Weather and Weather Forecasting

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ABSTRACT

All human activities are linked with the state of the atmosphere i.e., the weather. One can plan one's activities if the weather conditions are known in advance. Weather forecasting is the attempt by the meteorologists to predict the state of the atmosphere at some future time. Though weather forecasting started in ancient times but the modern scientific methods of forecasting started only in the middle of the nineteenth century. For weather forecasting most important component is observations. In addition to the conventional instrumental observations, RADAR and satellite observations are used for weather forecasting. There exist several types of weather forecasts for various users as well as many techniques of forecasting like persistence, analogue, synoptic, statistical, Artificial Neural Network, Artificial Intelligence and Machine Learning, NWP. Nowadays, guidance from NWP models is used for weather forecasting worldwide including in India. With the advancement of the science of meteorology and High Performance Computing (HPC) systems, the skills of the forecasts have improved considerably but a lot more has to be achieved.

Keywords: *Synoptic, Mesoscale, Artificial Neural Network, Artificial Intelligence and NWP.*

1. Introduction

Atmosphere is a mixture of gas molecules, microscopically tiny suspended solid and liquid particles. It envelops the Entire Earth. About 99.99% of the Atmosphere is below 100 km. 100 km thickness is minimal (~ 2 %) compared to the radius of the Earth 6400 km. One of the components of the atmosphere is water vapor. Water Vapor accounts for only about 0. 25% by volume. Most of the water vapor is found in the lowest 5 km. Though the water vapor accounts for only a small portion of the atmosphere, it plays a crucial role in weather formation. It is needed for the formation of clouds, it absorbs the energy emitted by the Earth and it changes into liquid and solid phase both at the surface of the earth as well as in the atmosphere. The state of the atmosphere of a place and at a particular time is known as the *Weather* of the place. By the state of the atmosphere we mean the atmospheric conditions like Air Temperature, Barometric Pressure, Humidity, Sunshine, Wind, Cloudiness, Rainfall, Snowfall etc. Most of the weather phenomena occur in the lowest part of the atmosphere. The long-term average of weather conditions of a place is called Climate. Climate gives us an idea about the atmospheric condition that is expected to get on a particular day but we may not get the same on that day.

All human activities depend on the weather conditions. 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. A Lot of research in going worldwide on different aspects of Atmospheric science but the ultimate goal 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 as well as for organizations. One can decide whether to take an umbrella or carry warm clothing or put on light clothing etc., while venturing outside. Depending on the weather forecasts a farmer can decide whether to sow the seeds or harvest the crops; an 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 warn the fishermen 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 necessary steps for procuring sufficient quantities of food and take other precautionary measures.

2. Weather Forecasting through Ages

The ancient civilizations realized the importance of Weather forecasting. 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 suggested some theory for the formation of clouds, rain, hail etc. He made some important observations concerning the weather. However, 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 processes 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 deep knowledge of atmospheric processes existed during that time. Scientific measurements of rainfall have been mentioned in Kautilya Arthashastra. Kalidasa wrote his epic Meghaduta during the seventh century. He mentioned the date of onset of Monsoon over Ujjain, a city in Central India and the movement of monsoon clouds.

For many centuries, weather forecasting was made based on the weather lore and personal speculations. But instrumental observations were not used. During the seventeenth century, it was realized, that instrumental observations of atmospheric temperature, humidity, pressure etc. are essential for understanding the atmospheric conditions and also for weather forecasting. The significant step towards that was achieved when the Italian scientist Torricelli invented the mercury Barometer for the measurement of atmospheric pressure during the middle of the seventeenth century. Lower barometric pressure is an indicator of bad weather whereas high pressure indicates good weather. Invention of Mercury Thermometer by the physicist Daniel Gabriel Fahrenheit 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 instruments like thermometers, Hygrometers, Anemometers, Barometers etc. we have, nowadays, optical and electronic sensor based instruments for accurate measurements of meteorological parameters. 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.

Initially hydrogen or helium gas filled balloons were released and tracked by optical theodolites to get the wind observations at the upper levels. These are known as Pilot Balloon observations. Even now these observations are available and used by the meteorologists to forecast weather. The problem with this system is that the optical theodolites cannot track the balloons when it enters the cloud. This difficulty has been overcome by using radio theodolites. The balloons are attached with temperature and humidity sensors along with a transmitter for transmission of data. The data collected are transmitted to the ground stations where receivers are installed for receiving the data. These observations are known as Radio sonde observations. The same principle is also used in the GPS sondes. Data are also collected by Drop sondes where parachutes, carrying meteorological sensors and transmitter, are released from aircraft and rockets instead of releasing balloons from ground stations.

