MAUSAM, **76**, 1 (January 2025), 65-78

MAUSAM

DOI : https://doi.org/10.54302/mausam.v76i1.6406
Homepage: https://mausamjournal.imd.gov.in/index.php/MAUSAM

UDC No. 551.509 (540)

Journey of operational weather forecasting in India

P. N. SEN, SUNNY CHUG* and ARTI BANDGAR**

Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune

**India Meteorological Department, MoES, New Delhi*

***India Meteorological Department, MoES, Pune*

e mail : drpnsen@gmail.com

सार – भारत मौसम विज्ञान विभाग (आईएमडी) की स्थापना 1875 में हुई थी। इसका कार्य समग्र रूप से भारत की जलवायु और मौसम का अध्ययन करना और तूफान और अन्य चेतावनियाँ और दैनिक मौसम पूर्वानुमान जारी करना था। आईएमडी ने चक्रवात पूर्वानुमान और चेतावनियाँ जारी कीं; दिन-प्रतिदिन के पूर्वानुमान, मध्यम अवधि और विस्तारित सीमा और लंबी दूरी के पूर्वानुमान; विमानन गतिविधियों के लिए पूर्वानुमान; नाउकास्टिंग; बाढ़ की चेतावनी आदि के लिए मात्रात्मक वर्षा पूर्वानुमान। प्रारंभ में, पूर्वानुमान सिनोप्टिक और सांख्यिकीय तरीकों से किया जाता था। आजकल, संख्यात्मक तरीकों का उपयोग करके पूर्वानुमान जारी किए जाते हैं। पूर्वानुमान कार्य में सतह और ऊपरी वायु डेटा के साथ-साथ रडार और सैटेलाइट डेटा का उपयोग किया जाता है। पिछले एक सौ पचास वर्षों में पूर्वानुमान कार्य कैसे विकसित हुआ, इसका वर्णन इस पेपर में किया गया है।

ABSTRACT. India Meteorological Department (IMD) was established in 1875. Its mandate was to study climate and weather of India as a whole and to issue storm and other warnings and daily weather forecast. IMD issues Cyclone Forecasts and Warnings; Day to day Forecasts, Medium Range and Extended Range and Long Range Forecasts; Forecast for Aviation activities; Nowcasting; Quantitative Precipitation Forecast for Flood warning etc. Initially, forecasting was done by Synoptic and Statistical methods. Nowadays, forecasts are issued using Numerical methods. Surface and upper air data along with Radar and Satellite data are used in forecasting work. How the forecasting work evolved in the last one hundred fifty years has been described in this paper.

Key words – Nowcasting, Long range forecast, Extended and Medium range forecast, AI/ML.

1. Introduction

The state of atmosphere of a place at a particular time is known as Weather of the place. The state of atmosphere means the atmospheric conditions like Air Temperature, Barometric Pressure, Humidity, Sunshine, Wind, Cloudiness, Rainfall, Snowfall *etc*. The long-term average of Weather conditions of a place is called Climate. Climate gives an idea about the atmospheric condition one may expect on a particular day. But it may not come true on that particular day because climate is the average condition.

Weather forecasting is the attempt by the meteorologists to predict the state of the atmosphere at some future time and the weather conditions that one may expect. Weather forecasting is one of the most important components of meteorology. Extensive research is going on all over the world on various aspects of Atmospheric science. But the ultimate goal of a meteorologist is to give accurate forecast of weather conditions. Weather forecasting is thus the single most important practical reason for the existence of meteorology as a science. Knowing the future of the weather can be important for individuals and organizations. One can decide whether to take an umbrella or to carry warm clothing or to put on light clothing *etc*. while venturing outside. If the weather forecasts are accurate a farmer can decide whether to sow the seeds or harvest the crops; air traffic controller can allow an aircraft to land or take off. If a cyclone is likely to strike the coast, the residents of the coastal areas could be evacuated and taken to a safer place and the fishermen could be warned not to venture into the sea. If drought or flood is expected to occur the government could be informed about it so that they can procure adequate quantities of food and take other precautionary measures so that people do not suffer (Sen 2021). India Meteorological

Department (IMD) has been rendering service to the nation since 1875.

2. Weather forecasting through ages

The importance of Weather forecasting was realized even during the ancient times. Probably, the first attempt to predict the future state of the atmosphere was made in Babylon during the seventh century B. C. The Greek philosopher Aristotle wrote a philosophical treatise, Meteorologica, during the fourth century B.C. He theorized the formation of clouds, rain, hail *etc*. He made some important observations concerning weather. During the seventeenth century AD it was found that many of the claims made by Aristotle were not correct and therefore, discarded. In India studies on weather can be traced to ancient times. The process of formation of clouds and rain have been described in Upanishad around 3000 B.C. Around 500 A. D., Varahamihira in his classical work, the Brihatsamhita, gave clear evidence that there existed deep knowledge of atmospheric processes during that time. Scientific measurements of rainfall have been mentioned in Kautilya Arthashastra. Kalidasa wrote his epic Meghdoot probably during the First century A. D. He mentioned the date of onset of Monsoon over Ujjain in Central India as Ashadhasya Prathama Divase the first day of Ashadha, which coincides with the middle of June and the movement of monsoon clouds. The date mentioned by him is almost the same as 19 June, the normal date of onset of southwest monsoon, over the same area as determined by India Meteorological Department.

For many centuries, weather forecasting was made on the basis of the weather lore, movements of animals and birds; personal speculations *etc*. But instrumental observations were not used. It was realized, during the seventeenth century, that instrumental observations of atmospheric temperature, humidity, pressure *etc*. are essential for understanding the atmospheric conditions also for weather forecasting. The major step towards that was achieved when the Italian scientist Torricelli invented the mercury Barometer for the measurement of atmospheric pressure during in 1643. Lower barometric pressure is an indicator of bad weather whereas higher pressure indicates good weather. Invention of Mercury Thermometer by the physicist Daniel Gabriel Fahrenheit in 1714, helped in the measurement of atmospheric temperature. Since then a revolution has taken place in electronics and technology. Nowadays observations are available not only from ground based instruments but also space based instruments. In addition to conventional Thermometers, Hygrometers, Anemometers, Barometers *etc*. we have, nowadays, optical and electronic sensor based instruments for accurate measurements of meteorological parameters.

Weather knows no political boundary. Therefore, for issuing Weather Forecasts for a particular place, weather data from the neighboring areas are essential. In order to obtain those observational data an efficient communication system is required. It was possible only when the first of telecommunication systems was developed. Samuel Morse, an American inventor and painter invented and developed the first telecommunication system Telegraph in 1830 and demonstrated in 1838. With the advent of the satellite and development of electronics there has been a revolution in communication system. Communication has become much easier and faster nowadays. Now we can get observational data from any part of the world in no time. Meteorological data are now exchanged by different National Meteorological Services through the Global Telecommunication System (GTS) of World Meteorological Organization (WMO). Now, meteorological observations at the surface as well as at different altitudes all over the world are available to the forecasters for understanding and forecasting of weather. (Sen 2021).

