IMD-WMO Joint group fellowship training program on NWP

Theme: Introduction

Lecture-1 & 2

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Atmosphere as a dynamical system

- Any system which evolves/ changes with time may be called as a dynamical system.
- We are interested to know the future state of such dynamical system.
- Prediction of a dynamical system requires a set of rule(s)/law(s) governing the time evolution of the dynamical system and complete information about the present state of the system.
- As atmospheric condition also varies with time, so it is also a dynamical system and accordingly its prediction requires complete information about the current/present state of the atmosphere and the set of physical rule(s)/law(s) governing the time evolution of the atmosphere.

Initial & boundary value problems

- In Mathematical literature an IVP is expressed as:
  - Solve the equation $\frac{\partial\varphi}{\partial t} = f(x;t)$ for the unknown variable $\varphi(x;t)\ for\ all\ x\ \&\ t > t_0$;
  - Given $\varphi(x, t_0) = \varphi_0(x)$ for all x
  - t_0 is the initial time.
  - $f(x;t)$ is a known forcing function.
- Above equation is the mathematical form of the rules for time evolution of the atmosphere and the condition $\varphi(x, t_0) = \varphi_0(x)$ represents the mathematical form of present state of the same called initial condition (IC).

…. Initial & boundary value problems

- If an infinitesimally small change/error in the initial condition results in a similar small change in the solution of the above equation, i.e, in the future values of the variable, then the IVP is known as a well posed/properly posed IVP.
- In contrary if an infinitesimally small change/error in the initial condition results in a large change/errors in the in the future values of the variable, then the IVP is known as an ill posed/improperly posed IVP.
- A boundary value problem is a differential equation together with a set of additional constraints, called the boundary conditions. A solution to a boundary value problem is a solution to the differential equation which also satisfies the boundary conditions.
- Example: Solve $\frac{\partial^2\varphi}{\partial x^2} + \frac{\partial^2\varphi}{\partial y^2} = g(x, y)$, where, $g(x, y)$ is a known function and given the following boundary condition: $\varphi(x, -b) = \varphi_{-b}, \varphi(x, b) = \varphi_b, \varphi(-a, y) = \varphi_{-a}, \varphi(a, y) = \varphi_a$

Basic Philosophy of weather prediction

- Weather at any place at any time is the result of time evolution of atmosphere.
- Weather at any place at any time is a function, of 7 basic Meteorological Variables, viz., three components of wind (u, v, w), pressure(p), temperature(T), density(ρ) and specific humidity(q).
- So, $wx(\hat{x}; t) = f[u(\hat{x}; t), v(\hat{x}; t), w(\hat{x}; t), T(\hat{x}; t), \rho(\hat{x}; t), p(\hat{x}; t), q(\hat{x}; t)]$; where, $\hat{x} = (x, y, z)^T$ is space vector.
- So, if at any point $\hat{x}$ and at time $'t'$, the values of these 7 variables are known, then it is possible to get the weather at that time at that point; by setting up of a functional relation between them and the concerned weather.
- Thus the problem of forecasting weather can be translated to the problem of forecasting the future values of these 7 variables.

….Basic Philosophy of weather prediction

- Now future value of any one of these 7 variables can be found out:
  - If we know it's present value (known as initial value/initial condition).
  - If we have a rule (governing equation), which tells about it's time evolution and the factors responsible for the change (called forcing).

- In 1904, V. Bjerknes first realized that problem of predicting the atmospheric condition (weather forecast) is an initial value problem (IVP).
- As the problem of forecasting weather requires the complete information about the present state of the atmosphere, hence it is essentially an IVP.
- At the same time as the weather condition at a place at a given time is also dependent on the weather condition over the surrounding of the place also. So, this is a BVP also.
- Thus, problem of forecasting weather at a place is essentially an IVP as well as a BVP.

Different types of weather forecasting methods.

Broadly we have three major types of weather forecasting method:

- Synoptic method
- Statistical Method
- Dynamical method or Numerical Weather Prediction
- Ensemble prediction system (Dynamical-Statistical)

Different types of weather forecasting methods: Synoptic Method

- It's a suite of following tasks:
  - Taking observation over the entire globe simultaneously at some fixed time (expressed in terms of GMT/UTC), known as Synoptic hours of observation.
  - Preparation of coded message for the observed information.
  - Exchange of coded messages among all centers for weather forecasting.
  - Decoding of coded messages.
  - Plotting of weather elements (wind, pressure, temperature etc.) on weather charts, for respective stations.

…Different types of weather forecasting methods: Synoptic Method

- Analysis of charts for different weather parameters: Drawing isolines of different weather parameters, viz., pressure, temperature etc.
- Once analysis is completed, zones with maximum value or minimum value of different parameters will be brought out clearly, know as synoptic features.
- Forecasters through their qualifications and professional trainings have the knowledge of weather associated with different synoptic features. For example: cold wave and fog occurs over a station, once a western disturbance passed away through it.
- Accordingly a synoptic weather forecast bulletin is issued.

Difficulties

- However this method can give forecast for a broad region for a broad period.
- It involves lots of subjectivity, like knowledge, experience of the forecasters.
- Location & time specific forecast is difficult.

Different types of weather forecasting methods: Statistical Method

- In statistical method, long period past data (known as time series) of the predictand and the predictors are used.
- Then correlation between each of the predictors and the predictand is computed.
- Then a Regression equation is established between the predictand and those predictors, having significant statistical association.
- Then this equation is used to forecast the future value of predictand using known values of predictors.