Scottish Physicist, Sir Robert Watson Watt studied atmospheric phenomena using radio signals. The first RAdio Detection And Ranging (RADAR) system was produced in 1935. It is used to locate clouds, calculate their motion, precipitation, and estimate its type (rain, snow, hail etc.). There are several types of weather Radars. Precipitation Radars (S – band, C – band, X – band); Cloud Radars (K – band, W – band), Mesosphere – Stratosphere – Troposphere (MST/ST) Radar, Avionics Weather Radar, NEXRAD etc. are some examples. At present there is a very good network of Radars all over the World which facilitates to understand the weather conditions.

One of the most important observational aids for understanding the weather and forecasting of weather is the satellite i.e., artificial satellite. The first artificial satellite, Sputnik 1, was put into orbit by the Soviet scientists on 4 October 1957. Since then thousands of satellites have been launched by different countries. There are several types of satellites: Communication Satellites, Meteorological Satellites, Navigation Satellites, Earth Observation Satellites etc. Meteorological satellite is meant for monitoring weather and climate. It is used to detect the formation, intensity, location and movement of fronts, cyclones both tropical and extra tropical, clouds, aerosol, rain, snow, water vapor, sea surface temperature, soil moisture, Outgoing Long Wave Radiation (OLR), and monitoring Antarctic ozone hole, El Nino etc. Thus Satellite is an invaluable source of information for operational forecasters especially for the data sparse areas. At present weather satellites have been put in orbit by India, the United States, European countries, Russia, Japan and China. There are two types of meteorological satellites, Geostationary and Polar Orbiting. Geostationary satellites revolve around the earth, spin at the same rate of the Earth, i.e., they complete one revolution in 24 hours synchronized with earth's rotation about its own axis. They are located over the Equator at an altitude of about 36000 kms and they remain over the same location on the Equator and constantly focus on the same area. A Polar orbiting satellite revolves round the earth nearly from Pole to Pole, not exactly from pole to pole, at an inclination of about 90 degree to the Equator. It crosses the Equator at different longitude on each of its orbits. Polar orbiting weather satellite circles the Earth at an altitude of about 900 km. Polar orbiting weather satellite follows sun-synchronous orbits, that means it can observe any place on the Earth twice every day with the same general lighting conditions due to the near-constant local solar time. Polar orbiting weather satellites offer a much better resolution than their geostationary counterparts due their closeness to the Earth. Satellite observations are made in different regions of the electromagnetic spectrum, visible, infrared, microwave etc. Cloud images and digital data of several meteorological parameters can be obtained from satellites. At present many weather satellites both the types are in orbit. Some of them are United States' GOES and NOAA series; European Meteosat and EUMETSAT series, Japanese Himawari series, India's INSAT series etc. There is another type of satellite which circles the earth at an altitude of less than 1000 km but could be as low as 160 km above the Earth. Such orbit is known as Low Earth Orbit (LEO). A lot of information can be obtained from such satellites. These satellites have very high resolution.

Weather knows no political boundary. Therefore, for issuing Weather Forecasts for a particular place, weather data from the neighboring areas are essential. An efficient communication system is required in order to obtain those observational data. It was possible only when the first of telecommunication systems was developed i.e., after Samuel Morse, an American inventor and painter invented the Telegraphic System. With the advent of the satellite and development of electronics there has been a revolution in the communication system. Communication has become much easier and faster. 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).

3. 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 spans 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 is large enough. It 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 small area like a city or a town. Therefore, it comes under the category Mesoscale.

Temporal Scale: Temporal scales may be from hours to days. They are classified as:

(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 agriculturists and farmers. They 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 Forecasts. These are issued by the India Meteorological Department (IMD) every year. IMD has been doing this for almost 140 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.

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.

4. 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. 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 the Persistence Method of forecasting. This was followed in the early days. 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 vital role during the Second World period. This method was used in planning the D – Day invasion of Normandy in 1944. But it is very tough to find enough useful analogs from past weather catalogs. At present more sophisticated analogue techniques are used.

In addition to the above method 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 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 India as well as in many other countries synoptic techniques used to be the main stay of weather 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.

The Statistical technique comprises 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 the linear trend and the other nonlinear trend analysis.