3. Need for meteorological services for India

India is surrounded by oceans on three sides, the Bay of Bengal to the East, Arabian Sea to the West and Indian Ocean to the south. It is visited by devastating Tropical Cyclones every year. Indian mariners have been experiencing the fury of these storms for centuries. It is also causing loss of lives and properties. There was no method of detecting the storms out in the ocean till the middle of the nineteenth century. The British East India Company lost many of their ships because of these storms. British Meteorologists in India took interest in the research on Tropical storms. Henry Piddington, a British sailor, fell in love for the science of the storm. He studied, and tried to understand the various aspects of storms (IMD 1975). He published almost 40 papers dealing with tropical storms in The Journal of the Asiatic Society between 1835 and 1855. He also coined the term Cyclone, meaning the coil of a snake. He published his monumental work Laws of the Storms in 1842. A severe cyclone stuck Calcutta in 1864 causing death of more than 80,000 lives. This was followed by another cyclonic storm near Machilipattanam, which took life of about 40,000 people. Storm surge was mainly responsible for the devastation. The mercantile and shipping community; and the Bengal Chamber of Commerce expressed great concern about the tragedies and called for attention of the Government of Bengal to the inefficiency of the warning system. Government of India appointed a committee in 1865 to formulate a scheme for establishing meteorological observatory along the coast of the Bay of Bengal, Port of Calcutta, for giving effective warning about the approaching storm (IMD 1975). As per the recommendation of the committee storm warning for

Calcutta port was organized which involved obtaining meteorological observations from the stations in the coastal area and hoisting storm signal at the port. Moreover, there were failures of the monsoon rains in 1866 and 1871. In those days, meteorological observations, forecasting and other related activities were dealt with by meteorological reporters of provincial agencies in independent way. In 1875 Government of India decided to start Meteorological Department in order to bring all meteorological activities under one central organization and uniformity.

4. Meteorological studies before the establishment of IMD

Prior to 1875 meteorological observations were taken and warnings and weather forecasts used to be issued from different places by the provincial agencies, but not in an organized uniform manner. But the earliest Meteorological observatory in India was established in India at Madras (Chennai) by J Goldingham in September, 1793. It is one of the oldest Meteorological Observatories in the world (IMD 1975). The second one was set up at Colaba, Bombay (Mumbai) in 1823 and the third one at Trivandrum (Thiruvanthapuram). Meteorological observations were recorded in Simla (Shimla) during the period 1841 – 1845. Several other observatories were established in India during the first half of the 19^{th} century by various provincial governments. There were 77 Meteorological Observatories in India in 1874.

The Asiatic Society was founded in Calcutta in 1784 and in Bombay in 1804. Asiatic Society promoted the study of meteorology in India.

There were many private agencies that were recording observations; some were measuring barometric pressure, some temperature and some rainfall. They were using the observations for their own studies. As an example, hundred years prior to the establishment of IMD Colonel T. D. Pearse of Bengal Artillery undertook daily meteorological observations of Barometric pressure, Temperature, Humidity, Wind direction and speed and Rain fall at 7 am and 2:15 pm. He published the results in his Meteorological Journal during the period 6 March, 1785 to 28 February, 1788. During the eighteenth century tide observations along with weather parameters were made in the coastal areas for harbors, port warning as well for the safe entry of merchant and naval ships. The meteorological observatory at Calcutta was established at the office of the Surveyor General of India at Park Street in the year 1829. V. N. Rees was the first Superintendent of the Observatory and he used to record observations during the period 1829 to 1852. Radhanath Sikdar took charge of the Calcutta observatory in 1852. He prepared the table for reducing the Barometric Pressure to mean sea level (msl). He introduced accurate systematic hourly observations in the Calcutta observatory from December 1832. Meteorological Abstract containing daily and monthly means; also hourly means of a month of main weather parameters appeared regularly in the Proceedings and Journal of the Asiatic Society of Bengal from 1853 to 1876.

5. Establishment of India Meteorological Department

The India Meteorological Department (IMD) was set up with its Headquarters in Calcutta (presently Kolkata) by the Government of India in 1875.Thus the IMD was born. Its mandate was to study climate and weather of India as a whole and to issue storm and other warnings and daily weather forecast. H. F. Blanford F.R.S was appointed as the first Imperial Meteorological Reporter and the Head of the IMD. Although the office was established in 1875, there was no Central observatory with standard equipments. Blanford set up the Central Observatory at Alipur, Calcutta on 1 April 1877. He equipped it with the standard meteorological instruments available at that time and IMD was in a position to train observers and standardized instruments. India is a tropical country; the weather systems in India are different from those in the extra tropical region like in Europe and America. Blanford had immense knowledge of Indian meteorology and gave importance to the uniformity of observations all over India. A temporary branch of IMD was started at Simla in the same year. Later, four Provincial Meteorological Reporters were appointed to the Government of Bengal, Punjab, Madras and United Provinces (Uttar Pradesh) at Calcutta, Lahore, Madras and Allahabad respectively. All the observatories, excepting the Central Observatory at Alipur, were functioning under the direct control of the respective Provincial Meteorological Observers. Calcutta remained the Headquarters of IMD from 1875 to 1905. Simla was branch office of IMD. The Headquarters of IMD was shifted to Simla in 1905 and the Calcutta office was the given the status of Branch Office.

On 10 January 1885 Lala Ruchi Ram Sahni joined the Meteorological Department. He was the first Indian to have joined at a senior level, as Assistant Meteorological Reporter of the IMD. His main task was to prepare the ‘daily’ and ‘monthly’ weather reports regularly. In order to issue daily weather forecasts which methods were used is not very clear but definitely basic scientific knowledge was used. The most important responsibility of Lala Ruchi Ram was the issuance of the immediate danger signal to all the port stations in northern Bengal and Orissa to hoist the red ball. Lala Ruchi Ram (1997) in his Memoirs has mentioned that once he noticed unusually rapid fall of barometric pressure at Diamond Harbor station and issued warning of impending severe storm in the North Bay of Bengal and was successful in his prediction. That was the famous False point Cyclone. This is an evidence of scientific method used in forecasting cyclone.

Blanford retired from IMD on 8 May 1887. Sir John Eliot took over the IMD. The designation of the Imperial Reporter was changed to the Director General of Observatories (DGO) and Sir John Eliot became the first DGO on 1 April, 1899. He retired as DGO in 1903 and Sir Gilbert Walker took over the IMD as DGO. Sir Gilbert Walker was an outstanding mathematician and his research contribution in meteorology is invaluable. He developed a technique for long range forecast for Indian monsoon. India became the first country in the world to issue Long range forecast. Sir Gilbert Walker was succeeded by J. H. Field. He retired from service in March, 1928. Sir C. W. B. Normand, another outstanding Scientist assumed the charge of DGO. IMD was considering shifting its HQ to some suitable place in the plains with better facilities where the officers could undertake research on Monsoon. Sir Gilbert Walker proposed the name of Poona (Pune) in 1924. The HQ was shifted to Pune in 1928.

In 1877, a preliminary effort was made to prepare Weather charts by getting the meteorological data from field stations by post and analyzing them. Since there was a long-time difference of ten to fifteen days before the data could be put together these reports were of limited practical use. After the widespread drought of 1876-77, the Government desired to get early information of the progress of monsoon during 1878. To meet this requirement, the suggestions made by Eliot in May, 1878 for obtaining the weather reports from observatories by telegrams were approved. The first Daily Weather Report (DWR) of 15th June 1878 was published under the new system two days later. This DWR service functioned satisfactorily from July onwards till the end of monsoon season and the quickness with which it was established in full working order in those early days was indeed very creditable. On 1 September 1887 weather chart was included for the first time in Indian Daily Weather Report. The first chart published is given in Fig.1.

In addition to the DWR published from Calcutta, Simla also issued a DWR giving the observations at 10 AM for 51 stations and a short summary describing the chief features throughout the rainy season of 1878. A weekly summary of the weather was also published in the Gazette of India. As this service proved to be very useful, it continued for the rest of the year as well, even though it was started for rainy season only.

From 1928, the Indian Daily Weather Report (IDWR) covering the whole country was started which was issued from Weather Central, Pune. From 1936, ships' observations, upper winds measured by pilot balloons, and temperature and humidity data from aircraft ascents were also included. Publication of All India Weather Bulletin started on 1 April, 1928.

