be fully automated.
- More focus on space dynamic research to help different space agencies public or private in consultancy basis.
- To develop different atmospheric parameters with astronomical origin by which forecast of meteorological events will be more elegant.
- To start research independently/with collaboration in Ancient India astronomy
- To start different departments like (a) Astrometry, (b) Dynamical Astronomy, (c) Ancient India astronomy, (d) Astronomical publication, (e) Public outreach programme.

4.8.6 Strategy

- Promote phase wise training programme/workshop in astronomy, astrophysics, computer science and allied field.
- Promote distinctive research programmes that address the real life as well as futuristic issues of the country along with globe.
- To develop infrastructure of the centre to support work environment.
- To develop work environment more interesting for the workforce.
- Involve college/university students through observational programme, workshop, popular lectures and project work etc.

- Encourage officials for pursuing higher study, i.e. Ph.D. etc.
- Enhancement of scientific manpower having astronomy/ astrophysics background through recruitment in phase manner.

4.8.7 Outcome

- At the end of two years all the scientific officials become proficient in astronomy and Computer Science and some other allied subjects and capable of doing works of the centre with help of the seniors.
- At the end of ten years officials become capable of doing research work in astronomy astrophysics and allied fields of their own. They will also undertake work of the centre independently. Centre will be able to give inputs to Meteorologists regarding forecasts.
- Centre will be able to supply astronomical data on real time basis to the space agencies.
- Centre will be able to collaborate with other organizations for nuclear fueled rocket design to "Make in India".
- Centre will become global leader in the field of astronomy-astrophysics research.

Chapter 5 Climate Modeling and Services

5.1 CLIMATE MODELING

5.1.1 Current status and major achievements during the past 10 years

Climate modelling, a discipline deeply rooted in the principles of physics and mathematics, has experienced a remarkable evolution over the past several decades. The mid-20th century marked a significant turning point with the advent of numerical weather predictions. The scientific community capitalized on the growing computational power to anticipate short-term atmosphere variations and set the stage for a more data-driven approach to climate study. The late 20th century further pushed the boundaries of climate modelling with the emergence of Earth System Models (ESMs). India has also significantly developed climate modelling during the past decade. Under the Monsoon Mission program, operational dynamical prediction systems have been developed that provide seamless weather and climate forecasts at various temporal scales such as the short to medium range (up to 10 days), extended range (up to 2 weeks) and seasonal forecasts (1-4 months). To reduce the uncertainty of climate model forecasts, IMD recently introduced the Multi-Model Ensemble (MME) method for operational long-range forecasts using various climate model outputs around the globe. The present version of IITM-ESM 2.0 significantly improved in simulating the tele-connection of the Indian summer monsoon with sea surface temperature.

5.1.2 Challenges and Gap Areas

Currently, there are several challenges and gap areas to limit the quality of the climate forecast:

- There are incomplete representations of ocean circulation, especially deep ocean processes, sea ice dynamics, and interactions with the atmosphere. There are still limitations in simulating the Indian Ocean dynamics in models, which makes predicting Indian Ocean SST and associated monsoon rainfall challenging.
- There are still improvements needed in predicting the Monsoon Intra-seasonal Oscillation (MISO) active and break spells in Extended Range Predictions (As reported by Borah et al., 2015, Abhilash et al., 2012, 2013, 2014)
- There is difficulty in accurately modelling and predicting the intensity and location of extreme heavy rainfall events (e.g. intense rainfall events occur in the city)
- There are insufficient high-resolution models for effectively simulating local features and phenomena. Despite growth in computational capabilities, demands for more detailed and coupled models pose computational challenges.
- Most of the climate models can still not represent the correct type of precipitation (stratiform or convective), and this is due to inaccurate simulation of Convective Available Potential Energy (CAPE) values in models. Therefore, additional

enhancements to convective parameterization schemes are necessary to align CAPE values with observations better.

- The simulation of the Low-Pressure System and associated rainfall over India still needs to be improved in most models for a better seasonal prediction of monsoon.
- The systematic errors in the climate models need to be addressed in improving the seasonal forecasts.

Each of these points highlights a specific gap in the current state of climate modelling, emphasizing the need for focused research and development efforts to address these challenges, particularly in the context of India's unique climate concerns. Also, currently, we do not have an integrated forecasting system (IFS), which is normally used in the leading climate centres in different parts of the globe. Although, at this moment, IMD is not involved in developing the climate models, it is important to know the challenges associated with its operational forecasting. This will also help if the situation arises that IMD may involve in developing climate models.

5.1.3 Short-term Vision (next two years)

To develop impact-based climate forecasts to support adaptive planning**.** Effective communication of uncertainty has become integral to enhancing the usability of impact-based forecasts. Effectively communicating uncertainty in impact-based forecasts involves employing several essential strategies. Firstly, using probabilistic language such as stating, "There is a 70% chance of heavy rainfall" rather than giving deterministic statements helps convey uncertainty clearly. Secondly, presenting a range of possible outcomes based on forecast uncertainties, such as "Rainfall totals may range between 50-100 mm," provides decision-makers with a clearer picture of potential scenarios. It is crucial to articulate confidence levels in the forecast, like indicating "High confidence in temperature forecast, lower confidence in the timing and intensity of rain," to guide users on reliability. Visual tools like charts and graphs are invaluable for illustrating uncertainty, showing probability distributions or ensemble forecasts. Explaining sources of uncertainty, such as model limitations or data gaps, helps users understand the factors contributing to unpredictability. Regular updates based on new data or changes in confidence levels ensure information remains current and reliable. Finally, educating stakeholders about forecast uncertainty fosters trust and enables informed decision-making. Together, these strategies empower decision-makers and the public to navigate uncertainties effectively and make informed choices based on forecast information. At the same time, implementing real-time monitoring of climate model forecasts is necessary. Developing the climate indices suitable for the region (Index analog method) is important, which is helpful in understanding the operational forecast.

5.1.4 Medium-term Vision (next ten years)

- ❖ Improve the accuracy of climate models over various geographical regions and introduce state-level or sub-division-level climate forecasts.
- ❖ Aim to achieve accuracy, targeting 70% reliability in long-range forecast at least 6 months lead time.
- ❖ Incorporate additional forecast parameters such as ocean currents, thermocline depth, heat fluxes, wind fields, sea level pressure, vertical temperature profile, relative humidity, and Atmospheric Angular Momentum (AAM), as these govern the interactions of equatorial and subtropical waves across latitudes.
- ❖ To improve the spatial and temporal resolution of the climate models and introducing annual and decadal climate forecasts.
- ❖ Machine learning techniques will play a larger role in climate modelling. AI and ML can help analyze massive datasets, identify patterns, and improve model performance, especially in areas like weather prediction and climate pattern recognition.
- ❖ Climate models depend on accurate data and observations. Over the next decade, we can expect improvements in data collection and observational capabilities, enhancing the accuracy and reliability of models.
- ❖ Climate models like ESM will increasingly incorporate the various components of the Earth system, including the atmosphere, oceans, land, ice, and biogeochemical cycles. This holistic approach will provide a more comprehensive understanding of the Earth's climate system.
- ❖ To investigate different climate predictions and their impact on society for an improved decision-making process

5.1.5 Vision 2047

- ❖ To continue research to make the climate models up to date with the latest scientific advancements and understanding.
- ❖ To develop district-level and city-level impact-based climate forecasts. To develop tools to assess the risks associated with different climate forecasts and projections to help in the decision-making process

5.1.6 Strategy

- ❖ Develop new sets of climate models with high resolution and improved physical parameterizations for seamless weather and climate forecasts at various temporal scales such as the short to medium range (up to 10 days), extended range (up to 2 weeks) and seasonal forecasts (1-4 months). The idea of seamless prediction, whereby a single model family can be used for prediction across a range of time scales, is a key strategy for weather and climate forecasting. A key benefit of such a system is that it allows us to learn about climate model performance and errors. This approach not only enhances the accuracy and reliability of forecasts but also facilitates a deeper understanding of model behaviours and uncertainties, crucial for improving future predictions.

Implementing a Seamless Forecasting System at IMD entails a comprehensive approach integrating advanced technology, scientific innovation, and national/international collaborative partnerships. This involves developing high-resolution models capable of dynamically adjusting the resolution to focus on specific areas of interest, such as urban centres or coastal regions while refining model physics to simulate complex climate processes accurately. Integration of the Earth System Models (ESMs) will provide a holistic understanding of climate interactions across the atmosphere, oceans, land, and biosphere. Operationalization will include continuous validation against observational data and implementing ensemble forecasting to quantify uncertainties.

❖ Improving and operationalizing the various climate forecasts by Indian-origin models using high-performance computing and technologies such as AI/ML, cloud computing and trained manpower need to be prioritized. AI and machine learning techniques will be pivotal for data assimilation, pattern recognition, and optimizing model performance, ensuring more reliable forecasts and probabilistic assessments.
❖ Downscaling coarse resolution future climate projections is crucial for devising effective adaptation strategies across various sectors. Statistical downscaling techniques leverage relationships between large-scale climate variables and local-scale observational data, offering detailed insights into temperature, precipitation patterns, and extremes. This approach supports sectors like agriculture, water resources, and urban planning by assessing impacts on crop yields, water availability, and infrastructure vulnerabilities at a local level. Dynamic downscaling, using high-resolution regional climate models driven by global models, provides fine-scale projections essential for disaster management and renewable energy planning sectors, detailing local climate variables and storm patterns.
❖ It is important to develop collaboration between climate scientists, policymakers, and different stakeholders to integrate climate modelling into climate action plans. Tailor climate models to provide local climate predictions, helping communities prepare for local or regional challenges

5.1.7 Outcome

The "Vision for 2047 in Climate Modelling" outlines several potential outcomes for the IMD, such as enhanced forecast accuracy, Advanced Technological Integration, and Operational Improvements. Here are the key points:

❖ By developing integrated forecasting systems that cover local to global scales, IMD can enhance predictive accuracy and reliability. This will enable more precise and actionable weather and climate forecasts.

- ❖ Creating high-resolution forecasts up to district and block levels will improve the granularity of predictions, aiding local decision-making and preparedness.
- ❖ Developing impact-based climate model predictions will help provide specific services at the block level, enabling better disaster management and adaptive planning.
- ❖ Leveraging AI and machine learning for data-driven insights will enhance climate forecasts and make them more accurate and reliable. This includes better pattern recognition and optimization of model performance.
- ❖ Integrating ESMs will improve the representation of climate interactions across various components of the Earth system, providing a holistic understanding and better simulation capabilities.
- ❖ Implementing real-time monitoring of climate model forecasts will allow for timely updates and adjustments, improving forecast reliability.
- ❖ Enhancing physical parameterizations in models will address current limitations and improve the accuracy of various climate predictions, particularly for phenomena like monsoon rainfall and extreme weather events.
- ❖ Improvements in data collection and observational capabilities will provide more accurate and reliable input for climate models, enhancing their overall performance.
- ❖ Strengthening national and international collaborations will facilitate the exchange of knowledge and technologies, improving the overall quality of climate forecasting in India.