In the linear trend model a straight line is fitted for the past data using the 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 a single parameter a number of parameters can also be used to forecast, 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.

Artificial Neural Networks (ANN) model is another method of weather forecasting. 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 simplest 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 back propagation algorithm.

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 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 predictor and predictand 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 to be a 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 tale tell symptom of over fitting. This issue can be addressed by using only about 80% of 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 not take into account the 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.

To achieve the above, we require:

(i) A closed set of Prediction equations

(ii) Initial and Boundary values of the field variables

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

In the beginning of the twentieth century, Professor V. Bjerknes, the well-known Norwegian Meteorologist, recognized that the weather forecasting 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:

$$\frac{d\vec{V}}{dt} = -\frac{1}{\rho}\nabla p - 2\vec{\Omega} X \vec{V} + \vec{g} + \vec{F}$$

(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, $\vec{g}$ 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 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 the 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 the success is limited for the tropical region. 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.

The basic equations mentioned earlier are non – linear Partial Differential Equations (PDE). The nonlinear partial differential equations describing the evolution of the atmosphere do not possess analytical solutions even if the problem is well posed. An analytical function is the perfect way of representing a given physical field as it gives us the value of this field in any of the infinite number of points of space and at any instant of time. If an analytical solution does not exist generally numerical techniques are to be resorted to in order to find a certain approximation to the true solution of the system of equations using high power computing system. But computers cannot deal with infinite number of points; therefore, we have to represent the meteorological fields by a finite number of values. This process is known as Discretization. The discretization should be such that the solutions are consistent, stable, time efficient and accurate.

Time Derivatives: Almost Exclusively by Finite – Difference Method

Spatial Derivatives: Finite – Difference, Spectral Method, Finite – Volume, Finite – Element Methods etc.

In the Discretization Process we:

(i) Chose step size and time increment

(ii) Replace Continuous information by discrete nodal values

(iii) Construct Discretization (Algebraic) Equations with suitable numerical methods

(iv) Specify appropriate Auxiliary conditions for Discretization Equations

(v) Solve the system of Equations

Methods of obtaining the Spatial Derivatives:

(i) Finite – difference: Taylor Series Expansion

(ii) Spectral Method: The dependent variables are expressed as a sum of linearly independent orthogonal basis functions that have a prescribed spatial structure, i.e., those are expressed in terms of series of spherical harmonics.

(iii) Finite – element: They are analogous to Spectral Method. In the Finite – element modeling the basis functions are low order polynomials that are zero except in localized region. In the Finite – element modeling the computational domain is divided into a number of contiguous finite sub – regions known as Elements. On each element is defined a simple function, where continuity between the functions on adjacent element is required.

(iv) Finite – volume: In contrast to the Grid Point models where the Prognostic quantity is the value of the dependent variables at the grid points, with the Finite – Volume model it is the integrated value of a variable over a specific finite control volume. The control volumes are typically the traditional three dimensional model grid cells.

The Basic Objective of Spatial Derivatives is to convert Partial Differential Equations to Algebraic Equations.

Finite difference technique and Spectral method are most commonly used in Numerical Weather Prediction Models.

The initial conditions can be obtained from:

(i) Observing systems

(ii) Objective analysis

(iii) Initialization and

(iv) Data Assimilation

The Finite Difference Method: The three dimensions of space can be accounted for in various ways in numerical weather or climate prediction models. Most models are Grid Models, in which variables are computed at discrete grid points in the horizontal and vertical directions. The model resolution refers to the (horizontal) spacing between grid points. Less is the grid length higher the resolution. The grid spacing is not necessarily equidistant. Some models use longitude difference as zonal grid spacing. So near the poles the zonal grid spacing becomes zero. This is known as Pole Problem. The central idea of the Finite Difference approach is to approximate the derivatives in the equation by the difference between adjacent points in space or time, and thereby reduce the differential equation to a difference equation. Thus,

(i) An Analytical Problem becomes an Algebraic one

(ii) A problem with infinite degree of freedom is replaced by one with finite degrees of freedom

(iii) A continuous problem goes over to a discrete one.

In the Finite Difference technique a function *f(x)* is expanded in Taylor series. The first derivative $f'(x)$ can be approximated by Forward Difference, Backward Difference and Central Differencing or Leap Frog Methods. Leap frog method is the better than the other two methods because the truncation error in the Leap Frog method is less than that in the other two methods. The second derivatives are obtained by the derivative of the first derivative in the same way.