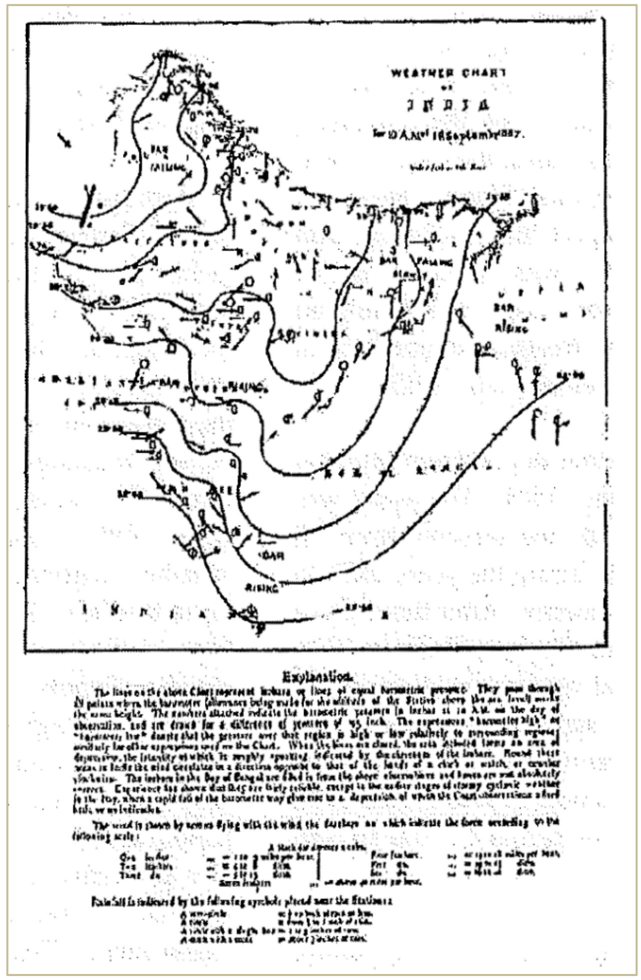

Fig. 1. First Chart published with India daily Weather Report (1September 1887)

The responsibility of the Weather Section at Pune was to issue daily telegraphic summary for the whole country as well as the forecast for the next 24 hours; publication of Daily, Weekly and Monthly Reports, storm warning for Arabian Sea and west coast and inland warning. The Second World War started on 1 September, 1939. The Government of India felt that the Director General of Observatory should be in close touch with the Air Head Quarter and other departments involved in war efforts for providing meteorological information to the maximum extent. As a consequence the office of the DGO was transferred to Delhi during the war period in 1942 and has been continuing there since then. The department was given responsibility of weather forecast for whole of India to the Royal Air Force (RAF). Aircraft reconnaissance for collecting meteorological observations was started over the

Bay of Bengal. Dr. Normand retired as the DGO on 9 September 1944. Dr. S. K. Banerji took over from him and he was the first Indian Director General of IMD. Dr. Normand is remembered for his outstanding scientific work, especially for the famous Normand Proposition or theorem involving Dry bulb Temperature, Wet bulb temperature and humidity mixing ratio. India became independent on 15 August, 1947 and country was partitioned into India and Pakistan. The Pakistan Meteorological Services got separated from IMD. The designation of the Director General of Observatory was changed to the Director General of Meteorology (DGM) in 1980. Dr. P. K. Das was the first DGM of IMD.

6. Establishment of surface observatories

For the measurement of atmospheric pressure Fortin's Barometers and Kew Pattern Barometers were used. Barometers were suspended inside masonry buildings. Standard barometers were installed in Calcutta, Bombay and Madras. The Indian standard Barometer was installed Alipur Observatory in 1877. This was used for standardization of the barometers installed all other observatories. Two other barometers were obtained from the office of the Surveyor General, Calcutta for use in Alipur as secondary standard. These barometers are still in use. Thermometers (Dry Bulb, Wet Bulb, Maximum and Minimum) were housed in a cage suspended in open stand. The cage was at a height of four and half feet from the ground. These cages were replaced by Stevenson Screens in 1921. Anemometers and Wind Vanes were generally mounted on the roof of a building or on a mast. Raingauges with 5-inch diameter were in use in Bengal, Assam and Madras. Gauges of various types were in other places. Recording instruments for pressure, temperature, humidity, wind and rainfall were available at Bombay from 1871 and a few years later at Calcutta and Madras. Initially IMD started giving the daily weather forecasts using the surface data obtained from observatories. The change in pressure, temperature was main criterion used for issuing forecasts. Experiences of the forecasters used play the main role.

7. Upper air and other observations

It was recognized by Blanford as early as 1877 that only surface data are not sufficient for issuing weather forecast, upper air observations are also needed. He thought of using Balloon observations. But the first upper air observation was made in India much earlier. Dr. Buist, in charge of Colaba observatory released a balloon in January, 1843 from Byculla (Bombay) to study the upper winds. It was observed that the balloon followed the direction of sea breeze up to a height of about 500 ft, then went vertically up to about 1 mile then moved in the opposite direction. On 19 March, 1889 a balloon was released from Calcutta Maidan. Moderate Southwesterly wind was observed up to about 500 meters above ground, then Southerly and thereafter strong Northwesterly. The second balloon ascent in Calcutta was made in April, 1889. It showed the similar results. In Calcutta an attempt was made to find upper air temperature in 1878. This was done putting a thermometer cage on top of a palm tree at a height of 40 ft. Specially designed Kite with meteorograph containing sensitive elements for measuring upper air temperature and humidity was also tried. Balloon made of guttaparcha tissue was released at Simla and it was followed by optical theodolites in 1905. The first Pilot Balloon observations were made in 1905. Later on balloon made of rubber was also used. A lot of experiments were conducted with different types of balloons. Light equipment like improved Dines Meteorograph for measuring accurate temperature and humidity was developed in 1932. Some trials flights were taken at Jhang in Punjab in September and October 1908; three flights even reached Stratosphere and the maximum height reached was 65000 feet (9.8 km). More flights were taken in the following year in June, July and December. Very Strong Westerly winds were observed in December.

In 1914, an upper air observatory was established at Agra. Plants for preparation Hydrogen for Balloon observation was also set up there. J. H. Field was appointed as the Director of this observatory. During the next ten years upper air observations were taken at Simla, Agra, Kojak, Darjeeling, Allahabad, Bangalore, Poona., Lahore, Akyab, Calcutta, Quetta, Bombay, Peshawar and other places. METEOR reports were prepared for artillery on a regular basis during that time. The technique for Pilot Balloon ascents at night time was developed by 1935. At present there are 62 Pilot Balloon Stations spread all over India.

Pilot balloon flight has the drawback that it cannot be tracked during cloudy weather. Moreover, the temperature and humidity cannot be obtained from pilot balloon ascents. Accurate observations of temperature and humidity at high altitude are needed for forecasting of weather. These data are needed for aviation forecasting also. Radisonde observations can provide that. During the Second World War the radiosonde ascents were taken in India with US equipments. India started thinking of development of Radisonde indigenously. Rai Bahadur G. Chatterji initiated the development of radiosonde in the country in 1940. In 1943 Clock type and Fan Type Radiosondes were developed by Dr. L. S. Mathur and his group and S. P. Venkiteshwaran and his group respectively. Various components of the Radiosonde were developed indigenously. Only about twenty percent components were imported. After the World war jet flights started for which very acute data for high altitudes were required. The radio sonde instruments developed earlier were inadequate for that purpose. Development of Audio - frequency Modulated Radiosonde was started in Delhi in December, 1966. By March, 1971 all the radiosonde stations were using these new instruments. (IMD 1875) Transistorized radiosonde receivers and transmitters were developed subsequently. Now all the Radiosonde stations in India are equipped with instrument with advanced technology. There are 56 Radiosonde and Radio Wind (RSRW) stations under IMD's control.