By focusing on these outcomes, IMD can significantly enhance its capabilities in climate modelling and forecasting, contributing to improved socio-economic resilience and sustainable development in India.

5.2 CLIMATE SERVICES

5.2.1 Background

Climate services refer to the systematic provision of information and data about climate-related factors, trends, and projections to support decision-making and planning across various sectors. These services aim to help individuals, communities, businesses, and governments better understand and respond to the impacts of climate variability and change, enabling them to make decisions accordingly. On June 4, 1886, Sir H. F. Blanford, the Imperial Meteorological Reporter in India and the founding head of the IMD in 1875, issued the first operational seasonal forecast for Indian summer monsoon rainfall, encompassing the entire region of India and Burma. This may be treated as an example of initiating a climate service in India. Since then, the operational seasonal forecasting system in India has evolved significantly in its approach and scope. Over the years, climate services in India have progressed to meet the increasing demand for the precise and timely delivery of climate-related information.

After the 3rd WMO World Climate Conference held in 2009, a considerable thrust was noticed in climate services in different countries. In the last decade, with the improvement in climate models and enabling high-performance computing technology-based solutions, climate service has entered a new epoch, with emphasis given to improving product outreach to the user sector. The delivery of climate service is always a challenging task and requires constant thrust to improve technology-driven solutions. The climate forecast has inbuilt intrinsic uncertainty due to errors in long series observations, initial conditions database, and of course, model limitations. This must be always kept in mind while the long-time projections are derived. Though there has been significant improvement in all these factors over a period of time, still the climate scientist always needs to be very humble in his/her approach while arriving at very firm conclusions/remarks about climate projections. The advances in modelling capability are striving to provide more useful and actionable information such as for anticipating impactful events, including heat waves, cold spells, intense precipitation, coastal inundation and tropical storms. The document below provides a vision for the development of IMD's climate services.

In 2017, under the Global Framework for Climate Services (**GFCS**), IMD established a new office named the Climate Research and Services Division in Pune. This office was created by merging various divisions and other offices in Pune with the aim of improving the quality of climate services. The key services presently offered by this office encompass operational long-range forecasting and its verification, climate monitoring, preparation of annual and seasonal climate statements and reports, revision of climate normal, creation of climate applications for sectors such as agriculture, disaster risk reductions, water, health, and energy, provision of long-time scale quality-controlled climate data sets, and capacity building in the field of climate sciences and services. Climate services are the provision to use the climate information to improve society's resilience to climate-related risks.

5.2.2 Current status and major achievements during the past 10 years

The climate services globally and in the country have undergone a sea change in the last ten years as far as the science, modelling and observational data sets are concerned. However, the same momentum could not be achieved in the outreach sector and in developing the desired level of confidence among the user group. Though this part is yet to gain its full momentum, the various programs on climate awareness and their impact projections conducted by the government and different agencies, are now picking up. Current climate services in IMD are now migrating from the conventional era to the modern technology-based era, which is tailor-made to address the needs of stakeholders from various user sectors. Some major achievements are:

- ❖ Expansion of observational network, both ground-based and upper air, has been taken up in mission mode under different schemes of the Ministry, like ACROSS and quality of data collection, model assimilations and visualization have improved over a period of time.
- ❖ The Climate services now primarily depend on state-of-the-art global climate monitoring and prediction systems guidance. Development of an integrated multi-model-based forecasting system for the monsoon season and other seasons has recently started in IMD, and the results are encouraging. Still, it would take some more time to improve upon it.
- ❖ The projects like Monsoon Mission are helping researchers in the country and outside for atmosphere-ocean coupled model system runs and to aggregate the outputs
- ❖ Development of climate statistics on various spatio-temporal scales with a focus on extreme events
- ❖ Development of district level vulnerability assessments related to meteorological disasters.
- ❖ As a Regional Climate Center (RCC) recognized by WMO, IMD Pune provides state of the art seasonal outlook to neighbouring countries under the SASCOF framework. Recently, the recognition of RCC Pune as Global Producing Center (GPC) by WMO is a major achievement.
- ❖ In line with GFCS by WMO, IMD as NMHS in the country, has taken up the initiative to establish NFCS-India for improved climate services at the national level. This initiative is aimed at bringing all climate service-related stakeholders, users, policymakers, industries, and the general public under one structured umbrella of CSIS (Climate Service Information System) India.
- ❖ Use of climate information for generating different applications in the sectors of Health, Power, Agriculture, etc. This further needs development with closed-loop data feedback from users.
- ❖ Monthly El-Nino-related updates in the form of bulletins.
- ❖ Capacity building in climate services has been taken up in IMD by WMO recognized Regional Training Centre (RTC) at Pune, with specially designed course contents and experts.

5.2.3 Challenges and Gap Areas

IMD plays a crucial role in providing a wide array of climate services tailored to various user sectors. These services are indispensable for informed decision-making in sectors ranging from agriculture and water resources to disaster management and urban planning. However, despite our commendable efforts, there are certain critical areas where our climate services exhibit gaps. Some of the notable gap-areas include:

- **User-Centric Design:** Climate services should be designed with end-users in mind, ensuring that information is presented in a format that is easily understandable and applicable to their specific needs. This requires active engagement with the user community to identify their priorities and preferences. IMD currently operates in this manner to provide climate services, but it requires further enhancements and regular engagement with users.

- **Need of Localized and high-resolution Data**: The existing datasets owned by IMD contain meteorological variables ranging from station-level measurements to broader regional scales. However, a significant challenge arises from the non-uniform distribution of these data points. Across different parts of the country, there is an evident imbalance in the number of observatories; some regions are densely monitored, while others are sparsely covered. Moreover, not all observatories record crucial meteorological variables, creating gaps in our understanding of local climates. This data disparity underscores a critical need for more localized and granular information tailored to specific geographical areas. Such detailed insights are very important for informed decision-making at a local level. Therefore, a concerted effort to enhance data collection and analysis at a micro-level is very much essential.

- **Integration of Multi-Sectoral Data and Development of a Database:** The integration of multi-sectoral data plays a pivotal role in comprehending and effectively addressing the far-reaching impacts of climate change. Recognizing the pressing need for collaboration and knowledge-sharing, IMD has embarked on an ambitious endeavour to establish a collaborative platform with diverse user sectors and agencies. The primary objective is to forge a comprehensive multi-sectoral database that can serve as a foundation for informed decision-making and policy formulation. However, a substantial challenge lies in the fact that many of these sectors lack standardized methods for data collection and robust archival systems. This data deficit not only hampers immediate responses to climate-related issues but also delays long-term planning and policy development. It is imperative to recognize this critical gap in our approach to climate resilience.

- **Implementation of effective visualizations in climate services:** Visual communication plays a pivotal role in climate services, helping to make complex climate information accessible, engaging, and actionable for a wide range of audiences. It complements textual and numerical information, allowing for more effective communication of climate-related issues and encouraging informed decision-making and action. Presently, IMD employs various data visualization techniques utilizing tools like Python and GIS. This practice should not only be endorsed but also broadened, with a focus on keeping these visualizations up-to-date using the most current available technologies minimizing manual interventions.

❖ **Enhancing the Feedback Mechanisms for Continuous Improvement**: While IMD has made commendable strides in implementing feedback mechanisms for the data and climate services, there remains a pressing need for expansion and refinement. These existing mechanisms, though valuable, may not be sufficient in capturing the demands and preferences of diverse users. Hence, it is crucial to strengthen and broaden these channels through the utilization of novel feedback methods and available technologies, aiming to engage a broader spectrum of perspectives.

❖ **Inclusivity and Accessibility:** Climate services should be accessible to a wide range of users, including those with varying levels of technological access and literacy. Ensuring inclusivity requires developing user-friendly interfaces and considering the needs of marginalized and vulnerable communities.

❖ **Capacity Building and Training for the Users:** Many users may lack the necessary skills and knowledge to interpret and utilize climate information effectively. Capacity-building efforts are required to empower users to make informed decisions based on available climate data.

5.2.4 Short-term Vision (next two years)

❖ **Further improving the observational data sets and integration:**

- IMD as NMHS needs to further take up for expansion of the observational network in the country, with sector use approaches for DRR, Urban, Agriculture and food security, health, air quality and more. Also, integration of the other observational networks from different agencies in the country is also needed.

❖ **Implementation of National Framework for Climate Services for India**

- Engage relevant stakeholders including government agencies, research institutions, NGOs, the private sector, and local communities, to ensure a coordinated approach toward the National Framework for climate services.

❖ **Advanced Climate Modelling**

- Develop and deploy high-resolution regional climate models tailored to Indian sub-continental conditions.
- Integrate climate models with socio-economic data to provide impact assessments on sectors like agriculture, water resources, and health.

- Enhancing climate forecasting accuracy and expertise to match institutions like ECMWF, JMA and the Bureau of Meteorology, Australia, is a priority. This involves advancing forecasting techniques and capabilities to achieve comparable levels of precision and skill in climate predictions.

❖ **Public-Private Partnerships**

- Foster collaborations with private sector entities for innovative climate solutions, such as climate-resilient technologies, insurance products, and sustainable infrastructure.

❖ **Enhancing the current National Data Centre by incorporating additional data visualization tools and expanding the array of available statistics.**

- This enhancement will empower policymakers, analysts, and researchers with a dynamic platform, enabling them to dissect complex information with unprecedented clarity and efficiency.

❖ **Tailored Climate Information**

- Provide specialized climate information for key sectors (e.g., agriculture, water management, disaster preparedness) with a focus on vulnerability and adaptation similar to Climate explorer by the Royal Netherlands Meteorological Institute. Additionally, it will generate reanalysis data specifically tailored for the Indian or broader Asian region, akin to the NCEP-NCAR Reanalysis.
- Develop user-friendly platforms for delivering climate information, including web portals, mobile apps, and SMS services.

5.2.5 Medium-term Vision (next ten years)

❖ **Downscaling of climate models to higher resolution:** Most of the climate model projections run into resolution of order of 100 kms and hence using them directly for regional level is not possible. The down-scaling of global models to a higher resolution of 10-50 kms (CORDEX) needs to be carried out for improved projections at regional levels.