The stability of the numerical solution depends on both the space and time grids. The condition necessary for the stability is known as Courant – Friedrich – Levy (CFL) condition for stability. It is, $\Delta t \leq \frac{\Delta x}{c}$, where c is the velocity of the wave.

For the spectral method, the atmosphere has to be represented in terms of spectral components. In the spectral method, we assume that an unknown variable can be approximated in terms of a sum of the basis functions. The basis functions are orthogonal. The dependent variables are expressed as a sum of linearly independent orthogonal functions. The coefficient associated with each function is normally a function of time. This procedure transforms a partial differential equation into a set of ordinary differential equations of the coefficients. These differential equations are solved with finite differences in time. Global models use spherical harmonics, a combination of Fourier (sine and cosine) functions that represent the zonal structure and associated Legendre functions that represent the meridional structure. In all practical applications, the series expansion of spherical harmonic functions must be truncated at some finite point. There are two types of truncation are commonly used: Triangular truncation Rhomboidal truncation.

In Spectral Models the horizontal resolution is designated by T, which indicates the number of waves used to represent the data. Thus T382L64 model would indicate 'triangular' truncation at wave-number 382, with 64 levels in the vertical. To convert the wave-number 'horizontal resolution' to an approximate grid-length, the following formula is used: $\Delta x = \frac{360}{3T+1}$. Then it multiplied by 111 km (per deg. latitude). In T382 model the horizontal resolution is approximately 35 km.

Since the Derivatives in these types of model are exact there is no computational Instability. More over, on the sphere there is no Pole problem. Spectral methods are mainly used for global models because spherical harmonics are not suitable for limited area models. The double sine-cosine series are most popular for regional spectral modeling because of their simplicity.

Meteorological Observations are taken at a number of stations which are unevenly located at different places. Objective Analysis is the advanced methods of interpolating the observations to the grid points. There are a number of methods of objective analysis: Fitting of Polynomial Surfaces, Successive Corrections Methods, Cressman Technique, Barnes Scheme, Optimal Interpolation, Variational Techniques etc. Objectively analyzed data in Numerical Weather Prediction models may generate a large number of spurious waves in the atmosphere. The speeds of these waves may be much larger than the speeds of usual meteorological systems. The procedure of eliminating these waves before the integration of the mathematical equations is known as Initialization. There are several methods of Initialization like Static Initialization, Dynamic Initialization, and Normal Mode Initialization etc. There are some physical processes in the atmosphere which are too small, too complex to understand but play important role in the formation of weather. Parameterization is a process by which the bulk effects of these processes are explicitly represented in the NWP models. In most models, the following parameterizations are used to represent Cumulus convection, Microphysical processes, Radiation (short wave and long wave), Turbulence, Boundary layer and Surface fluxes. Each of these parameterizations has several schemes.

5. Modelling

A mathematical model describes a system using mathematical concepts and language. It is a technique that represents a field situation or real world system. A numerical model solves an equation or a set of equations that describes the behavior of a real world system. It is a computer program designed to simulate some real system. When a numerical model is used to forecast the weather the process is called Numerical Weather Prediction (NWP). Before running a NWP model or being able to interpret its output, modelers and forecasters ought to develop an understanding to have a successful NWP forecast.

Major Steps in the Forecast Process are: Data Collection, Quality Control of data, Data Assimilation, Model Integration, Post Processing of Model Forecasts, Human Interpretation and generation of Product.

Post-Processing: Numerical model output sometimes contains systematic biases and other problems. These are to be removed. The solution to these problems is done by a process known as Post - Processing.

In early days of NWP, post-processing used to be done using statistical method known as Model Output Statistics (MOS) and it greatly improved the quality of model prediction. Nowadays, there are several other methods of post - processing.

Professor Edward Lorenz has shown that the atmosphere is a chaotic system, which means small differences in the initial condition can have large impacts on the forecasts, particularly for forecasts for longer periods. Similarly, uncertainty in model physics can result in large differences and errors. This is often referred to as the Butterfly Effect.

The problem of sensitivity to initial conditions in NWP and climate models is best addressed by Ensemble Forecasting. Instead of running one forecast, run a collection or Ensemble of forecasts, each starting from a different initial state or with different physics. One of the approaches is to combine several models, weighing them by previous performance. The variations in the resulting forecasts could be used to estimate the uncertainty of the prediction. If an idealized forecast ensemble that properly characterizes all sources of forecast errors can be constructed, then the forecast would be reliable and skillful. There exist several models and a few of them are mentioned below.