Radio theodolites and wind finding radars are capable of measuring winds at great heights accurately. Even wind of the jet stream can be measured. After the Second World War some surplus anti aircraft radars were available. IMD acquired those and after reconditioning took some test flights at Delhi and Poona. Routine observation began in 1948 - 49. Later on similar observations were taken at Madras, Calcutta, Nagpur and Allahabad. These were replaced by 401 MHz radio theodolites during the mid nineteen fifties. In mid sixties, 1680 MHz radio theodolites and X – Band wind finding radars were imported.

Radiosonde observations are taken twice daily, at 0000 UTC (0530 IST) and at 1200 UTC (1730 IST), and Pilot balloon observations are taken at 0600 UTC (1130 IST) and 1800 UTC (2330 IST). The Radiosonde observations provide vertical profiles of temperature, pressure, humidity, and wind up to about 30 km, whereas Pilot balloon observation provides only the wind profiles at lower tropospheric levels. The data undergo rigorous quality checks as per the WMO (World Meteorological Organization) standards and is archived at IMD Pune.

With the availability of upper air data IMD started preparing upper air charts and analyzed those charts. Probably the upper air data were included in the charts in 1936. Thus the three dimensional structure of the atmosphere were available to the forecaster and weather forecasting started with the available surface and upper air data.

8. New developments

In the nineteen sixties a lot of changes took place in the forecasting service in India and new centers were opened. In early 1960's, progress in techniques of analysis for high level aviation assumed a lot of importance and considerable impetus. The first to be formed was the Northern Hemisphere Exchange and Analysis Centre (NHEAC) at New Delhi. A radio teletype channel linking between New Delhi and Moscow was established in 1960. A similar type of channel between New Delhi and Tokyo was also established in 1961. A large volume of meteorological data for the northern hemisphere became available to the Indian meteorologists for the first time. The Northern Hemisphere Analysis Centre (NHAC) was entrusted with the task of processing these data, preparing constant pressure charts and examining different techniques of prognosis. A scheme for routine broadcast of analyzed and prognostic charts by facsimile transmission was also put into operation. These charts were disseminated at different centers in India and abroad.

International Indian Ocean Expedition (IIOE) was conducted. This was a large-scale multinational hydrographic survey of the Indian Ocean which took place from September 1, 1959 to December 31, 1965, It worked to describe and understand the basic features of the Indian Ocean. The expedition involved vessels from more than twelve countries for collection of data. In 1963 the International Meteorological Centre (IMC) was established in Bombay in connection with the meteorology program. A large volume of data from the Southern Hemisphere was available at this centre, in addition to the data for the northern hemisphere. Meteorological Charts covering from 20° E to 155° E and 50° S to 45° N were prepared and analyzed at the IMC. On completion of the IIOE program the IMC was shifted to Pune in June 1966. It was named as the Indian Ocean and Southern Hemisphere Analysis Centre (INOSHAC). It started working under the Office of the Deputy Director General of Meteorology (Weather Forecasting). The center has been carrying out Marine meteorological forecasting services since 1966. It also issues advisories and meteorological forecasts over the Indian Ocean north of 10º S. as per WMO requirement.

This centre provides following meteorological forecasts:

(*i*) Fleet forecasts for Indian Navy twice a day over the Indian Ocean to the north of 10º S between Longitude 60º E to 100º E.

(ii) Under the Global Maritime and Distress Safety System (GMDSS) weather forecasts twice a day for Indian Ocean area to the north of the Equator and the consolidated forecast for the area of the Indian Ocean enclosed by lines from the India/Pakistan frontier at 23° 45' N 68° E to 12° N 63° E, then to Cape Gardafui and the East African coast southward to the Equator, then to 95° E, to 6° N, then north east to the Myanmar/Thailand frontier at 10° N 98° 30' E *i.e.*, Met-area VIII(N). Similar inputs for the Arabian Sea and the Bay of Bengal received from Area Cyclone Warning Centers (ACWCs) Mumbai and Kolkata are transmitted. This frequency increases during tropical cyclone period.

Another important change took place in the nineteen sixties. A new branch of meteorology known as Satellite Meteorology was born. (Kelkar 2021) The first weather

Satellite, Television Infrared Observation Satellite (TIROS -1), was launched by the National Aeronautics and Space Administration, U. S. on 1 April 1960. Automatic Picture transmission (APT) transmitted at ground station became available from 1964. IMD established APT station in Mumbai in 1965. Indian Meteorologists started getting Cloud imageries of India and joining areas, twice a day. Six more APT stations were established in 1970. This helped the meteorologists to get images of tropical cyclone over the oceanic region and also research on monsoon other important weather systems. India started its own space program and Indian Space Research Organization (ISRO) was established on 15 August 1969. ISRO launched the first satellite Aryabhata in 1975 and thereafter Bhaskara – I and Bhaskara – II in 1979 and 1991 respectively. But the real satellite program started in a big way with the launching of Indian National Satellite (INSAT – 1) on 10 April 1982. INSAT – 1 system was a multipurpose satellite. It had the facility of communication, television, radio broadcasting and meteorology in a single system. The INSAT – 1 series was fabricated in U.S. and launched from foreign countries. However, the INSAT – 2 series and the INSAT – 3A series were fabricated indigenously by ISRO. The METSAT, exclusively dedicated to Meteorology, was launched in 2002. It was later on named Kalpana – 1. INSAT – 3D, very advanced, primarily a meteorological satellite was launched in 2013. It generates images in Visible, Short wave Infrared, Middle Infrared, Water vapor and two bands in thermal Infrared regions and has 1 km resolution in the visible region. Another advanced satellite INSAT 3DR was launched by ISRO in 2016. In order to process the real time Very High Resolution Radiometer (VHRR) Data a data processing facility was established in IMD Complex in New Delhi in 1982. This was replaced by a new computer system in 1992. All INSAT satellites are Geostationary Satellites. INSAT – 3D was launched on 26 July 2013. To process the data received from a new processing system was established in IMD, New Delhi. With the availability of satellite imageries meteorologist can watch the growth of Cumulonimbus Cloud, fog *etc* monitor the movement of tropical cyclones, western disturbances, and monsoon depressions, identify and locate surface Lows, troughs and ridges, jet streams, region of intense Convection. With the INSAT imageries meteorologists can locate and estimate intensity of tropical cyclones. It helps him in forecasting the intensity, the track and the land fall region accurately. The imageries are also helpful in monitoring the onset of monsoon over Kerala and its further advancement. Further, satellite measured radiance can estimate several atmosphere, ocean and land parameters. Several quantitative parameters like Cloud motion vector (CMV), Outgoing Longwave Radiation (OLR), Quantitative Precipitation Estimates (QPE), Sea Surface temperature (SST), Aerosol Optical Depth, Snow cover, Fog, Fire, Smoke, temperature and humidity profiles, Geo-potential Height, Layer Precipitable Water, Total Precipitable Water, Lifted Index, Dry Microburst Index, Maximum Vertical θ_e Differential profiles, and Wind Index etc. can be obtained. These data help the meteorologists in understanding the weather phenomena and forecasting. OLR data play a very important role in monitoring the onset of monsoon over Kerala.

9. Types of weather forecasts

There are several types of weather forecasts. These are meant for different users. The weather forecasts can be of both spatial and time scales.

Spatial Scale: It ranges from Local to Regional and Global. Broadly, spatial scales include the Planetary, Synoptic, and Mesoscale.

Planetary or global scale is the largest and generally span tens of thousands of kilometers in size, extending from one end of the globe to another.