❖ **Development of Climate adaptation strategies through close collaborations with governmental bodies, NGOs, and local communities:** Provide evidence-based climate information to support policy formulation at national and regional levels. And to take the governance in confidence for implementation of the same. Advocate for climate-resilient policies, including adaptation strategies and sustainable development goals.

❖ **Enhance Climate Monitoring services:** Employ advanced technologies, high computing facilities and remote sensing systems to provide real-time, high-resolution data on atmospheric conditions for different climate variables. The new approaches like AL-ML also needs to developed strongly along with NWP approach.

- ❖ **Community Engagement and Awareness:** Conduct outreach programs, workshops, and seminars to raise climate awareness at the grassroots level. This point would be common for 2 and 10 years

  Engage with local communities, NGOs, and civil society to co-create solutions for climate resilience

- ❖ **Enhancing Capacity Building and Training:** Upgrade the existing training curriculum for IMD personnel, government officials, researchers, and the general public in climate services and data analysis.

  Cultivate partnerships with universities and research organizations to push forward climate research and its practical applications.

- ❖ **Monitoring and Evaluation:** Create a strong monitoring and evaluation framework to measure progress towards established goals and adjust strategies in response to feedback and insights gained from experience.

- ❖ Achieve **25 km** resolution for global seasonal forecast models to improve the precision of seasonal climate forecasts.

- ❖ Achieve **4-6 months** lead time for accurate seasonal predictions, with skilful forecasts of temperature and precipitation anomalies for the upcoming season.

- ❖ Implement early warning systems for extreme seasonal events like floods, droughts, or heatwaves, ensuring proactive responses.

- ❖ Strengthen the application of seasonal forecasts in key sectors like agriculture (e.g., crop planning), water resources (e.g., flood and drought management), and health (e.g., heat stress and vector-borne disease prediction).

- ❖ Develop updated seasonal indices for the ENSO and Indian Ocean Dipole (IOD) to account for long-term global sea surface warming.

5.2.6 Vision 2047

The short and the medium-term mission objectives will provide the pathway for vision 2047. Beyond ten years the climate service will work on the mission 2047 objective. The short- and medium-term objectives are aimed to transform climate services in India, providing timely, precise, and easily accessible information to empower communities, policymakers, and industries in their efforts to adapt to and combat climate change. In the long term, climate services will focus on

- The improved integration of climate services with artificial intelligence for 360-degree digital convergence. Every locality and urban community would have its own model and observation system.

- Development of climate information-controlled food and agriculture industry to reduce damage impact due to extreme events. Development of sector-specific climate services with a focus on individualistic solution-based collective and individual information models.
- Integrating Climate services to National Adaptation policies and plans on different customizable administrative boundaries.
- Self-reliant climate monitoring services and public information dissemination in personalized kiosk. User can customize the product themselves.
- Disaster Management: Multi-hazard disaster management and advisories.
- Weather and climate Modification: Customized geo-hazard reduction technology over different regions as per requirement, fog and pollution dispersion in city level, block level etc.
- Achieve **5-10 km** resolution for global seasonal forecast models to improve the precision of seasonal climate forecasts.
- Extend lead time for reliable forecasts to **6-9 months** for seasonal predictions, with the capacity to predict extreme events such as droughts, floods, and heatwaves several months ahead.
- Deliver fully integrated seasonal climate services that provide forecasts, monitoring, and scenario analysis for various sectors. These services will be highly interactive and allow users to model the potential impacts of different climate scenarios on specific regions and sectors.
- Enable proactive seasonal risk management for sectors, particularly in vulnerable regions, by incorporating seasonal forecasts into long-term adaptation and mitigation strategies.
- Deliver high-resolution seasonal forecasts at both regional and local levels, focusing on highly localized predictions for temperature, rainfall, and extreme events.
- Provide integrated seasonal products that predict compound extreme events (e.g., simultaneous droughts and heatwaves), supporting decision-making for sectors like agriculture, disaster management, and infrastructure planning.

5.2.7 Evaluation of Climate Services and Key Performance Indicators

It is important to keep an evaluation mechanism and develop performance indicators for each solution. Hence performance indicators are to be devised. Some important performance indicators are given below.

- Number of the quality-controlled climate data sets and network improvements.
- Improvement in accuracy and lead time of climate forecasts.
- Number of trained personnel in climate services.
- Number of successful public-private partnerships established.
- Number of impactful climate research publications and innovations.
- Reduction in disaster-related fatalities attributed to improved early warning systems.
- Number of climate-informed policies adopted.
- User satisfaction and feedback ratings

Chapter 6 Data Communication and Warning Dissemination

6.1 DATA COMMUNICATION

6.1.1 Current status and major achievements during the past 10 years

The current data communication infrastructure of IMD facilitates real-time exchange of meteorological data and weather products for national and international users. It manages IT systems for data processing, storage, and workflow integration. Additionally, it operates the WMO-recognized ICITC in New Delhi to train personnel in meteorological telecommunications.

The existing Regional Telecom Hub (RTH) switching system "TRANSMET" is the state-of-the-art technology system. It has two Separate Automatic Message Switching System (AMSS) for National and International data exchange, each works in hot standby mode for 100% redundancy.

6 Mbps Regional Meteorological Data Communication Network Next-Gen (RMDCN-NG)link handles 6 circuits viz. Tokyo, Moscow, Beijing , Germany, Exeter and Toulouse.

46 IMD stations are connected with MPLS VPN connectivity speeds ranging from 512 kbps to 10 mbps. These VPN circuits are connected with forecasting Systems at various out stations, Doppler Weather Radar Stations, AMSS Centres and Regional Centres.

IMD has Internet leased links of 450 Mbps and 1 Gbps for internet and data exchange. Various types of data such as surface, upper air, Radar, satellite, Air quality etc. are being exchange national and international level.

Surface data are being collected both manually and through Automatic Weather Stations (AWS) & Automatic Rain Gauge (ARG). AWS and ARG data are being quality checked as per World Meteorological organisation guideline before exchange on GTS.

At present, minimum data reception frequency is once every 15 mins interval for AWS and ARG data with latency 10 mins. Manual observational data is every 3hours with latency 20 mins and upper air data is every 6 hours with latency 20 mins. Daily Total volume of data is being exchange per day is 17 TB.

Satellite and Radar data is being shared with National Centre for Medium Range Weather Forecasting (NCMRWF)through National Knowledge Network (NKN) NKN CUG and Internet.

India Meteorological Department Issues Global Maritime Distress and Safety System (GMDSS) bulletins for Met. Area VIII (N). BSNL Ghaziabad Earth Station uplinks this information to INMARSAT for broadcast to all ships on high seas in Met Area VIII (N).

Automation of various types of bulletins such as all India weather bulletins, coastal weather bulletins and sea area bulletin for all CWC/ACWC.

Under the frame work of WMO Information System (WIS), Global Information System Centre (GISC) New Delhi is operational from since 2016. This can be access through url http://wis.imd.gov.in. IMD has deployed WIS 2 Box and integrated SYNOP data, TEMP data and Satellite data. The URL is https://wis2box.imd.gov.in

IMD has Online Meteorological services for airlines through dedicated Online Briefing System (OLBS).

IMD has in-house WebGIS based Decision Support system for forecaster, which provides a single window solution for visualization and decision making for upcoming weather and its impact by integrating all kinds of data like observation, radar, satellite, upper air, Surface, Marine, Numerical Weather Model data, exposure etc.

The India Meteorological Department (IMD) currently utilizes GIS (Geographic Information System) technology to collect, integrate, and visualize geospatial data for weather forecasting and hazard preparedness. GIS plays a vital role in generating graphics for warnings and bulletins related to cyclones, heavy rainfall, thunderstorms, floods, and other severe weather events. By overlaying satellite imagery, weather models, and observational data—both present and historical—GIS enables effective monitoring and visualization. Impact-Based Forecasting (IBF) is developed for severe weather events, incorporating socio-economic data to assess potential impacts. Real-time hazard monitoring is supported through GIS using remote sensing, and crowd-sourced data. The GIS is instrumental in analysing exposure and vulnerability by overlaying hazard zones with socio-economic data, providing quantifiable insights that help prioritize emergency responses. Additionally, IBF leverages GIS to model potential impacts and generate tailored early warnings, enabling decision-makers to simulate evacuation plans, risk reduction strategies, and resource allocation.

India Meteorological Department has launched its Crowd source web interface and mobile App to allow users to report their observations of weather phenomenon like Rain, Thunder/lightning, Hailstorm, Dust storm, Fog, Snow, Gusty wind and the associated damage.

IMD has also implemented video conferencing solution for all offices

The 10 Gbps optical fibre backbone support is being used to provide high availability of Local Area Network (LAN) as well as high volume of data flow IMD HQ.

The video wall system has been installed in all forecasting offices of IMD for visualization of weather observations, forecasts and products.

IMD launched its first major e-Governance initiative on July 27, 2008, with the creation of METNET, an intra-IMD portal developed in-house. METNET enabled the sharing of administrative information, including office orders, circulars, notifications, and more, across IMD locations which has improve in document management, transparency, and operational efficiency.. Key features included:

E-Service Book: Digitization of the service book for all IMD officials across India.

- Online Leave Management: Integrated with NIC’s Biometric Attendance System, this module streamlined leave applications and records.
- IMD-ATITHI: An online guest house booking platform.
- IMD e-AWAS: A unified housing allotment system.
- Visitor Management System: Generates digital gate passes for visitors.

- Directory and Administrative Systems: Contains searchable directories and centralized e-administration support systems for promotions, transfers, training, and more.
- Additional Modules: Budget and accounts management, court case tracking, inventory and library systems, and secure API-based user authentication for online applications.

On January 1, 2021, IMD implemented NIC's eOffice Lite (eFile) system, with 3,500 users actively using the platform across all IMD offices. This eOffice system has led to a complete transition to electronic filing, with over 40,000 files and 2,00,000 electronic receipts created to date. It includes a comprehensive network of IMD's central and sub-offices, enabling faster file movement, digital documentation, and enhanced tracking capabilities and transparency.

Advance Training Course in Met Instrumentation & Information Communication System" an onsite training conducted every 6 months by Information Communication and Instrumentation Training Centre (ICITC), DGM New Delhi. This training course is published on the WMO Website and open to National and International Participants from IMD and Meteorological Organizations around the world.

Short Term Refresher training courses (5 days) published on WMO Website and conducted every month by ICITC Centre, DGM New Delhi in Online Mode on topics Database Management, AI/ML fundamentals, Cyber Security, Python Basics, Networking, Met Telecommunication, Surface Instruments, Airport Met Instruments, Radar, RS/RW

Regular basis training program is being conducted on using Common Alerting Protocol (CAP) based Integrated Alert System of NDMA for participants from India Meteorological Department.