5.1 Weather Research and Forecasting (WRF) Model

The WRF model (Skamarock et al. 2018) is a Mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting applications. The model serves a wide range of meteorological applications across scales from tens of meters to thousands of kilometers. Currently, many national meteorological services including IMD use WRF model for operational weather forecasting.

5.2 Regional Model RegCM4

The Regional Climate Model system RegCM (Coppola et al. 2021) can be applied to any region of the World, with grid spacing of up to about 10 km and for a wide range of studies, from Climate of the past and the future climate simulation. The model is flexible, portable and easy to use.

5.3 The Advanced Regional Prediction System (ARPS)

This is a comprehensive regional to storm scale atmospheric modeling / prediction system (Xue et al. 2013). It is a complete system that includes a real-time data analysis and assimilation system, the forward prediction model and a post-analysis package. Presently, ARPS5.3.4 model version is available for the users.

5.4 ECMWF Integrated Forecasting System (IFS)

European Centre for Medium-Range Weather Forecasts (ECMWF) has developed own atmospheric model and data assimilation system which is called the Integrated Forecasting System (IFS). Currently it has ~9 km resolution and 137 vertical levels.

5.5 Global model ICON

German Weather Service (DWD) has developed global forecast model (Zangle et al. 2015) ICON (ICON = ICOsahedral Nonhydrostatic) with the collaboration of Max-Planck Institute for Meteorology. The grid structure of ICON is based on an icosahedral (triangular) grid of the earth's sphere. ICON's native grid resolution is 13 km. There are 90 atmosphere levels in the vertical up to the maximum height of 75 km. Model is used for the operational usage and up to 180 hours.

5.6 Nested higher resolution ICON-EU (European Union) Regional model

ICON-EU is a tightly coupled two-way interaction between the ICON-EU regional model and the global ICON. The native model grid has a horizontal grid spacing of 6.5 km; the output grid spacing is 0.0625° (~ 7 km). In the vertical, ICON-EU has 60 vertical levels up to a height of 22.5 km. It is capable of forecasting up to 120 hours

5.7 Regional model ICON-D2

The DWD's ICON-D2 model is a forecast model which is operated for the very-short range up to 27 hours. Due to its fine mesh size, the ICON-D2 is useful for forecasting hazardous weather conditions, e.g. super and multi-cell thunderstorms, squall lines, mesoscale convective complexes and weather events that are influenced by fine-scale topographic effects, e.g. Ground fog, intense downslope winds, flash floods etc.

5.8 Korean Integrated Model (KIM)

Global numerical weather prediction system has been developed by the Korean Meteorological Administration (KMA)/Korea Institute of Atmospheric Prediction System (KIAPS) and operationally launched on April 2020 (Hong et al. 2018). KIM consists of a spectral element non-hydrostatic dynamical core with full physics package.

5.9 Global Forecast System (GFS) Model

The Global Forecast System (GFS) is a global numerical weather prediction system containing a global computer model and variational analysis run by the U.S. National Weather Service (NWS). The forecast component uses the Finite Volume Cubed Sphere (FV3) dynamical core with a resolution of ~13 km (GFS version 16). In the vertical, there are 127 vertical layers.

5.10 NCEP Climate Forecast System (CFSv2) Model

The Climate Forecast System (CFS) version 2 models are a fully coupled ocean–atmosphere–land model with advanced physics, increased resolution and refined initialization. National Centers for Environmental Prediction (NCEP) has developed CFSv2 (Climate Forecast System, Version 2) model to improve the seasonal climate forecasts (Saha et al. 2014 and Rao et al. 2019). Present operational model has 0.5 degree horizontal resolution (approximately 56 km). NCEP CFSv2 consists of a spectral atmospheric model called as GFS and Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model.

5.11 Monsoon Mission CFSv2 model

The base model is the same as NCEP CFS v2 (Dutta et al. 2021, Hazra et al. 2017, Saha et al. 2019 and Pokhrel et al. 2018). The atmospheric component of CFSv2 is Global Forecast System (GFS) with spectral resolution of T382 and 64 hybrid vertical levels and the ocean component is Geophysical Fluid Dynamics Laboratory's (GFDL) Modular Ocean Model version 4 (MOM4). Model is run operationally by the India Meteorological Department (IMD) for the extended-range and seasonal forecasts.