Synoptic or Large Scale is smaller than the Planetary scale, yet it large enough and covers distances of a few hundred to several thousand kilometers.

Mesoscale is smaller than the synoptic scale and it ranges from a few kilometers to several hundred kilometers in size. Mesoscale is further subdivided into Meso - α (200 - 2000 km), Meso - β(20 - 200 km) and Meso - γ (2 - 20 km).

Local Forecast encompasses a city or a town *i.e.*, a small area. It comes under the category of Mesoscale.

Temporal Scale: Temporal scales may be from hours to days.

(*i*) Short Range Weather Forecast

(*ii*) Medium Range Weather Forecast

(*iii*) Extended Range Weather Forecast

(*iv*) Long Range Weather Forecast

Short Range Weather Forecast is valid up to 2-3 days. This is specially meant for common man. He can plan his activities according to the forecast.

Medium Range Weather Forecast is valid between 3 and 10 days. Extended Range Weather Forecast is valid for 10 to 30 days. Both these forecasts are basically meant for the farmers. Farmers can decide their lines of action regarding farming activities.

Long Range Weather Forecast is valid for one month to a season. This is meant mainly for the Administrators and Planners. The most important examples are the South West Monsoon (June to September) and Northeast Monsoon (October to December) Rainfall Forecast. These are issued by the India Meteorological Department every year. IMD has been doing this for almost 150 years.

There is another type of forecast known as Nowcasting. It is a form of very short-range weather forecasting; that is, the current weather along with forecasts up to about six hours. This is mainly for aviation activities, thunderstorm forecast and flash flood.

Climate Predictions or Outlooks are about the future climate conditions on timescales ranging from decades to centuries and on spatial scales ranging from local to regional and global.

10. Methods of weather forecasting

Weather forecasting is a critical and challenging job. It involves formulating and disseminating information about future atmospheric conditions. The modern scientific method of weather forecasting has its origin in the middle of the nineteenth century. The Scientific weather forecasting is based on the collection, analysis of meteorological data and extrapolation to determine the future state of the atmosphere.

One method of extrapolation is to conclude that the weather features will continue to remain the same as they have been. This is known as Persistence Method of forecasting. This was followed in the early days of weather forecasting. Planetary-scale phenomena are persistent but the synoptic and smaller scale phenomena are not. This method is not in use now because day to day weather varies a lot.

Another method was in use is the Analogue forecasting. It is based on the principle of making predictions by comparing current weather patterns to similar patterns (or analogs) from the past. It played a key role during the Second World period. This method was used in planning the D – Day invasion of Normandy in 1944. But it is very difficult to find enough useful analogs from past weather catalogs.

In addition to the above methods there are primarily three methods of weather forecasting:

(*i*) Synoptic Method

(*ii*) Statistical Method and

(*iii*) Numerical Method

Meteorological observations, both surface and upper air, constitute the raw material for weather forecasting. These observations are plotted on maps and charts to have an idea about the three dimensional structure of the atmosphere. Satellite and RADAR Observations are also collected as additional information. The forecaster uses his knowledge of meteorology. He uses his knowledge of the Physical and Dynamical laws governing the behavior of the atmosphere to prognosticate the future state of the atmosphere. This forecast is mainly qualitative. This is known as Synoptic method. In the early days this method was used for weather forecasting.

In India as well as in many other countries synoptic techniques used to be the main stay of prediction till a few years back. This method is rather empirical and subjective and the experience of the person giving forecast plays a dominant role in it.

Statistical technique comprises of correlation, regression, contingency, stochastic deterministic methods etc. Time series data of meteorological parameters are often used in the statistical method. One such method is trend analysis. One is linear trend and other nonlinear trend analysis. In linear trend model a straight line is fitted for the past data using least square method but unfortunately the deviation of the straight fit from the data is often the largest near the end of the time series, where the forecasting is to be made. This error can be reduced by using nonlinear trend models in which nonlinear fits like quadratic or higher order polynomials, exponential or logarithmic relations etc. Instead of single parameter a number of parameters can also be used to forecast which is known as multiple regression models. This is better than the linear regression method.

Autoregressive Moving Average (ARMA) model and Autoregressive Integrated Moving Average (ARIMA) models are also used in weather forecasting. (Kulkarni *et al* 2008) An ARMA model is a stationary model and is used to describe time series in terms of two polynomials. The first of these polynomials is for auto regression, the second for the moving average. The only difference, between these is the word “Integrated”. Integrated refers to the number of times needed to difference a series in order to achieve stationarity. These models have been used for forecasting temperature, winds and rainfall *etc*. It is also used for long range forecasts

Artificial Neural Networks (ANN) model is another method of weather forecasting (Kulkarni 2008). It is based on simple mathematical models of the brain. It is a network of "neurons" which are organized in layers. A neural network has many layers and each layer performs a specific function, and as the complexity of the model increases, the number of layers also increases. The purest form of a neural network has three layers: the Input layer, the Hidden layer, and the Output layer. The predictors form the input layer, intermediate layer containing hidden neurons and the forecasts form the output layer. The input layer picks up the input signals and transfers them to the next layer and finally, the output layer gives the final prediction. These neural networks have to be trained with some training. The network is designed by trial and error method.

Of late, Artificial Intelligence (AI) and Machine Learning (ML) have found applications in increasing number of domains including the problem of weather and climate forecasting. ML is a subset of AI while Deep learning (DL) is a technique within ML. The newly developed global weather model bases its predictions on the past 40 years of weather data. According to Jonathan Weyn "Machine Learning is essentially is a glorified version of pattern recognition. It sees a typical pattern, recognizes how it usually evolves and decides what to do based on the examples it has seen in the past 40 years of data" (Weyn *et al.*, 2020). ML techniques are subdivided into two types - supervised and unsupervised. Supervised techniques are more common in weather and climate forecasting. Supervised learning is further subdivided into classification and regression. In supervised regression learning a large number of predictors and predictants and pairs are used to tune the parameters of the statistical model using ML techniques. In linear regression these parameters happen to be the coefficients of regression. Even multivariate linear regression is considered as ML technique. Linear regression has been applied extensively in the field of atmospheric and ocean sciences. Deep learning is a type of Neural Network with multiple hidden layers. The number of tunable parameters in DL network is huge. These could be of the order of millions. If the amount of data is smaller in comparison to the number of free parameters, the DL over fits the data. An over fit model performs poorly. It has been found that even when the resulting training error is very small the error of prediction on new data is much larger. This is a telltale symptom of over fitting. This issue can be addressed by using only about 80% data for training and 20% data for testing before deploying the trained model in operations. Weyn *et al*. (2020) used data from 1979 to 2012 to train the DL model while 2013-2016 for validation. AI/ML techniques have demonstrated great potential in addressing unsolved problems in the domain of weather and climate forecasting (Mathew, 2021).

Many countries use synoptic-cum-statistical technique for weather forecasting. Statistical methods are also not fully objective because two parameters may show a very high correlation though there may not be having any physical connection between them. Also the method does take into account dynamics of fluid.

In order to bring in objectivity in Forecasting we require:

(*i*) A set of Prediction equations where the number of equations should be equal to the number of variables.

(*ii*) Initial and Boundary values of the field variables (Observations).

(*iii*) A method of integrating the equations in time to obtain future distribution of the field variables.

In the beginning of the twentieth century, Professor V. Bjerknes, the well-known Norwegian Meteorologist, recognized that the forecasting of weather could be done by solving the fundamental equations, which govern the atmospheric circulation. In this method the forecasts would not depend on the experience of the forecaster. This method would be totally objective. The Fundamental laws are:.

(*i*) The law of conservation of Momentum - Newton's Second law of Motion.