Global leadership in line with "Vasudhaiva Kutumbakam".India has been a global leader more than years to provide multinational services through provisions of data ,NWP products, advisory services policy & planning and execution of international programmes. Our special emphasis has always been on immediate neighbours, including Southeast Asia,middle east, both Bay of Bengal and Arabian region and small islands nations and least developed countries in the Asia Pacific.

6.1.2 Challenges and Gap Areas

The latency in data transmission and dissemination due to processing and manual intervention and infrastructure issue.

Loss of internet or network connection, data from sensors or devices may not be transmitted to the central server or platform.

Reliability of data communication is a big challenge in hilly terrains, heavy rainfall areas, Himalayan belt etc. e.g: North Eastern states and North west India.

- Less density of weather stations in underserved areas
- Quality of meteorological data is inconsistent to some extent due to various issues in meteorological observations like delay in fault monitoring and correction system.
- Keeping up with the trending technologies like IoT (Internet of Things), penetration of 5G presents a gap in knowledge and implementation in the Organisation.
- Ensuring seamless communication between different devices, protocols, and platforms remains a challenge, hindering the adoption of IoT and other advance technologies.

- At present, data samples are collected once every 15 mins and considering the last 3-minute average. Still real time data is not used for processing in case of weather parameters like temperature, rainfall, wind pressure etc.
- Still in areas with limited infrastructure (like Northern and North Eastern regions) data communication is handicapped with limitations on bandwidth, security, scalability and efficiency which is dividing other regions digitally.
- Moving to Cloud based applications will reduce the resources and increase availability, redundancy, security.
- Gap in crowd sourcing. Crowdsourced weather data depends on users voluntarily contributing data. Lack of motivation, or lack of awareness leads to reduce in data reception. Some users may report data incorrectly, intentionally or unintentionally, leading to gaps in accurate, reliable datasets. If the crowdsourced data is being aggregated from multiple sources and platforms, there may be delays or issues in collecting, merging, and processing all the incoming data, leading to periods where data is missing or incomplete. Extreme weather events (like storms or hurricanes) can disrupt the functioning of crowdsourced weather stations, either causing equipment damage or impairing communication infrastructure.
- Due to processing time there is delay in Radar data reception at user end by around 10 minutes,
- Less training programme for member countries on data communications

6.1.3 Short-term Vision (next two years)

- To establish a robust data communication framework, implementation of AI/ML tools that enhances real-time meteorological data sharing and decision-making which will reduce the data latency by 20%The new tolls will also improve both the data availability, quality and improve the data security.
- Data volume shall be increase by 35TB
- Upgrade data communication infrastructure including bandwidth from 1 Gbps to 100 Gbps for faster and more reliable data transmission and reception.
- Develop user-friendly interfaces for meteorologists and the public to access weather data.
- Strengthen collaboration with global meteorological organizations for data exchange.
- Promote data security and privacy standards to protect sensitive information.
- Foster data literacy among meteorologists and the public for better understanding and utilization of meteorological data.

- Expanding and improving the density of weather stations and partnerships with meteorological agencies or universities, state government in underserved areas to reduce data gaps and also improve the coverage and reliability of the crowdsourced data.
- To strengthen the data communication structure for fast and real time availability of data, which will further help in providing real time information to stakeholders using various developed decision support systems?
- Implementation of network management tools and solution to manage complex network scaled across wired, wireless, and virtual IT environments. Strengthening of data

communication and network infrastructure in all out station IMD observatories and offices.

- Upgradation of Automatic Message switching system into XML based as per Latest ICAO standard.
- Implementation of WIS2.0 as per the WMO guideline
- Invest in cyber security measures to protect meteorological data against evolving threats.
- Promote active engagement among the public, private and academics to better serve government, business and citizens.
- International Training Program on data communications for Member Countries for migration from legacy GTS communication to new WMO communications frameworks WIS 2.0.

6.1.4 Medium-term Vision (next ten years)

To be a global leader in innovative data communication solutions for meteorology, supporting climate resilience and disaster preparedness.

- Continuously innovate data transmission technologies to reduce latency by 40%
- Expand the use of AI/ML and deep learning for advanced weather forecasting and data analysis.
- Provide accessible and customizable meteorological data services to diverse user groups.
- Invest in cyber security measures to protect meteorological data and confidential matter of organization against evolving threats.
- Data is a new currency. Expansion of data marketing with strategy plays a major role in development of science and technology, applications, which will contribute to Nation's economy.
- Implementation of WIGOS frame work as per the WMO guideline.
- It is planned to enhance IBF capabilities by gathering more exhaustive socio-economic, geophysical, and climate data. The integration of AI is proposed to analyse historical patterns and improve the accuracy of risk predictions. Efforts will also focus on establishing global standards for IBF data collection and engaging local communities in GIS-based planning. Participatory GIS tools will be used to incorporate indigenous knowledge and local priorities, enriching IBF strategies. Future plan includes integrating GIS with climate projection models to evaluate long-term risks and develop adaptation strategies, particularly for urban resilience against extreme weather impacts on infrastructure and utilities. Advanced visualization techniques such as AR/VR will be employed to simulate impact scenarios, aiding in public awareness, stakeholder engagement, and disaster preparedness training.

6.1.5 Vision 2047

- Predicting the exact state of data communication in 2047 is challenging, but we can envision several key trends and possibilities.
- By 2047, high speed internet access will likely be ubiquitous with global coverage through advanced technologies like Low Earth Orbit satellite constellations, 6G or more. Instantaneous data transmission regardless of location can be expected and experienced.
- AI driven network management will enhance security, QoS, resource allocation, fault management and greater penetration visibility.
- IoT will be deeply integrated into daily life with several billions of devices connected to internet, which will improve efficiency.
- To be at the forefront of meteorological data communication, shaping a sustainable and resilient future through comprehensive data-driven insights.
- Pioneer the development of advanced satellite, radar and sensor technologies for enhanced data collection.
- Foster international collaboration on climate change mitigation and adaptation through data sharing.
- Drive research and innovation in predictive meteorology, using quantum computing and other cutting-edge technologies.
- Educate future generations in meteorological sciences and data communication.
- Advocate for global policies that prioritize meteorological data for disaster risk reduction and climate action.
- Improvement in observational network with more number of radars, AWS total data volume shall be increase 50TB per day
- Continuously innovate data transmission technologies to reduce latency by 40%
- Implementation of edge computing which will enhances the speed and efficiency of data exchange by enabling local processing and only sending critical data to the central server.
- Promote the citizen science for collection of more crowdsource data

6.1.6 Strategy

- Providing inputs according to the requirement for development of precise and accurate sensors.
- Encouraging people for crowdsourcing of met data.
- Educate future generations in meteorological sciences and data communication.
- Know the needs of various sectors relying on weather data keenly and tailoring communication to their level of specific requirements.
- Collecting accurate data, relevant and structure the data properly. Reprocess of data to remove errors and inconsistencies. Continuous monitoring and evaluation of data for effectiveness.
- Partnerships with meteorological agencies or universities, state government in underserved areas to reduce data gaps
- Definite selection of communication channels for different services and sectors is crucial.
- Usage of effective data visualization techniques to convey insights clearly. It helps to understand data more understandable.

- ❖ Feedback mechanism may be established for continuous improvement.
- ❖ Test environment to be set up for testing the effectiveness of latest technology and further adaptation of it all over India.
- ❖ Encourage start-up and Make in India initiate to develop new technology for improvement of data exchange and quality

6.1.7 Outcome

Improved assistance in risk assessment and mitigation. Better and informed decision making enables individuals and organisations to understand trends, patterns and insights within the data leading to better choices. Achieving zero causality and minimizing loss of property due to weather calamities. Data communication aids in strategic planning of future projects. It also helps us to set goals, tracking the progress and adjusting strategies as per need. Transparent data ensures accountability and increases efficiency. Able to provide weather forecasting to each and every household of this Nation. Reducing latency is crucial for real-time weather forecasting, as quicker responses can improve the timeliness of weather warnings, especially for severe weather events like lightning and thunderstorms. However, a balance between low latency and data accuracy/quality must be maintained.

6.2 WARNING DISSEMINATION

6.2.1 Current status and major achievements during the past 10 years

IMD is responsible for monitoring and forecasting weather conditions across the country. IMD has taken various initiatives in recent years for improvement in data reception and dissemination of weather forecast and warning services based on latest tools and technologies. IMD issue warnings for cyclones, heavy rainfall, thunderstorm, heat waves, and other weather-related hazards. These warnings are disseminated through various channels, including radio, television, websites, mobile applications, and social media platforms.

- **Social Media** like Facebook, Twitter, and Instagram etc.: IMD very actively posts weather related warning for public though its social media accounts in Hindi/English and regional languages. These warnings can be seen by anyone.
- **YouTube**: IMD uploads weather information and warning twice daily in Hindi/English and regional languages. YouTube Channel is open to all.
- **APIs**: India Meteorological Department has developed APIs for various observations and forecast products. Data through these APIs are available to stockholders on request. Currently more than 100 stakeholders are utilizing IMD's APIs to disseminate warnings in their applications.
- **Website**: In recent years, IMD has updated its website mausam.imd.gov.in and all websites operated under MCs and RMCs. Any weather related update or warning is disseminated through these websites. The yearly access of the IMD website is approx. 15 crore.
- **SMS and Email**: In case of severe weather, warning dissemination is done via email and SMS to registered users and stake holders.
- **Mobile Application**: IMD has mobile applications Meghdoot (provides crop advisories to the farmers based on the weather information)/DAMINI (Lightning alert) /RAIN ALARM, UMANG for weather information and warning dissemination. IMD has launched new MAUSAM unified mobile App which provides weather forecast 1 hour to 7 days. Under the Agenda "Har Har Mausam, Har Ghar Mausam" this mobile app promises users to provide weather information and warning based on their location.
- **CAP alerts**: IMD has started CAP (Common Alerting Protocol) alerts to disseminate timely and meaningful warning information about the possible severe weather like heavy rainfall, lightning, Thunderstorm, Dust Storm etc.
- Warnings are being disseminate through international organization like Global Multi-Hazard Alert System (GMAS), Tropical Cyclone Advisory Centre (TCAC), Regional Specialized Meteorological Centre (RSMC) and South Asia Flash Flood Guidance System (SAsiaFFGS)
- Since 2019 nearly 3600 crores, 2.5 crore SMS has been sent to general public through CAP and CDAC SMS service.
- At present directly or indirectly IMDs warnings is being used by 60% of Indian population directly or indirectly

6.2.2 Challenges and Gap Areas

- **Last-mile connectivity**: One of the major challenges in warning dissemination is the lack of effective last-mile connectivity in many remote areas of India. This affects the timely and efficient dissemination of warnings to the people at risk.
- **Language Barrier**: India has wide variety of spoken languages across different regions. While warnings are issued only in limited languages.
- **Technological Divide**: Many regions in India have limited access to internet services and smartphones. This affects the dissemination of warnings through digital platforms and mobile apps in such regions.
- **Awareness and Education**: Lack of awareness and education about the importance of warnings and how to respond to them is another challenge. Many people may not be aware of how to interpret warnings, leading to delayed or inadequate responses during emergencies.
- **Addressing False Information**: With the rise of social media and instant messaging platforms, false information and rumours can spread rapidly, causing panic and confusion during emergency situations. Addressing the spread of false information and ensuring accurate warnings reach the public is a significant challenge.
- There is a **delay in warning dissemination through CAP. This may be due to network overload and failure**. It may be due to utilization of proper technology for SMS dissemination.