5.12 Indian Institute of Tropical Meteorology Earth System Model (IITM-ESMv2)

This model is suitable for long-term climate (Swapna et al. 2015). It has both ocean and atmospheric components having horizontal resolution of T62.

5.13 Global National Center for Medium Range Forecast NCMRWF Unified Model (NCUM-G) System

It is used for Seamless Forecasts i.e., it can be used for broad range of spatial and temporal scales.

5.14 NCUM Regional High Resolution Models

It is the regional version of NCUM (NCUM-R) at 4 km resolution, covering the entire Indian region Three days forecasts are generated routinely.

5.15 Global Ensemble Forecast System (GEFS)

It has 21 ensembles (a combination of 21models) and runs at 12 Km resolution with 64 vertical levels. The model runs twice a day on Operational mode. Various products are generated from this model for the Indian region.

There are many more models. The basic equations are the same for all the models but the other aspects like methods of solving equations, coordinate systems, spatial and temporal scales, Objective analysis methods, parameterization schemes, methods of initialization, data assimilated etc. differ.

The forecasters play a very significant role once all the numerical simulations and post-processing are done. They evaluate the model output, make adjustments if needed and translate the forecasts in a language which is easily understood by the public and other users.

The guidance from NWP models has vastly helped to improve the skill of the forecasts of all spatial and temporal scales. Nowadays, the short, the medium, the extended and the long range forecasts are issued by taking guidance from NWP. As a result, the forecasting skill has improved considerably and the forecasts for Tropical Storms, Hurricanes, in particular, have been excellent.

6. Weather Forecasting: Indian Perspective

India Meteorological Department (IMD) used to give short range weather forecast mainly by synoptic techniques in earlier days. Nowadays, weather forecasting is given by taking guidance from NWP. IMD runs a global model, viz., GFS, WRF model and Global Ensemble Forecasting System (GEFS). The GFS and WRF models are run four times a day based on 0000, 0600, 1200 and 1800 UTC observations respectively. The GEFS model is run twice a day based on 0000 and 1200 UTC observations. In addition to these dynamical models, IMD also runs a cyclone prediction model, Hurricane weather research and forecasting (HWRF) during Cyclone periods.

India is bounded by the Bay of Bengal, the Indian Ocean and the Arabian Sea. Every year a number of Cyclonic storms, Depressions form over the oceanic areas and cross the coast and cause devastation in the country. The lives and properties of thousands of people in coastal states can be saved by forewarning and evacuating people to safer places. In recent years forecasts issued by IMD for Cyclonic storms and Depressions, their movement, intensities and time and places of landfall using the guidance from NWP are almost 100% correct and thus IMD is saving lives and properties of thousands of people.

IMD used to issue the Medium and Extended Range Weather Forecasts by statistical methods till a few years back. At present, IMD in collaboration with IITM issues medium and extended forecasts using NWP models (Sahai 2013). In addition, NCMRWF also issues ensemble forecasts for 10 days on a regular basis.

India is the first country in the world to issue Long range forecast (LRF). Sir H.F. Blanford, the first Chief Reporter of IMD, issued tentative forecasts for the Indian Summer Monson rainfall from 1882 to 1885 utilizing snowfall in Himalayas as a predictor. The first of the regular forecasts was issued in 1886. Sir Gilbert Walker, Director General of IMD, developed the first objective models based on statistical correlations between monsoon rainfall and antecedent global atmosphere–ocean parameters. This process of LRF for the Indian Summer Monson rainfall (ISMR) has been continuing since then; but its format and content have undergone changes with time. In 1988, India Meteorological Department introduced the 16 parameter power regression and parametric models and started issuing forecasts for the southwest monsoon rainfall over the country as a whole. After the failure of monsoon rainfall forecast in 2002, IMD introduced two stage forecasts, the first one in April and an update in June in 2003. This process continued till 2006 using less number of parameters. In 2007, IMD introduced new statistical forecasting system based on ensemble technique for the south-west monsoon season (June – September) rainfall over the country as a whole. For the LRF of the ISMR, three main approaches are used, statistical method, empirical method based on a time series analysis and dynamical method. The dynamical methods which use general circulation models of the atmosphere and oceans have not shown the required skill. Rajeevan et al. (2007) developed new statistical models based on the ensemble multiple linear regression and projection pursuit regression techniques, which used new methods of predictor selection and model development. In the ensemble method, all possible models based on all the combination of predictors are considered instead of relying on a single model. Out of all the possible models, the models which show better skills are selected and the forecast is then generated from the weighted average of the forecast from the selected models.