(*ii*) The law of conservation of Energy - The first law of Thermodynamics.

(*iii*) The law of conservation of Mass - Mass Continuity Equation.

(iv) The Gas Laws – Combined Charles Law and Boyle's Law.

(*v*) The law of conservation of Moisture – Moisture Continuity Equation.

The corresponding Equations are respectively:

$\frac{d\vec{V}}{dt} = -\frac{1}{\rho}\nabla p - \vec{\Omega} X \vec{V} + \vec{g} + \vec{F}$ (Equation of Motion)

$\frac{dQ}{dt} = c_v \frac{dT}{dt} + p\frac{d\alpha}{dt} = c_p \frac{dT}{dt} - \alpha \frac{dp}{dt}$ (First Law of Thermodynamics)

$\frac{1}{\rho}\frac{d\rho}{dt} + \nabla \bullet \vec{V} = 0$ (Equation of Continuity)

$p\alpha = RT$ (Gas Law or Equation of State)

$\frac{dq}{dt} = E - P$ (Moisture Continuity Equation)

Where, $\frac{d}{dt} = \frac{\partial}{\partial t} + \vec{V} \bullet \nabla$; $\vec{V}$is the wind vector, $\vec{\Omega}$ angular velocity of the Earth,$\vec{\boldsymbol{g}}$gravity, $\vec{F}$ Friction, E = Evaporation, P = Condensation $q$is any moisture parameter and $\alpha = \frac{1}{\rho}$, ρ the density of air.

But these equations are highly nonlinear in character and do not possess any analytical solution. These equations can be solved numerically. In addition, data were inadequate to determine the initial conditions. Since the problem was so difficult that no serious attempt on this kind of approach was made until the First World War. The first attempt to solve the system of equations numerically using desk calculators was made by the British Mathematical Physicist, Lewis Fry Richardson, around 1920. He brought out a Monograph entitled Weather Prediction by Numerical Process, which described a method for numerically integrating the governing equations. Unfortunately, his experimental results, which required a long time, were in error by orders of magnitude. As a consequence, his monumental work was ignored for more than two decades. It was found out that his results were in error mainly because he had not filtered out unwanted spurious waves in his model. Moreover, he did not remove the Instability, known as Computational Instability, caused while solving the governing equations by the finite difference technique. The disappointing nature of his results discouraged further attempt in this direction till the beginning of the Second World War. The real breakthrough came in the late 1940's with the advent of Computer. Using the "Electronic Numerical Integrator and Computer" (ENIAC), Meteorologists Professor Jule Gregory Charney, Professor Ragnar Fjortoft and Mathematician Professor John von Neumann produced the first successful numerical prediction in 1950. The prediction schemes designed by them yielded results that showed reasonable agreement with reality. They used a far simpler model than the one used by Richardson. They used derived equation rather than the basic equations. That was the beginning of the dynamical forecasting by numerical methods. This is commonly referred to as Numerical Weather Prediction (NWP).

During the past six decades there has been a rapid advance in all phases of NWP concomitant with the remarkable advancement in the field of electronic computer. Several sophisticated models have been developed. Many of these models are in operation for day to day forecasts. The forecasts issued using these models have been reasonably successful in the extra tropical region and in the higher latitudes but for the tropical region the success is limited. The physics of the atmosphere in the tropics is quite complicated and many of the physical phenomena have not yet been understood completely. The dynamics of wave motion is also different for low latitudes. The effect of earth's rotation is also very small there. NWP models indicate that tropical weather systems are generated largely by variations on the earth's surface, that is, the weather systems are forced by changes in boundary conditions. With the advancement in the science of Tropical Meteorology and with availability of high speed computers with a very large memory it is expected that the position would improve considerably. At present, Numerical Weather Prediction Models are used by almost all the countries in the world to give forecast of weather and climate.

11. Numerical weather prediction in India

Dr. P. K. Das may be considered as the father of NWP in IMD. He was the first person in IMD to start research on NWP and published a paper on NWP titled "Numerical Prediction of the movement of Bay Depressions" along with B. L. Bose as early as in 1958 in the Indian Journal of Meteorology and Geophysics. They used non divergent Barotropic model of Charney and Estoque's Baroclinic model for their work. A research Group was set up in 1969. Initially IMD Started running Barotropic model and the output was transmitted by facsimile to the forecasting offices as advisory. Attempts were made to forecast the movement of tropical storms and depressions in nineteen eighties. Limited area Analysis and Forecast Model (LAM) was used operationally in the nineteen nineties. In the new millennium, there was a quantum leap in Numerical weather prediction in IMD. In the early twenty first century IMD started using Regional model Weather Research and Forecasting (WRF) operationally. Also the Advanced Regional Prediction (ARPS) model, which is a comprehensive regional to storm scale atmospheric modeling / prediction system, was also implemented operationally. In 2010 IMD acquired a high power computing system IBM - P5 HPCS and operationally implemented the Global Forecast System Model IMD - GFS (T - 254) and the Regional Model WRF. A few years later Coupled model was used operationally. The Climate Forecast System Version 2 (CFSv2) produced by the National Centers for Environmental Prediction (NCEP) is a fully coupled model representing the interaction between the oceans, land and atmosphere was used for real time extended forecast up to four weeks in 2016. The Hurricane Weather Research and Forecasting (HWRF) model is a specialized version of the weather research and forecasting model. This model along with the Princeton Ocean Model (POM-TC) was used to forecast the track and intensity of tropical cyclones in 2018. IMD used another model HYbrid Coordinate Ocean Model (HYCOM) coupled with HWRF for Tropical cyclone forecast in 2019. The Global Ensemble Forecast System (GEFS) is another weather Forecast model. It is created by the National Centers for Environmental Prediction (NCEP). It can generate 21 separate forecasts (ensemble members). This model was also operationalized by IMD in 2018. Presently, IMD is using high resolution (12 km) global model and global ensemble forecasting system for short and medium range weather forecasting; coupled model for extended range forecast; High resolution cloud resolving mesoscale forecasting system for very short range forecast; HWRF Ocean coupled model for tropical cyclone forecast and Multi – model ensemble / dynamical statistical model for cyclone track and intensity prediction. IMD is now equipped with synoptic charts surface and upper air, NWP products, satellite and radar data. All these information has given a shot in the arm of the forecaster. IMD has been doing very good job in day to day weather forecasting. IMD has excelled in Tropical cyclone forecasting. The forecast of the track, intensity and Land fall time and location has become very accurate.

Prior to 2009, the synoptic charts were analyzed manually. In 2009 IMD acquired Amplitude Modulation Signaling System (AMSS) from Meteo France International (MFI) along with the Synergie tool (Visualization of Charts in computers). This has reduced time for plotting and analysis of charts.

For day-to-day operational forecasting, IMD uses various global and regional models. Some of the models run by the organizations under MOES for operational medium-range forecasting include,

(*i*) IMD GFS (Global Model, Resolution 12 km)

(*ii*) IMD GEFS (Global Ensemble Model with 21 members, Resolution 12 km)

(*iii*) IMD WRF (Regional Model, Resolution 3 km)

(*iv*) NCMRWF NCUM (Global Model, Resolution 12 km)

(*v*) NCMRWF NCUM – R (Regional Model, Resolution 4 km)

(*vi*) NCMRWF NEPS (Global Ensemble Model with 23 members, Resolution 12 km)

Apart from these, IMD also takes guidance from medium-range forecasting models by the NCEP, Japan Meteorological Agency (JMA), and European Centre for Medium-Range Weather Forecasts (ECMWF).

12. Evolution of weather forecasting in India

One of the most important activities of IMD is weather forecasting. IMD has been issuing different types of forecasts since its formation. In this article we will confine our discussion mainly about Short Medium and Extended range forecasts.