6.2.3 Short-term Vision (next two years)

- **New Interactive Website**: A new interactive website with interactive chat bot and multi lingual support will help communities to understand the warning better.
- **Local Weather Videos**: In case of severe weather, short videos can be made at RMC/MC level and disseminated through social platforms in different languages as and when necessary.
- **Collaboration with other agencies**: IMD is working in collaboration with disaster management authorities and other stake holders; we can expand this network coordinating with more agencies and relevant stakeholders to streamline the warning dissemination process and to improve coordination during emergencies.
- Popularise the Application Programming Interface (API) of forecast and warnings developed by IMD to improve the warning dissemination
- **Public Awareness and Education**: Continued focus on public awareness and education can help in building a culture of preparedness and response. Efforts can be made to promote awareness campaigns, conduct training programs, and collaborate with educational institutions to ensure that individuals are well-informed about warnings and know how to respond appropriately.
- **CAP alerts**: Dissemination of warnings via CAP alerts through Cell broadcasting, TV and Radio Railway announcements, siren etc. which will reduce the delay of dissemination of warnings.

- **Missed call and SMS alerts** can be beneficial for people who are using dial Pad phones.
- **Satellite dissemination**: Dissemination of warnings through satellite like GAGAN, NAVIC etc.
- **Warning shall be disseminating through MausamGPT**

6.2.4 Medium-term Vision (next ten years)

- Dynamic IBF warnings to be fully implemented with inclusion of all geographical and socio-economic data and secondary hazards data at panchayat level.
- **Multi-lingual and Localized Warnings**: Efforts can be made on providing warnings in multiple languages that are widely spoken across different regions.
- **Strengthened Digital Platforms:** The utilization of digital platforms, such as official websites and mobile apps, can be further strengthened for warning dissemination. This can include improving user experience, incorporating real-time data, and ensuring accessibility for a wider section of the population.
- Disseminating weather warnings to drivers while they are operating vehicles is an important aspect of road safety and can help drivers make informed decisions about their travel plans and actions. This can be done by using Dedicated In-car radio services, Traffic and Navigation system and Smartphone Notifications.
- Disseminating weather warnings all like farmers, fisherman, street vendors, tourist, daily labours etc.
- IMD will be a global leader in ICT enabling zero latency in early warning communities with consistency & accuracy to each and every person/household within country.
- **OTT Platforms**: As OTT platforms have gained vast popularity in recent years, warning dissemination through OTT Platforms can be explored.
- Development of tools to disseminate IMD's warnings in all local languages to all households.
- By 2035 IMD's warnings will be use by 80% of Indian populations.

6.2.5 Vision 2047

- **Automatic alert generation** when predefined weather conditions exceed safe thresholds. For example, when wind speed surpasses a certain limit, an automatic alert is issued
- Conversion of alerts into various languages through **AI-powered translation** systems to disseminate warnings to diverse communities
- Analyse images and geospatial data through **AI/ ML** to **identify weather-related risks**, such as landslides, wildfires, or storm damage, and send alerts accordingly.
- AI based alerts through **various communication channels**, including text messages, smartphone apps, email, social media, and even through voice assistants, to reach a wide range of individuals.
- **IoT-enabled electronic road signs** can display real-time weather warnings and instructions to drivers. For instance, they can warn of icy roads or suggest reduced speed limits during heavy rain.
- IMD may adopt Hybrid Intelligence Biometric Avatar technology for warning dissemination by 2047.

- Implementation of various tools disseminate IMD's warnings in all local languages to each & every household.

6.2.6 Strategy

- A series of organized surveillance mechanisms or actions that collect information on potential hazards in a given location, in order to trigger timely, coordinated responses. Early warning systems build resilience to disasters and thus mitigate their impact.

- The flow of information needs to be coordinated and shared among multiple stakeholders with a high degree of redundancy in the dissemination channels, since people are most likely to act on warnings corroborated from multiple sources.
- **Automated warning** using the thresholds and scientific understanding to be disseminated to the stake holders.
- **Multiple communication mediums** used for warning dissemination (e.g. mass media and informal communication).
- Time to time **awareness programs** to reach local communities to make them aware and educate about the severe weather and their impacts. This will help in building trust between people and organization leading adequate responses during emergencies.

6.2.7 Outcome

- Disaster resilient India with zero loss of life and minimal loss of livelihood by 2047.
- Real time dissemination of warning leading to more effective emergency preparedness.
- All forms of ICT tools include AI/ML and IOT based dissemination system will be in place.
- Effective Decision support system integrated with auto dissemination system
- Dissemination of warnings in all languages and through all mode of communications including Common Alerting Protocols(CAP) in coordination with communicating agencies.

Chapter 7 Capacity Building and Collaboration

7.1 CAPACITY BUILDING

7.1.1 Current Status and Major Achievement during past 10 years

- India Meteorological Department (IMD) is the National Meteorological Service of India and the principal government agency in all matters relating to Operational Meteorology (weather forecasting & climate services), Climatology and allied subjects.
- Acknowledging the importance of the above, formal training in General Meteorology commenced at IMD in 1943 at Pune, pioneering the meteorological education in India.
- Acknowledging the importance of Meteorological Instruments & Tele-communication in improvement of weather services in the country, formal training in the above aspects started at IMD, New Delhi in 1970s.
- Since then, the training activities in IMD have undergone significant changes in the spheres of training infrastructure, capabilities, objectives and contents keeping pace with latest developments in the field of operational meteorology and for catering to the needs of meteorological personnel at different levels.
- IMD has also established training centres at Chennai and Kolkata for catering to the regional needs.
- The training activities at Pune and New Delhi are World Meteorological Organisation (WMO) recognized Regional Training Centre (RTC) (Earlier known as Regional Meteorological Training Centre) since 1986. Being RTC components, IMD training has national as well as international commitments towards capacity building in different aspects of operational meteorology.
- IMD has undergone major transformation in terms of state-of-the-art observational platforms, meteorological data transmission & processing, numerical weather prediction, research & development activities and sector specific services. Designing and conducting different trainings for fulfilment of above commitments is also an operational service.
- Major achievements during past decade include designing new trainings for direct recruit scientists of IMD and project scientists, conducting regular trainings in online mode during pandemic situation and in hybrid mode (Physical/offline and online) post pandemic situation, conducting workshops, online refresher courses and training for departmental personnel and foreign participants
- Training activities of IMD have also kept pace with this modernization through modern infrastructure, latest forecasters' work-stations for the trainees, providing training in blended mode through virtual class room, facilities to remotely register for training courses through training web portal; and a fully furnished hostel etc.

Operational importance of Training Activities in IMD

- ❖ IMD and some other organizations such as the Indian Air Force, Indian Navy and Coast Guard recruit scientific personnel in Group-A and Group-B (non-gazetted) cadres, most of who are not from the background of Atmospheric Science or Meteorology. Design & conduction of training for such meteorological professionals, departmental as well as non-departmental and overseas. Hence capacity building in different aspects of the above fields of the personnel recruited in IMD other organizations at different levels is very much essential.
- ❖ Community capacity development in enhancing awareness among common people, stake holders about interpretation and application of weather & climate service's products.

Present Training activities

IMD designs and conducts various long term (4-12 months) routine certificate training programs and short term (one to a few weeks) customized tailor-made training/refresher training courses for the meteorological personnel working at different levels. Long term certified training programs are in the disciplines of General Meteorology (Weather & Climate services), Meteorological Instruments - Communication & Information system and in Agro Meteorology.

- ❖ **Long term ab-initio & competency requirement certificate training programs:**
    - Meteorologist Gr-II Training course
    - Integrated Meteorological Training Course (IMTC)
- ❖ **Long term career progression & competency requirement training programs for departmental personnel**
    - Intermediate training course
    - Forecasters Training course (FTC) & Advanced training in Instruments, Communication & Information System (ATICIS)
- ❖ **Long term competency requirement courses for personnel from Other Govt of India Organizations and from NMHS of neighboring countries:**
    - Advanced Meteorological Training Course
- ❖ **Orientation Training course for Multi-Tasking Staff & part time observation personnel**
- ❖ **Short term customized tailor-made training course/Advanced refresher training course**

Training delivery mechanisms

- ❖ Design & conduction of training for Meteorological professionals, departmental as well as non-departmental and overseas.
- ❖ Presently training delivery is done through a blended mode, consisting of both Physical presence mode and distance learning mode.
- ❖ Local participants can join a course by physically attending it, whereas remote participants join through distance learning mode (online & off line both).

- Distance learning has both online and offline versions. Through the online version, using generic online software, remote participants can concurrently interact with the resource person as well as with other participants.
- If any trainee due to any reasons, like non-matching of time zone (especially for overseas participant) or being pre-occupied with other office work in exigency, may join the training through off line mode by accessing saved recorded lectures.
- Training Infrastructure: At present all the 4 training centres of IMD, viz., Pune, Delhi, Chennai and Kolkata, consist of training building and hostels.
- Training building consists of necessary number of class rooms equipped with traditional Black board Chalk Duster/ white board pen as well as audio-visual facilities, like smart interactive board, Video wall, etc. Hostel is equipped with self-contained rooms.
- Training centres and hostels are Wi-Fi enabled and have backup for uninterrupted power supply. Each training centre is also equipped with an operational observatory, which is utilised for hands on practical observation session.
- Training examinations and evaluation of answer books are done in physical mode.
- All courses are certificate courses only.
- Scholarship programs have been launched
- MoU with the various University/ Institution/Organisation to provide the research facility to the students at IMD.