In 2021, IMD implemented a new method of issuing monthly and seasonal operational forecasts for the southwest monsoon rainfall over India. IMD used their existing statistical forecasting system to generate these forecasts along with a newly developed Multi-Model Ensemble (MME) forecasting system based on coupled global climate models (CGCMs) from different global climate prediction and research centers including IMD's Monsoon Mission CFS (MMCFS) model. IMD also issued for the first time probabilistic forecasts for the seasonal rainfall (June to September) in 2021. IMD applied the same strategy for the forecasts of the Northeast Monsoon (October to December) rainfall for the southern peninsular region Tamil Nadu, Coastal Andhra Pradesh, Rayalaseema, Kerala and South Interior Karnataka.

7. Conclusions

Weather forecasting is a difficult and challenging job. 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 remain challenging in future also. With the advancement of the science of meteorology and High Performance Computing (HPC) systems the skills of the forecasts have improved considerably over the years but a lot more has to be achieved.

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References

Coppola E., Stocchi P., Pitchell E., Alavez J. A. T., Glazer R., Giuliani G., Sante F. D., Nogherotto R., and Giorgi F., (2021) Non – Hydrostatic Reg CM4 (RegCM4 – NH): Model description and case studies over multiple domains, 14, Geoscientific Model Development 14, 7705 – 7723.

Dutta U., Hazra A.,Chaudhari H. S., Saha S. K., Pokhrel S., Shiu C. J. and Chen J. P., (2021): Role of Microphysics and Convective Autoconversion for the Better Simulation of Tropical Intraseasonal Oscillations (MISO and MJO). J. Advance Model Earth Sys. http.//doi.org10.1029/2021MS002540

Hazra A., Chaudhari H. S., Saha S. K., Pokhrel S., and Goswami B. N., (2017): Progress Towards Achieving the Challenge of Indian Summer Monsoon Climate Simulation in a Coupled Ocean-Atmosphere model, J. Advance Model Earth Sys, 9, 2268–2290, https://doi.org/10.1002/2017MS000966

Hong S.Y, Kwon Y.C., Kim T.H., Kim J.E.E., Choi S. K., Kwon I. H., Kim J. Lee E . H., Park R. S., and Kim Dong –II. (2018) : The Korean Integrated Model (KIM) System for Global Weather Forecasting, Asia Pacific J. Atmosph Sci 54, 267 – 292.

Kulkarni M. A., Patil S., Rama G. V. and P. N. Sen. (2008): Wind Speed Prediction Using Statistical Regression and Neural Network, J. Earth Sys. Sci. 117, 3, 457

Matthew C., Christensen H., Dueben P. and Palmer T., (2021): Opportunities and challenges for machine learning in weather and climate modeling: hard, medium and soft AI. Phil. Trans. R. Soc. A.37920200083202000083http://doi.org/10.1098/rsta.2020.0083

Pokhrel S., Hazra A., Chaudhari H. S., Saha S. K., Paulose F., Krishna S., Krishna, P. M. and Rao S. A., (2018): Hindcast skill improvement in Climate Forecast System (CFSv2) using modified cloud scheme. Int. J. Climatol., 38, 2994–3012

Rajeevan M., Pai D. S., Anil Kumar R. and Lal B. (2007): New statistical models for long-range forecasting of southwest monsoon rainfall over India, Clim Dyn, 28, No. 7-8, 813-828. doi:10.1007/s00382-006-0197-6

Rao S. A., Goswami B.N, Sahai A.K, Rajagopal E.N, Mukhopadhyay P, Rajeevan M., Nayak S, Rathore L. S., Shenoi S.S.C., Ramesh K. J., Nanjundiah R., Ravichandran M., Mitra A. K., Pai D. S., Roy Bhowmik S. K., Hazra A., Mahapatra S., Saha S. K., Chaudhari H. S., Joseph S., Pentakota S., Pokhrel S., Pillai P.A., Chattopadhyay R., Deshpande M., Krishna R.P.M., Siddharth R., Prasad V.S., Abhilash S., Panickal S., Krishnan R., Kumar S., Ramu D.A., Reddy S.S., Arora A., Goswami T., Rai A., Srivastava A., Pradhan M., Tirkey S., Ganai M., Mandal R., Dey A., Sarkar S., Malviya S., Dhakate A., Salunke K.,and Maini P. (2019): Monsoon Mission: A targeted activity to improve monsoon prediction across scales, Bull Amer Meteorol. Soc,100: 2509-2532