Forecasting of weather is a difficult job. The raw materials for weather forecasting are meteorological observations of pressure, temperature, humidity, wind direction and speeds *etc*. When IMD was established in 1875 the number of observatories was only a few. Scientists of IMD took up the challenge with limited facilities and started issuing forecasts. At that time IMD had to mainly issue warning for ships of the impending storm in the Bay of Bengal and local forecasts. Weather forecasting was probably done by considering the variation of atmospheric pressure and wind. The experience of the forecaster was playing a significant role. Persistence method was also used. As more observatories were established the responsibility also increased. Most of these observatories were equipped with Barometers, Thermometers and Wind Instruments. By 1887 full isobaric charts with atmospheric pressure plotted in inches were prepared. Surface winds were available on the isobaric chart. Troughs, ridges, cyclones and anticyclones were delineated and is allobaric analysis used to be done. The forecasting tool might have been the Kinematics of the pressure field. In addition basic physics of atmosphere was taken into consideration. Weather forecasts were given on regular basis for larger areas. Weather forecasts were quite useful to the users.

Systematic upper air observations began in the Department in 1905. By 1936 some upper winds observations, ships observations and upper air temperature and humidity from aircraft were available to the Indian meteorologists. This was a shot in the arm to the forecaster. They got fair idea about the three dimensional structure of the atmosphere and the knowledge of synoptic meteorology helped them in issuing weather forecasts. Subsequently, by the second half of the twentieth century radiosonde observations were taken on a regular basis two times a day. Upper air observations of winds, temperature and humidity at various levels helped the forecasters. They plotted and analyzed the surface and upper charts. T - ϕ grams were plotted and analyzed for the upper air stations twice daily. All this information was used to prognosticate the weather for various meteorological subdivisions for 24 hours. The outlook for the next 3 days was also issued. Forecasts were issued for general weather condition, maximum and minimum temperatures, rainfall. Warnings for heavy rainfall, thunderstorms, cyclones, heat and cold waves were also issued. Satellite observations were available from 1970. Cloud imageries from the data sparse regions and the over the oceanic regions became available. With all these observations the skill of weather forecasts improved considerably. Forecasts were issued from the Office of Deputy Director General of Observatories (Forecasting)

Pune for whole of India and the Regional Meteorological Centers for the regions under their responsibility. Knowledge of Synoptic Meteorology, Dynamic Meteorology, Atmospheric Thermodynamics and the experience of the forecaster were the main tools for forecasting.

In 1970 IMD started running Barotropic Model in NHAC computer and output of this model was available at all the forecasting centers. This information was used as an advisory to the forecasters. IMD started using Numerical Weather Prediction (NWP) models for weather forecasting in the 1990s. The specific model used initially was the Operational implementation of Limited Area Analysis & Forecast Model (LAM) and Quasi-Lagrangian Model (QLM) for cyclone track prediction.

At present IMD is using Regional IMD-WRF Model for short range weather forecasting. 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 uses High-Resolution Rapid Refresh (IMD-HRRR) Model for Nowcasting. The is a 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 10-15 minutes.

IMD-GFS for Medium Range forecasting: - Initially the GFS model's resolution was T382 The resolution was increased to T574 (25 km) in 2012. Its resolution was further increased to T1534 (12 km) in 2016. At present the IMD-GFS global model is run with ~12 km horizontal resolution 2 times a day (00 and 12 UTC) to generate 10 days forecast and additional 2 times a day (06 and 18 UTC) up to 5 days.

IMD-GEFS for Medium Range forecasting: - In 2018 IMD also implemented the IMD-GEFS global ensemble model (21 members) is run with ~12 km horizontal resolution 2 times a day to generate 10 days forecast. At present, it is the highest resolution global ensemble model operationally run in the world.

CFSv2 coupled model for Extended Range forecasting: - IMD implemented CFsv2 coupled model for operational extended range forecasting in year 2016. This suite of multi-model is based on CFSv2 and GFS system. It is run operationally for 32 days based on every Wednesday initial condition with 16 ensemble members to forecast for 4 weeks.

Dynamical-Statistical modeling for Tropical Cyclone Forecasting: The Cyclone Genesis Potential Parameter (GPP), Multi-Model Ensemble (MME) technique for cyclone track prediction and SCIP and decay models for tropical cyclone intensity forecast are run for to provide objective guidance for tropical cyclone forecasting.

IMD-HWRF-HYCOM/POM coupled model:-I IMD-HWRF ocean coupled model is triple nested (18x6x2km) and run 4 times a day during cyclones over NIO to give 5 day forecast products for tropical cyclone predictions. It is the only regional ocean coupled modeling system being run operationally in India for Tropical Cyclone forecasting.

With the introduction of NWP models along with the conventional Synoptic method the skill of Weather Forecasting has improved a lot.

13. Extended range and medium range forecasts – service for agricultural operations

IMD has been issuing MRF since long, particularly for the agricultural operations. Initially, it was done by statistical methods. Of late, there have been some efforts by various research groups to predict the monsoon and topical weather on an extended range time scale. The extended range forecasting (forecasts between 7 and 30 days) fills the gap between medium-range weather forecasting and seasonal forecasting. It is often considered a difficult time range for weather forecasting, since the time scale is sufficiently long so that much of the memory of the atmospheric initial conditions is lost, and it is probably too short so that the variability of the ocean is not large enough, which makes it difficult to beat persistence.

With the efforts from the Ministry of Earth Sciences (MoES), operational implementation of the coupled model with a suite of models from Coupled Forecast System version 2 (CFSv2) coupled model has been implemented in IMD in July 2016. This dynamical prediction system developed at Indian Institute of Tropical Meteorology (IITM) has been transferred to IMD and the same has been implemented by IMD for generating operational Extended Range Forecast products to different users. This suite of models at different resolutions with atmospheric and oceanic Initial conditions obtained from National Center of Medium Range Forecast (NCMRWF) and Indian National Center of Ocean Information Services (INCOIS) assimilation systems respectively are

(*i*) CFSv2 at T382 (≈ 38 km)

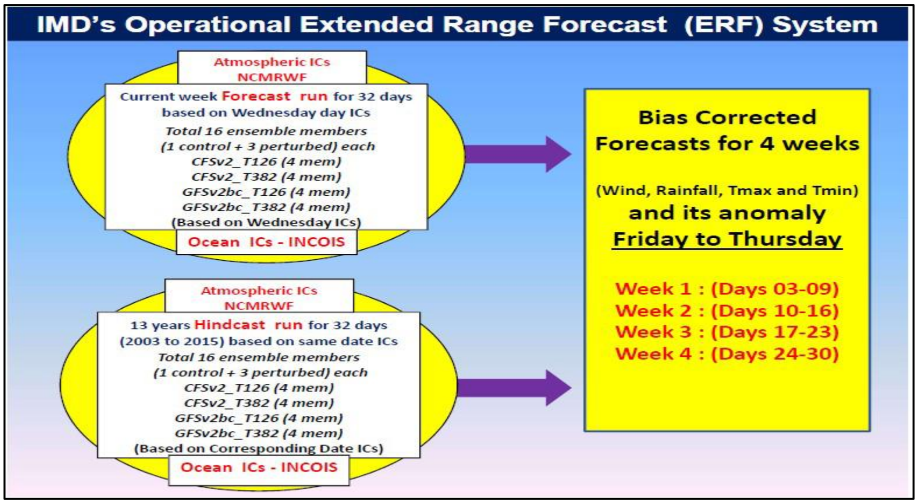

Fig. 2. IMD's Operational Extended Range Forecast (ERF) System

(*ii*) CFSv2 at T126 (≈ 100 km)

(*iii*) GFSbc (bias-corrected SST from CFSv2) at T382 and

(*iv*) GFSbc at T126.