7.1.2 Challenges and Gap areas

- The present training building at Pune was constructed in 1993 with provision of only 4 class rooms for conducting regular training classes in addition to an auditorium and a conference hall.
- Conversion of parts of the old training building into a modern library with on-line reference facility.
- In the existing setup, trainees and faculty members do not have facilities for using library after office hours or on holidays.
- It is recommended to convert the existing training building partly into a modern library with on-line reference facility, with sufficiently long hours of operation.
- Construction of Gymnasium Room and Recreation room Facilities: This training centre does not have games and recreation facilities for the trainees/ faculty members.
- Optimal use of cutting edge Technology-App based training
- Accreditation for degree / diploma of the courses by the universities
- Seamless training
- Capacity building program for general public and stakeholders
- Up gradation of the status of IMD's training service.
- Systematic approach for proactive International co-operation in the Capacity development.

7.1.3 Short term Vision (next 2 years)

- To set up a cell that will be responsible to develop the Outreach Programme which focuses on strengthening the knowledge of meteorology and its application using Online and well as physical mode Learning Platforms.
- To facilitate the existing system of training centres with all tech-enabled equipment and tools for better and timely impart of the training programs.
- To create a dynamic training website for training division (MTI at Pune & ICITC at New Delhi), which provide all the information such as location, climate information of the place, Historical background of IMD training, its objectives, commitments, different types of training programs offered along with their learning objectives, information about the link for training e-web portal, general information about IMD's virtual training class & programs, etc. The website should also contain yearly training calendar, information about the results out of different routine long term certificate training courses, information about holding of any short-term tailor-made refresher courses, etc.
- Automation in invitation of training course, their registration and issuing of certificate in online mode.
- To enhance or improve the on-job training program structure for more practical usage of the learned technologies.
- Addition of new courses with latest tools and technology which are useful in meteorological applications.
- Collaboration with international organizations for training and research
- Capacity building of the IMD staff with latest technology to keep up the pace for latest research and trends.
- **Physical or Virtual Training Targets :**
  - **Advanced Training Course in MI & IS (Physical & Virtual)** will be conducted twice annually, with each session spanning two weeks within a six-month period.
  - **Short-Term Refresher Course** (Virtual) will be organized 12 times a year, each lasting one week.
  - **Summer Training Program (Physical)**, lasting 6 to 8 weeks, will be held annually to provide in-depth learning opportunities
  - **Familiarization Training (Physical)**, sessions of five days each will be conducted twice a year
  - **Modular Training Courses (Physical)**, which will focus on specific skillsets in concise two-day formats, offered twice annually.
- Aiming for 100 participants in on-site workshops and training annually national and internationally.
- Aiming for 200 attendees in online modules monthly national and internationally.

7.1.4 Medium term Vision (next ten years)

Research capacity strengthening is the process by which individuals, institutions and societies develop abilities – individually and collectively – to perform research effectively, efficiently and in a sustainable manner.

- To renovate training building with enough class rooms, equipped with state-of-the-art teaching facilities, enabled with conduction of both physical mode and distance learning mode (on line & offline both), computer lab, NWP lab, Synoptic lab & instrument lab, examination hall etc.
- The lab should be spacious enough & equipped to accommodate at least 50 trainees at a time. Computer lab and NWP lab are recommended to be equipped with LAN/WiFi and high-speed broadband internet facilities.
- There should be more collaborative national as well as international projects.
- Virtual classroom and smart class rooms upto 2030 having all hi-tech facilities of distance learning as well as physical learning at Pune and New Delhi Centres.
- Capacity-building at various levels, including strengthening the base of curiosity-driven scientific research;
- Creating 30 centers of excellence in priority areas in existing institutions; and setting up new institutions in gap areas that allows for leveraging the global and national knowledge-base.
- To continue functioning as effective RTC components in RA-II region to design and organize Capacity development program for Overseas participants from neighboring countries in the field of operational weather and climate services and allied fields.
- Digitization of live lectures of complete courses delivered by the expert faculties.
- Integration of Augmented and Virtual reality based platforms with Virtual Classroom
- Setting up of training web portal integrated with Virtual Classroom.
- To create YouTube learning modules on different topics under Operational Weather and Climate services and allied subjects for the general public.
- Accreditation of IMD's one year duration Advanced Course for M.Tech in Atmospheric Science / Technology by universities.
- Preparation of a comprehensive proposal and getting approval for transforming IMD's training services into a National Academy for Meteorology and Earth System Science (NAMESS) by Institutional Collaborations within and across MoES.
- Signing of MoU with WMO for enhanced International co-operation by India in the capacity building of overseas participants from Least Developed Countries / Island Countries / developing Countries.
- Introduction of full online examination and evaluation system using AI/ML.
- Development of a Software/App based system using training and other information/database enabling IMD to introduce Seamless training system.
- Aiming for 200 participants in on-site workshops and training annually national and internationally with 5% increase annually.
- Aiming for 500 attendees in online modules monthly national and internationally with 10% increase annually.

- ICITC programs aspire to become a benchmark for advanced training in meteorological instrumentation, aligning with the latest World Meteorological Organization (WMO) guidelines and international best practices.

7.1.5 Vision for 2047

- Building and strengthening of the capacity of personnel in the field of Operational Weather & Climate services and in other allied fields for meeting their required job competencies as set by WMO, ICAO and other standard international agencies for providing highest level of operational Weather and Climate services.
- By 2047 IMD's training facilities will be transformed into an Academic Center for Excellence equipped with cutting edge and App based learning technologies, enabling to award degree/ diploma after successful completion of training and with seamless training facilities and facilitating outreach among common people and stake holders in the field of operational weather and climate services.
- Upgrade IMD training facility to a National Academy for Meteorology and Earth System Science (NAMESS).
- IMD's all routine long term Certificate training courses to convert into Appropriate Degree / Diploma.
- Seamless training system for the departmental and other participants.
- To continue functioning as effective and active RTC components of WMO.
- The training aims to achieve 95% competency, ensuring participants thoroughly understand advanced concepts in meteorological instrumentation and other advanced technologies.
- ICITC has global reach where Participants from RA-II and other countries participate in virtual and physical modes and ICITC aims to do trainings on International platform in collaboration with foreign countries
- By focusing on building global competence, technological innovation, and ethical leadership, the Centre will ensure that India is well-positioned to lead the world in meteorological excellence.

7.1.6 Strategy

- Construction of training building/training annex building/ Hostel at different training centres.
- To continue functioning as effective RTC components in RA-II region to design and organize Capacity development program for Overseas participants from neighbouring countries in the field of operational weather and climate services and allied fields.
- Digitization of live lectures of complete courses delivered by the expert faculties.
- Setting up Virtual Classroom facilities at Pune and New Delhi Centres.
- Integration of Augmented and Virtual reality based platforms with Virtual Classroom
- Setting up of training web portal integrated with Virtual Classroom.
- Institutional Collaboration among Institutes within MoES to upgrade the knowledge base.

- ❖ To create YouTube learning modules on different topics under Operational Weather and Climate services and allied subjects for the general public.
- ❖ Accreditation of IMD's one year duration Advanced Course for M.Tech in Atmospheric Science / Technology by universities.
- ❖ Preparation of a comprehensive proposal and getting approval for transforming IMD's training services into a National Academy for Meteorology and Earth System Science (NAMESS) by Institutional Collaborations within and across MoES.
- ❖ Signing of MoU with WMO for enhanced International co-operation by India in the capacity building of overseas participants from Least Developed Countries / Island Countries / developing Countries.
- ❖ Capacity development program for different categories of general public using YouTube learning module.
- ❖ Full-fledged Online/ Blended/ Hybrid mode as and whenever required depending on target audience.
- ❖ Introduction of full online examination and evaluation system using AI/ML.
- ❖ Development of a Software/App based system using training and other information/database enabling IMD to introduce Seamless training system.

7.1.7 Outcome

- ❖ Enhanced knowledge, skills, and self-efficacy
- ❖ Improved management and governance
- ❖ Increased sustainability
- ❖ Improved collaboration and partnerships
- ❖ Greater control over future development
- ❖ Being a leader in addressing meteorological challenge.

7.2 NATIONAL AND INTERNATIONAL COLLABORATION

7.2.1 Current status and major achievements during the past 10 years

The IMD has been actively engaged in forging collaborations with both national and international organizations to bolster essential weather and climate services, facilitate data sharing, contribute to global research endeavours, and promote cooperation in tackling weather-related challenges while advancing scientific understanding. Over the past decade, IMD has entered into approximately 100 Memoranda of Understanding (MoUs) and IoAs within the country. These agreements encompass partnerships with central universities, state universities, Indian Institutes of Technology (IITs), National Institutes of Technology (NITs), agricultural universities, the power sector, disaster management authorities, and private sector entities etc. These partnerships serve the dual purpose of enhancing weather and climate services and pushing the boundaries of scientific knowledge.

Furthermore, IMD has also established approximately 15MoUs and IoAs with esteemed international organizations. These collaborations involve International organizations such as the United Nations Development Programme (UNDP), UN World Food Programme (UN WFP), World Meteorological Organization (WMO) along with many other foreign entities like the Nigerian Meteorological Department (NiMET), and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), National Meteorological office of Dominican Republic (ONAMET), Kagawa University of Japan, Synoptic Data Public Benefit Corpn USAetc. Through these agreements, IMD strives to facilitate the exchange of best practices, knowledge, and expertise on a global scaleso as to augment India's contribution to the global community in terms of providing state-of-art weather information spanning different fields of meteorology and disaster risk reduction.

7.2.2 Challenges and Gap Areas

IMD faces several challenges and gap areas in both national and international collaboration efforts. These challenges can hinder its ability to provide accurate forecasts, monitor climate change, and coordinate responses to weather-related disasters. Some of the key challenges and gap areas include:

- **Data Access:** Limited access to data from other countries or regions, especially in politically sensitive areas, can hinder the accuracy of global weather forecasts.
- **Standardization Gaps:** Differences in measurement and reporting standards among nations can make it challenging to integrate data from diverse sources.
- **Inter-agency Coordination:** Coordination among various national agencies (e.g., meteorological, disaster management, transportation) can be complex, leading to delays in response to weather-related disasters.
- **International Coordination:** Coordinating responses to trans-boundary weather events with neighbouring countries can be logistically challenging, especially in regions with political tensions.

- **Training:** Ensuring a skilled and knowledgeable workforce requires continuous training and development programs.
- **Support for Developing Nations:** Providing assistance to less-developed countries to strengthen their meteorological capabilities can be resource-intensive.
- **Data Security:** Protecting meteorological data from cyber threats and ensuring data privacy can be challenging, especially when sharing data internationally.
- **Limited Public Understanding:** Public awareness of the importance of meteorological data and forecasts, as well as how to interpret warnings, may be lacking.

Addressing these challenges and filling the gap areas often requires sustained commitment, national as well as international cooperation, adequate funding, and continuous research and development efforts. IMD can also adapt to evolving technologies and scientific knowledge to enhance their national and international collaboration capabilities.