Saha Suranjana, Moorthi S., Wu X., Wang J., Nadiga S;, Tripp P., Behringer D., Hou Y-T., Chuang H-Y., Iredell M., Ek M., Meng J., Yang R., Mendez MP., an den Dool H., Zhang Q., Wang W., Chen M.and Becker E. (2014) : The NCEP Climate Forecast System Version 2. J. Clim. 27:https://doi.org/10.1175/JCLI-D-12-00823.1

Saha S. K., Hazra A., Pokhrel S., Chaudhari H. S., Sujith K., Rai A., Rahaman H., amd Goswami B. N., (2019): Unraveling the mystery of Indian Summer Monsoon prediction: Improved estimate of predictability limit, J. Geophys Res Atmospheres, 124: 1962-1974.2185–2208, doi: 10.1175/JCLI-D-12-00823.1.

Sahai A. K, Sharmila S., Abhilash S., Chattopadhyay R., Borah N., Krishna R. P. M., Joseph S., Roxy M., De S., Pattnaik S. and Pillai P. A. (2013): Simulation and Extended Range Prediction of Monsoon Intraseasonal Oscillations in NCEP CFS/GFS version 2 framework. Curr. Sci., 104, 1394–1408.

Skamarock W.C., Klemp J. B., Dudhia J., Gill D. O., Barner J., Wang W., Powers J. G., Dud M. G., Barker D. M., and Huang X. Y., (2019) A description of the Advanced Research WRF Version 4, NCAR Tech. Note NCAR?TN – 556 + STR, 145pp, doi: 10.5065/ 1 dfh – 6997.

Sen P. N., (2019): Lecture Notes on Numerical Weather Prediction, Department of Atmospheric and Space Sciences, Savitribai Phule Pune University, Pune

Sen P. N., (2021): Numerical Weather Prediction Guidance for Weather Forecasting, IMD Blog https://imdweather1875.wordpress.com/2021/10/24/numerical-weather-prediction-guidance-for-weather-forecasting/

Swapna, P., Roxy M. K., Aparna K., Kulkarni K., Prajeesh A. G., Ashok K., Krishnan R., Moorthi S., Kumar A., and Goswami B. N. (2015): The IITM Earth System Model: Transformation of a Seasonal Prediction Model to a Long Term Climate Model, Bull. Amer. Meteorol. Soc., 1351–1367, doi:10.1175/BAMS-D-13-00276.1.

Weyn, J. A, Durran D. R., and Caruana R. (2020). Improving data-driven Global Weather Prediction using Deep Convolutional Neural Networks on a Cubed Sphere. J. Advance Model Earth Sys. 12,e2020MS002109https://doi.org/10.1029/2020MS002109

Xue M. D., Wang D. J., Gao K., Breweaster K.,and DroegemeierK. K. (2003): The Advanced Reginal Prediction System (ARS), storm – scale numerical weather prediction and data assimilation, Meteorology Atmospheric Physics, 82, 139 – 170.

Zängl,G., Reinert G., Rípodas P., and Baldauf M., (2014):The ICON (ICOsahedral Non-hydrostatic) modelling framework of DWD and MPI-M: Description of the non-hydrostatic dynamical core, Quart. J. Royal Met Soc., http://doi.org/10.1012/qj.2378.

https://cfs.ncep.noaa.gov/

https://www.ncei.noaa.gov/

https://www.emc.ncep.noaa.gov/emc/pages/numerical_forecast_systems/gfs.php

https://www2.mmm.ucar.edu/wrf/users/

https://www.ictp.it/research/esp/models/regcm4.aspx

https://www.ecmwf.int/

https://www.dwd.de/

https://www.imdpune.gov.in/Clim_Pred_LRF_New/Models.html

https://web.kma.go.kr/

https://www.tropmet.res.in/

https://arxiv.org/ftp/arxiv/papers/2101/2101.03410.pdf

https://towardsdatascience.com/clearing-the-confusion-ai-vs-machine-learning-vs-deep-learning-differences-fce69b21d5eb

https://physicsbaseddeeplearning.org/intro.html

https://ruder.io/optimizing-gradient-descent/

https://imdweather1875.wordpress.com/2020/07/18/faqs-on-nwp-model-charts/Wikipedia