The operational suite is ported in ADITYA HPCS at IITM Pune for day-to-day operational run. The Multi-model ensemble (MME) out of the above 4 suite of models are run operationally for 32 days based on every Wednesday initial condition with 4 ensemble members (one control and 3 perturbed) each for CFSv2T382, CFSv2T126, GFSbcT382 and GFSbcT126. The same suites of model are also run on hind cast mode for 13 years (2003-2015). The average ensemble forecast anomaly of all the 4 set of model runs of 4 members each is calculated by subtracting corresponding 13-years model hind cast climatology. For the preparation of mean and anomaly forecast on every Thursday, which is valid for 4 weeks for days 3- 9 (week1; Friday to Thursday), days 10-16 (week2; Friday to Thursday), days 17-23 (week3; Friday to Thursday) and days 24-30 (week4; Friday to Thursday). The operational Extended Range Forecast System of IMD is shown in Fig 2.

14. Flood forecasting

India receives about 80% of its annual rainfall during the Southwest Monsoon Season June to September. The rainfall shows wide range of spatial variations. IMD renders assistance and advice on the meteorological aspects of hydrology, water management and multipurpose river valley projects management. These services are utilized by the Central Water Commission (CWC), Ministry of Agriculture, Ministry of Water Resources, Railways, Damodar Valley Corporation Flood Control Authorities and the State Governments. In the nineteen seventies IMD established ten Flood Meteorological Offices (FMO) in India. Each FMO provides valuable meteorological support including Quantitative Precipitation Forecast (QPF) for catchment areas of the rivers mentioned. This helps the CWC in issuing flood warnings. Rainfall Analysis, Synoptic charts, synoptic analogues, NWP products, satellite imageries/products and RADAR products (if available) are utilized for formulation of QPF Bulletin and Hydromet Bulletin.

15. Nowcasting

In India Meteorological Department, Nowcasting comprises the detailed description of the current weather along with forecasts obtained by extrapolation for a period of 0 to 3 hours ahead. In this time frame, it is possible to forecast small features such as individual storms with reasonable accuracy. A forecaster using the latest radar, satellite and observational data is able to make analysis of the small-scale features present in a small area such as a city and make an accurate forecast for the following few hours. It is, therefore, a powerful tool in warning the public of hazardous, high-impact weather including tropical cyclones, thunderstorms and tornados which cause heavy rains, flash floods, hails, lightning strikes and destructive winds. In addition to using Now-casting for warning the public of hazardous weather, it is also used for aviation weather forecasts in the terminal and en-route environment, marine safety, water and power management, off-shore oil drilling, construction industry and leisure industry. The strength of Nowcasting lies in the fact that it provides location-specific forecasts of storm initiation, growth, movement and dissipation, which allows for specific preparation for a certain weather event by people in a specific location. Nowcasting is done by the National Weather Forecasting Centre, IMD New Delhi in collaboration with all the Meteorological Centers across the country.

16. Artificial intelligence and machine learning technique for weather forecasting in India

IMD has in its archive excellent records of weather parameters. This record is for more than 100 years. IMD is exploring the possibility of using Artificial Intelligence and Machine Learning techniques for weather service during the Monsoon Season. IMD has used AI to generate public alerts regarding heat waves.

17. Conclusion

Weather forecasting is a very difficult and challenging job, particularly for the tropical region. Atmospheric Dynamics is chaotic in nature, so errors can grow exponentially. Forecasting is complex in the sense that a lot of components are interacting with each other. Forecaster is on the receiving end when his forecast goes wrong. This is, of course, an occupational hazard. Since there is uncertainty in it, forecasting will always remain challenging. IMD made modest beginning in 1875. Since then it has been rendering services to various sectors; Government as well as Private. The journey started almost 150 years back. This long journey has not been smooth. There were hurdles in between but all have been overcome. A few decades back numerical model for Seasonal forecasts was unimaginable but today it is a reality. IMD has been using Numerical models for Seasonal forecasting. Challenges will be coming in future also. With the advancement of technology and with more knowledge on the subject the new challenges will be coming. Demands from Various Sectors also will be more. Challenges have to be accepted.

Numerical models like WRF with GFS and CFS with higher resolutions are showing good results now. Of late, Artificial Intelligence has assumed a lot of importance and is rapidly emerging as a faster and cheaper alternative for improving forecasts of extreme weather. AI originated in early 1950. In India the research on AI and ML was started by Indian Statistical Institute and Indian Institute of Technology, Kanpur in nineteen hundred sixties. Using AI for weather prediction is in use since the 1970s. Professor Dale Durran and his group in the Department of Atmospheric Science, University of Washington has been trying to develop models using AI that will have the ability to forecast the weather more accurately. (Weyn et al 2019). AI is still in the nascent stage in weather forecasting. But AI has potential to forecast correctly. AI algorithms enable remarkable speed in processing vast amounts of data, resulting in faster and more immediate weather predictions. IMD has a wealth of meteorological data. These data will be of great use to develop AI/ML models for weather forecasts. It is believed that the future lies in AI.

Presently, IMD issues weather forecasts using NWP Models and Synoptic Meteorology quite successfully. The skill of forecast has improved a lot in the last decade. The forecasts for the formation, intensification, movement and landfall of tropical cyclones have become excellent. Since AI has potential, a combination of Synoptic Meteorology, NWP and AI with human expertise may lead to a much improved forecasts. Only time will tell what lies in future. For the accuracy and efficiency of weather prediction, the role of the forecaster is very important for interpreting and communicating weather information effectively.

Acknowledgement

Shri Chinmay Khadke and Shri Ranjan Phukan Scientists in the Indian Meteorological Department have supplied us with a lot of information. The authors are grateful to them for their kind help.

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

References

India Meteorological Department, 1975, Hundred Years of Weather Service (1875-1975).

Narendra, K. Segal and Subodh Mahanta (Editors), 1995, Memoirs of Ruchi Ram Sahni , Published by Vigyan Prasar, India.

India Meteorological Department, 2000, 125 years of Service to the Nation. A retrospective and Futuristic Review.

Makarand, A. Kulkarni, Sunil Patil, G. V. Rama and P. N. Sen, 2008, "Wind speed prediction using statistical regression and neural network", *J. Earth Ss Sci*. **117**, 3, 457.

Weyn, J. A., D. R. Durran and R. Caruana, 2019, "Can Machine Learning to Predict Weather? Using Deep learning to Predict Gridded 500 hPa Geopotential from Height from Historical data", *J. Advances Model Earth Sys*. doi : https://doi.org/10.1029/2019MS001075.

J. A. Weyn, D. R. Durran and R. Caruana, 2020, "Improving data-driven global weather prediction using deep convolutional neural networks on a cubed sphere", *J. Advances Model Earth Sys*.12, e2020MS002109, doi : https://doi.org/10.1029/2020MS002109.

Kelkar, R.R. 2021, "History of Satellite Meteorology in India", IMD Blog.

C. Mathew, H. Christensen, P. Dueben and T. Palmer, 2021, Opportunities and challenges for machine learning in weather and climate modeling: hard, medium and soft AI. Phil. Trans. R. Soc. A.3792020008320200083,http://doi.org/10.1098/rsta.2020.0083

Sen, P. N., 2021, "Numerical Weather Prediction Guidance for Weather Forecasting", IMD Blog.

Sen, P. N., 2021, "Weather & Weather Forecasting", *Vayu Mandal* **47**,2.

India Meteorological Department, 2023, https://mausam.imd.gov.in/.

India Meteorological Department, 2023, Annual Report 2022.