7.2.3 Short-term Vision (next two years)

This collaborative approach is essential in an increasingly inter-connected world where weather and climate-related events can have far-reaching impacts. Some key aspects of the vision for collaboration among national meteorological organizations are given below:

- Prioritize data exchange agreements with national and state agencies, central and state universities, and private partners to integrate diverse observations into forecasting models, thereby improving forecast accuracy.
- Enhance national collaboration with government agencies, emergency services, state and local emergency management, and local authorities to provide timely, precise weather and disaster information, and enhance disaster preparedness and response.
- Strengthen regional partnerships with neighbouring Asian countries to share real-time weather data, improving regional forecasting accuracy and benefiting disaster preparedness and response.
- Actively engage in international meteorological conferences and initiatives to promote knowledge sharing and best practices.
- Establish a fellowship program aimed at fostering formal connections with individuals conducting pioneering research relevant to IMD's strategic goals.
- Promote collaborative efforts with media, educational institutions, and civil society organizations to raise public awareness about the importance of weather and climate information.
- IMD intends to stimulate innovation, foster entrepreneurship, and advance the state-of-the-art in meteorology, ultimately enhancing its capabilities for weather forecasting, climate monitoring, and disaster risk management by supporting start-ups in meteorological instrumentation, communication, and technological development through R&D innovations.
- Many more international collaborations for data sharing are under process with organizations like Central Weather Agency of Taiwan, Seychelles Meteorological Authority, Hong Kong Observatory, etc.

7.2.4 Medium-term Vision (next ten years)

- ❖ Upgrade and modernize India's weather monitoring and data collection infrastructure, which includes radar systems, satellites, and observation networks, to enhance the precision of weather forecasts.
- ❖ Strengthen partnerships with space agencies, with a particular focus on ISRO, as well as regional and international space agencies, to obtain satellite data.
- ❖ Expand collaborations with regional meteorological agencies to boost the accuracy of short to medium-range weather predictions, particularly for events like cyclones, monsoons, heavy rainfall, dust storms, and heat waves.
- ❖ Foster cooperation with global organizations such as the World Meteorological Organization (WMO) and national meteorological agencies like ECMWF, NWS, JMA, CMA, and BAM to enhance global weather data sharing and forecasting capabilities.
- ❖ Intensify collaborative efforts with national research institutions and meteorological services, emphasizing advancements in forecasting technology, including emerging technologies like AI and machine learning.
- ❖ Participate in joint research projects with international organizations and partners to address regional and global climate challenges.
- ❖ Work in partnership with national, regional, and international institutes and organizations to develop a comprehensive coupled model encompassing the Atmosphere, Ocean, Land, and Biosphere, with the goal of applying the concept of "seamless prediction."
- ❖ Invest in medium-term capacity-building programs for national meteorological services, particularly in regions requiring support to enhance their operational forecasting capabilities.
- ❖ IMD intends to contribute building a more inclusive and resilient global meteorological community while addressing common challenges and advancing shared goals related to weather forecasting, climate monitoring, and disaster risk reduction by embracing Global South leadership principles and fostering collaboration with countries in the region.
- ❖ IMD can contribute to building a more inclusive and resilient global meteorological community while helping to address the unique challenges faced by countries with limited resources and capacity in meteorological services and disaster risk management by providing technological and knowledge support to developing nations through national and international collaboration.

7.2.5 Vision 2047

- ❖ Establish enduring climate monitoring networks to evaluate and address climate change and its consequences within India.
- ❖ Forge close collaborations with international climate research organizations to cooperate on strategies for both mitigating and adapting to climate change.

- Create and disseminate research findings on the impact of climate change in South Asia and high mountain regions, fostering international cooperation in addressing global climate challenges.
- Take a leading role in climate diplomacy initiatives to encourage international agreements and actions aimed at enhancing climate resilience and sustainability.
- Expand the commitment to capacity building, with a focus on providing sustained support to national meteorological services in developing countries, thereby promoting sustainability and self-reliance in forecasting.
- Embrace long-term planning by spearheading technological innovations and pioneering research projects that shape the future of meteorology and environmental science, ensuring that IMD remains at the forefront of forecasting capabilities.
- IMD intends to develop a robust policy framework for national and international collaboration through assessment of current capabilities, stakeholder analysis, policy formulation, capacity building, data sharing and exchange, research and innovation, and monitoring and evaluation.
- **Data /resources/tools/algorithms sharing as per the Guidelines of the Government to keep priority on societal needs up to village/ Panchayat levels or every household. The auto dissemination will be multilingual, specific and easily understandable. Priorities can be set up for early warnings, impact based, latest art of technologies and data mining algorithms including Artificial Intelligence, deep learning and virtual reality projections, climate projections from various scales. These implementations will be synchronized at regional, national as well as International levels.**

7.2.6 Strategy

These plans should be adaptable to changing circumstances and evolving technologies, with regular reviews and adjustments to meet the meteorological department's goals for national and international collaboration effectively.

7.2.7 Outcome

The role of meteorological department plays a pivotal role in national and international collaboration by providing essential weather and climate services, sharing data, contributing to global research efforts, and fostering cooperation to address weather-related challenges and advance scientific knowledge.

ABBREVIATIONS

3DEST	3D Earth-Specific Transformers
AAM	Atmospheric Angular Momentum
AAS	Agromet Advisory Service
ABI	Advanced Baseline Imager
ACC	Anomaly correlation coefficient
ACROSS	Atmosphere & Climate Research-Modelling Observing Systems & Services
ACS	Aeronautical Climatological Summary
ACWC	Area Cyclone Warning Centres
ADCP	Additional Data Collection Platforms
AFNO	Adaptive Fourier Neural Operators
AGRO AWS	Agrometeorological Automatic Weather Stations
Agro-DSS	Decision support system for Agromet Advisory Services
AHI	Advanced Himawari Imager
AI/ML	Artificial Intelligence and Machine Learning
AiDT	AI-enhanced Advanced Dvorak Technique
AIR	All India Radio
AIRS	Atmospheric Infrared Sounder
AMFU	Agro-Met Field Units
AMO	Aerodrome Meteorological offices
AMS	Aeronautical Meteorological Stations
AMSS	Automatic Message Switching System
AMSU	Advanced microwave sounding unit
AMV	Atmospheric Motion Vectors
ANSP	Air Navigation Service Providers
APAC	Asia-Pacific (A-sia PAC-ific)
APAR	Airborne Phased Array Radar
API	Application Programming Interface
AQ-EWS	Air Quality Early Warning System
AR/VR	Augmented Reality /Virtual Reality
AR6	Sixth Assessment Report
ARG	Automatic Rain Gauge
ARGOS	Advanced Research and Global Observation Satellite
AS	Arabian Sea
ASCAT	Advanced Scatterometer
ASG	Automatic Snow Gauge
ATDnet	Arrival Time Difference network
ATICIS	Advanced training in Instruments, Communication & Information System
ATMS	Advanced Technology Microwave Sounder
AUV	Autonomous Underwater Vehicle
AVHRR	Advanced Very High Resolution Radiometer
AWAP	Australian Water Availability Project

AWOS	Automatic Weather Observing System
AWS	Automatic Weather Stations
BAM	Brazilian Global Atmospheric Model
BC	Black carbon
BoB	Bay of Bengal
BOM	Bureau of Meteorology
BPL	Below Poverty Line
BSRN	Baseline Surface Radiation Network
CALO	Chemistry-Atmosphere-Land-Ocean
CAP	Common Alert Protocol
CAPE	Convective Available Potential Energy
CCD	Charge-Coupled Device
CCN	Cloud condensation nuclei
CD	Cyclonic Disturbance
CDAC	Centre for Development of Advanced Computing
CDM	Collaborative Decision Making
CFLOWS	Coastal Flood Warning system
CFsv2	Climate Forecast System version 2
CG lightning	Cloud-to-Ground Lightning
CGMS	Coordination Group for Meteorological Satellites
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CMA	China Meteorological Administration
CMC	Canadian Meteorological Centre
CMIP6	Coupled Model Inter-comparison Project 6
CORDEX	Coordinated Regional Climate Downscaling Experiment
CRIS	Customized Rainfall Information System
CS	Cyclonic Storm
CSIS	Climate Service Information System
CWC	Cyclone Warning Centres
CWC	Central Water Commission
DAC	Department Agriculture and Cooperation
DAHDF	Department of Animal Husbandry, Dairying, and Fisheries
DAMU	District Agro-Meteorological Units
DCP	Data Collection Platforms
DCRA	Dynamic Composite Risk Atlas
DCWIS	Digital Current Weather Instrument Systems
DD	Deep Depression
DEM	Digital Elevation Map
DGM	Director General of Meteorology
DRMS	District Rainfall Monitoring scheme
DRR	Disaster Risk Reduction
DSS	Decision Support System
DWR	Doppler weather Radar
E&NE	East & Northeast

EC/OC	Elemental Carbon/Organic Carbon
ECMWF	European Centre for Medium-Range Weather Forecasts
EMRC	Environment Monitoring and Research Center
ENFUSER	ENvironmental information FUsion SERvice
ENSO	El Niño–Southern Oscillation
EOS	Earth Observation Systems
ERA5	ECMWF reanalysis v5
ERFS	Extended Range Forecasting System
ESCS	Extremely Severe Cyclonic Storm
ESM	Earth System Models
ESSO	Earth System Science Organization
ETR	Ensemble transform rescaling
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EWRF	Electrical WRF
EWS	Early warning systems
FAPAR	Fraction of Absorbed Photosynthetically Active Radiation
FAP	Farmers Awareness Programmes
FAPS	Farmer Advisory and Problem Solving
FCI	Flexible Combined Imager
FCN	FourCastNet system
FDP	Forecast Demonstration Program
FFGS	Flash Flood Guidance System
FIR	Flight Information Region
FMO	Flood Meteorological Office
FNO	Fourier Neural Operator
FOR	Field-of-Regard
FSM	Forward Scatter Meter
FTC	Forecasters Training course
FTP	File Transfer Protocol
GAGAN	GPS-aided GEO Augmented Navigation
GAW	Global Atmosphere Watch
Gbps	Gigabits per Second
GCOS	Global Climate Observing System
GDP	Gross domestic product
GEFS	Global Ensemble Forecasting System
GEO	Geostationary equatorial orbit
GFCS	Global Framework for Climate Services
GFS	Global Forecast System
GHG	Green House Gases
GIS	Geographic Information System
GISC	Global Information System Centre
GLM	Geostationary Lightning Mapper
GMAS	Global Multi-Hazard Alert System
GMDSS	Global Maritime Distress and Safety System

GMS	Geostationary Meteorological Satellite
GNN	Graph Neural Networks
GOES-R	Geostationary Operational Environmental Satellite-R
GOS	Global Observing System
GPC	Global Producing Center
GPP	genesis potential parameter
GPP	Genesis Potential Parameter
GPRS	General Packet Radio Service
GPS	Global Position System
GPT	Generative Pre-Trained Transformers
GSM	Global Spectral Model
GSM	Global Spectral Mode
GTS	Global Telecommunication System
GUAN	Global Climate Observation System Upper Air Network
GUI	Graphical User Interface
H-AWOS	Heliport-AWOS
HEO	Highly Elliptical Orbit
HES	Hyper-spectral Environmental Suite
HIRS	High resolution Infrared Radiation Sounder
HPC	High-Performance Computer
HPCS	High Power Computing System
HRES	High Resolution Forecast
HRRR	High Resolution Rapid Refresh
HWRF	HURRICANE Weather Research & Forecast
HWSR	High Wind Speed Recorders
HYCOM	Hybrid Coordinate Ocean Model
IAAS	Integrated Agro-Meteorological Advisory Service
IAF	Indian Air Force
IASI	Infrared Atmospheric Sounding Interferometer
IATA	International Air Transport Association
IBF	Impact-Based Forecasting
IBF	Impact Based Forecast
ICAO	International Civil Aviation Organization
ICAR	Indian Council of Agricultural Research
ICITC	Information Communication and Instrumentation Training Centre
ICRS	International Centre for Radio Science
ICT	Information and Communication Technologies
IDF	Intensity Duration Frequency
IFLOWS	Integrated Flood Warning system
IFS	Integrated Forecasting System
IGP	Indo-Gangetic Plains
IIT	Indian Institute of Technology
IITM	Indian Institute of Tropical Meteorology
ILDN	Lightning Detection Networks

IMD	India Meteorological Department
IMTC	Integrated Meteorological Training Course
INCOIS	Indian National Centre for Ocean Information Services
INMARSAT	International Maritime Satellite Organization
INSAT	Indian National Satellite System
IoAs	Indications of Agreement
IOD	Indian Ocean Dipole
IOPs	Intensive Observation Periods
iOS	iPhone Operating System
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IRS	Indian Remote Sensing Satellite
IS	Information Systems
ISO	International Organization forInternational Organization for Standardization
ISRO	Indian Space Research Organization
IST	Indian Standard Time
IT	Information Technology
ITS	Intelligent Transportation SYSTEM
IVRS	Interactive Voice Response System
JMA	Japan Meteorological Agency
JMAEPS	Japan Meteorological Agency's Agrometeorological Prediction System
KMA	Korea Meteorological Administration
KPI	Key Performance Indicators
KVK	Krishi Vigyan Kendra
LAI	Leaf Area Index
LAN	Local Area Network
LAWP	Lower Atmospheric Wind Profilers
LDS	Lightning Detection System
LEO	Low Earth Orbit
LI	Lightning Imager
LIDAR	Light Detection and Ranging
LST	Land Surface Temperature
LSTM	Long Short-Term Memory
LW/SW	Long Wave and Short Wave
MC	Meteorological Centres
MeitY	Ministry of Electronics and Information Technology
METAR	Meteorological Aerodrome Report
meteoGAN	Meteorological Generative Adversarial Network
MI	Machine Intelligence
MIR	Millimeter-wave Imaging Radiometer
MISDA	Missed Start or Delay in Activation
MISO	Monsoon Intra-seasonal Oscillation
MJO	Madden Julian Oscillation
MLWP	Machine Learning Weather Prediction

MMCFS	Monsoon Miss Climate Forecast System
MMDRPS	Multi-Mission Meteorological Data Receiving and Processing System
MME	Multi-Model Ensemble
MNCFC	Mahalanobis National Crop Forecasting Centre
MODIS	Moderate Resolution Imaging Spectroradiometer
MoEFCC	Ministry of Environment, Forest and Climate Change
MoES	Ministry of Earth Sciences
MOM4	Modular Ocean model version 4
MOR	Meteorological Optical Range
MoU	Memorandam of Understanding
MPLS	Multiprotocol label switching
MR	Mixed Reality
MSG	Meteosat Second Generation
MTG	Meteosat Third Generation
MTI	Meteorological Training Institute
MWO	Meteorological Watch Offices
NABL	National Accreditation Board for Testing and Calibration Laboratories
NAL	National Aerospace Laboratories
NAM	North American Mesoscale
NAMESS	National Academy for Meteorology and Earth System Science
NASA	National Aeronautics and Space Administration
NAVIC	Navigation with Indian Constellation
NCAER	National Council of Applied Economic Research
NCAR	National Center for Atmospheric Research
NCC	National Cadet Corps
NCEP	National Centers for Environmental Prediction
NCMRWF	National Centre for Medium-Range Weather Forecasting
NCPOR	National Centre for Polar and Ocean Research
NCUM	National Centre for Medium Range Weather Forecasting Centre Unified Model
NDC	National Data Centre
NDMA	National Disaster Management Authority
NDRF	National Disaster Response Force
NDVI	Normalised Difference Vegetation Index
NEMS	NOAA Environmental Modelling system
NEPS	NCMRWF Ensemble Prediction System
NFCS	National Framework for Climate Services
NHAI	National Highways Authority of India
NIC	National Informatics Centre
NiMET	Nigerian Meteorological Department
NIO	North Indian Ocean
NIST	National Institute of Standards and Technology
NIT	National Institute of Technology
NKN	National Knowledge Network
NMHS	National Meteorological and Hydrological Services

NOAA	National Oceanic and Atmospheric Administration
NPP	National Polar Orbiting Partnership
NRSC	National Remote Sensing Centre
NSSL	National Severe Storms Laboratory
NSST	Near-Surface Sea Temperature
NTRL	National Thunderstorm Research Laboratory
NW	Northwest
NWFC	National Weather Forecasting Center
NWP	Numerical Weather Prediction
NWROC	National Weather Radar Operating Centre
NWS	National Weather Service
NWs	National Waterways
NWS	National Weather Service
OGC	Open Geospatial Consortium
OLBS	Online Briefing System
OLR	Outgoing Longwave Radiation
ONAMET	National Meteorological office of Dominican Republic
OTT	Over-The-Top
PAR	Phased-Array Radar
PB	Pilot balloon
pH	Potential of Hydrogen
PHC	Primary Health Centers
PM_{10}	Particulate Matter (10 micrometers or less in diameter)
PMP	Probable Maximum Precipitation
PMS	Panchayat Mausam Sewa
POAMA	Predictive Ocean Atmosphere Model for Australia
POD	Probability of detection
POM-TC	Princeton Ocean Model - Tropical Cyclone variant
PPP	Public-Private Partnership
PQPF	Probabilistic Quantitative Precipitation Forecast
PRBS	Pseudo Random Burst Sequence
PTO	Part Time State Observatories
PTR-TOF	Proton-Transfer-reaction-Time of Flight
QA	Quality Assurance
QoS	Quality of Service
QPE	Quantitative Precipitation Estimation
QPF	Quantitative Precipitation Forecast
R&D	Research and Development
RADAR	Radio Detection and Ranging
RA-II	Regional Association II
RBW	Risk Based Warning
RCC	Regional Climate Center
RF	Radio Frequency
RH	Relative Humidity

RIMES	Regional Integrated Multi-Hazard Early Warning System
RMC	Regional Meteorological Centre
RMDCN-NG	Regional Meteorological Data Communication Network Next-Gen
RMO	Regional Meteorological Office
RS	Remote Sensing
RS/RW	Radiosonde Radiowind
RSMC	Regional Specialized Meteorological Centre
RTC	Regional Training Centre
RTH	Regional Telecom Hub
RVR	Runway Visual Range
SAARC	South Asian Association for Regional Cooperation
SAC	Space Application Centre
SAC-ISRO	Space Applications Centre, Indian Space Research Organisation
SAFFGS	South Asian Forum for Gender and Sustainable Development
SAMEER	Society for Applied Microwave Electronics Engineering and Research
SASCOF	South Asian Climate Outlook Forum
SAsiaFFGS	South Asia Flash Flood Guidance System
SAU	State Agricultural Universities
SCIP	Statistical Cyclone intensity Prediction
SCS	Severe Cyclonic Storm
SEISS	Space Environment In-Situ Suite
SEO	Spanish Earth Observation
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SID	Surface Instrument Division
SILAM	System for Integrated modeLling of Atmospheric coMposition
SMOS	Soil Moisture and Ocean Salinity
SODAR	Sonic Detection and Ranging
SOM	Self Organizing Map
SOP	Standard Operating Procedure
SP	South Peninsular
SPI	Standardised Precipitation Index
SPS/PMP	Space Physics and Space Science / Project Management Plan
SSMIS	Special Sensor Microwave Imager/Sounder
SSP	Shared Socioeconomic Pathway
SSPA	Solid-State Power Amplifier
SST	Sea Surface Temperature
SuCS	Super Cyclonic Storm
SUVI	Solar Ultraviolet Imager
SWIR	Short Wavelength Infrared
SWIRLS	Short-range Warning of Intense Rainstorms in Localised Systems
TAF	Terminal Area Forecast
TAR	Third Assessment Report
TC	Tropical Cyclone
TCAC	Tropical Cyclone Advisory Centre

TCO	Total Columnar Ozone
TDMA	Time Division Multiple Access
ToT	Transfer of Technology
TPRCC	Third Pole Regional Climate Centre
TPW	Total Precipitable Water
TREC	Tracking Radar Echoes by Correlation
TTB	Thunderstorm Test Bed
UAV	Unmanned Aerial Vehicle
UHF	Ultra High Frequency
UHI	Urban Heat Island
UKMO	UK Meteorological Office
UN WFP	UN World Food Programme
UNDP	United Nations World Food Programme
UTC	Universal Time Coordinated
UVN	Ultra-violet, Visible and Near-Infrared
UV-VIS	Ultraviolet-visible
VIIRS	Visible Infrared Imaging Radiometer Suite
Vis/NIR	Visible/Near Infrared
ViT	Vision Transformer
VPN	Virtual Private Networks
VR	Virtual Reality
VSCS	Very Severe Cyclonic Storm
VSRF	Very Short Range Forecasting
VSSC	Vikram Sarabhai Space Centre
WD	Wind Direction
WebGIS	United Nations Development Programme
WIGOS	World Meteorological Organization Integrated Global Observing System
WIS	WMO Information System
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting model
WRF-LES	WRF Large Eddy Simulation
WS	Wind Speed
WV	Wind Velocity
WWLLN	World Wide Lightning Location Network
XML	Extensible Markup Language
XR	Xtended Reality

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