Difficulties

- Correlation between predictors & predictand changes from place to place, season to season.
- Even for a given place and time, Correlation/regression coefficients changes with time.
- Good for predicting mean, however forecast of extreme difficult

Different types of weather forecasting methods: NWP

- Already we have seen that the problem of forecasting weather at a place for a future time has been translated into predicting future values of 7 basic Meteorological variables, viz., u,v,w,p,T, q and ρ.
- Now future value of any one of these 7 variables can be found out:
  - If we know it's present value (known as initial value/initial condition).
  - If we have a rule (governing equation), which tells about it's time evolution and the factors responsible for the change (called forcing).

…Different types of weather forecasting methods: NWP

- Fortunately, in the Meteorology literature, for each of the 7 variables, such rules exist in the form of governing equations.
- Also through observation, followed by required quality checks & pre-processing, we have necessary initial condition for these 7 variables.
- Thus in – principle, NWP has the potential to give time & location specific weather forecast.

History of NWP

- In 1904, V. Bjerknes first realized that problem of forecasting weather is an initial value problem.
- In 1922, L.F. Richardson attempted to solve the governing equations for predicting pressure tendency using a desk computer. However, he failed as the computed 24 hours pressure change was a several order of magnitude greater than the observed 24 hours pressure change.
- The failure of Richardson's numerical treatment was, at that time, attributed to poor initial data available, especially the absence of upper air data.
- Later, it was discovered that the atmospheric equations in its complete form, so called 'primitive' form, admit solutions corresponding to not only the slow-moving atmospheric waves (Rossby Waves) but also fast-moving sound and gravity waves. These high-speed waves amplify spuriously with the time and mask the solutions relating to atmospheric waves if not properly controlled.

…. History of NWP

- Later, in 1948, Charney showed that by making use of hydrostatic and geostrophic assumptions the high-speed sound and gravity waves can be effectively 'filtered'.
- In 1950, using the first electronic calculator ENIAC and the filtered Barotropic/Equivalent barotropic model, Charney, Fjortoft and Von Neumann produced the first successful numerical prediction.
- Since then, there has been a rapid progress in all phases of NWP.
- These improvements are mainly due to considerable increase in the quantity of meteorological data, advances in telecommunication system, tremendous progress in computer technology and development of much better and sophisticated numerical models.

…. History of NWP

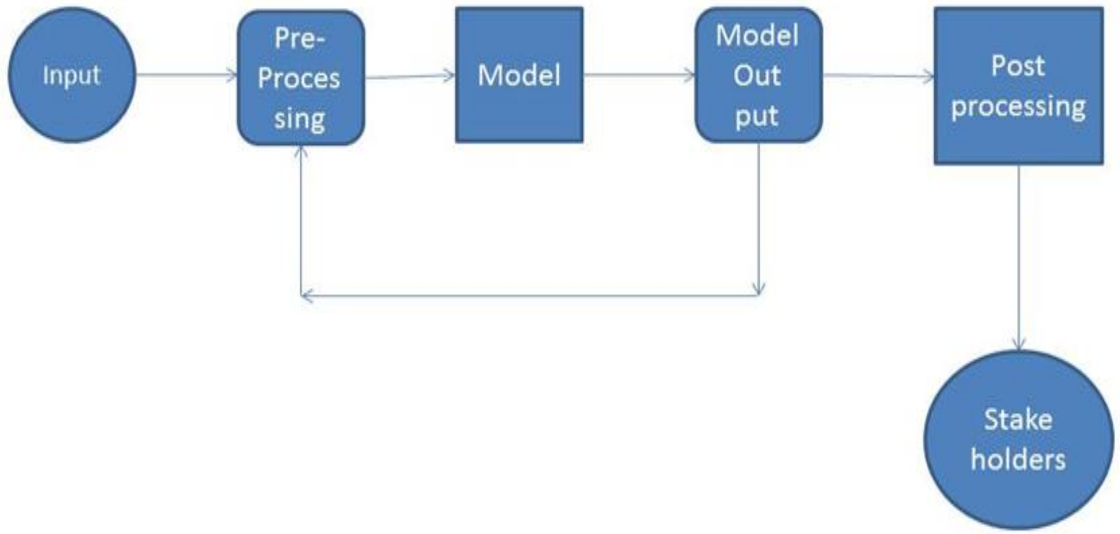
- Barotropic models do not allow temperature advection because wind is parallel to isotherms and hence, can't forecast the development of new weather systems. They, in fact only extrapolate the system by advection of vorticity.
- For more accuracy and reliability, prediction of development of new systems is essential.
- For this purpose, thermal advection has to be included in the numerical model and hence more than one level is required to be incorporated in the model. Accordingly 2-layer Baroclinic model (by Charney and Eady) developed.

…. History of NWP

- Barotropic and 2 or multi-layer baroclinic models, known as filtered model, have a definite limit on their accuracy due to the various approximations made.
- Further, these models can't be used in low latitudes where quasi-geostrophic assumption is not valid.
- Under these circumstances, it was thought that direct utilisation of basic hydrodynamic equations in their primitive form might improve the accuracy of numerical models in general.
- The availability of much faster computers and improved understanding of computational problems made it possible to carryout time integration for longer period of the basic primitive equations using small time space.
- The first successful experiments using primitive equations were carried out by Hinkelman in 1959. Since then NWP has marched steadily forward and now a day's primitive equations models are widely utilised world over for operational numerical weather prediction in different time scales.

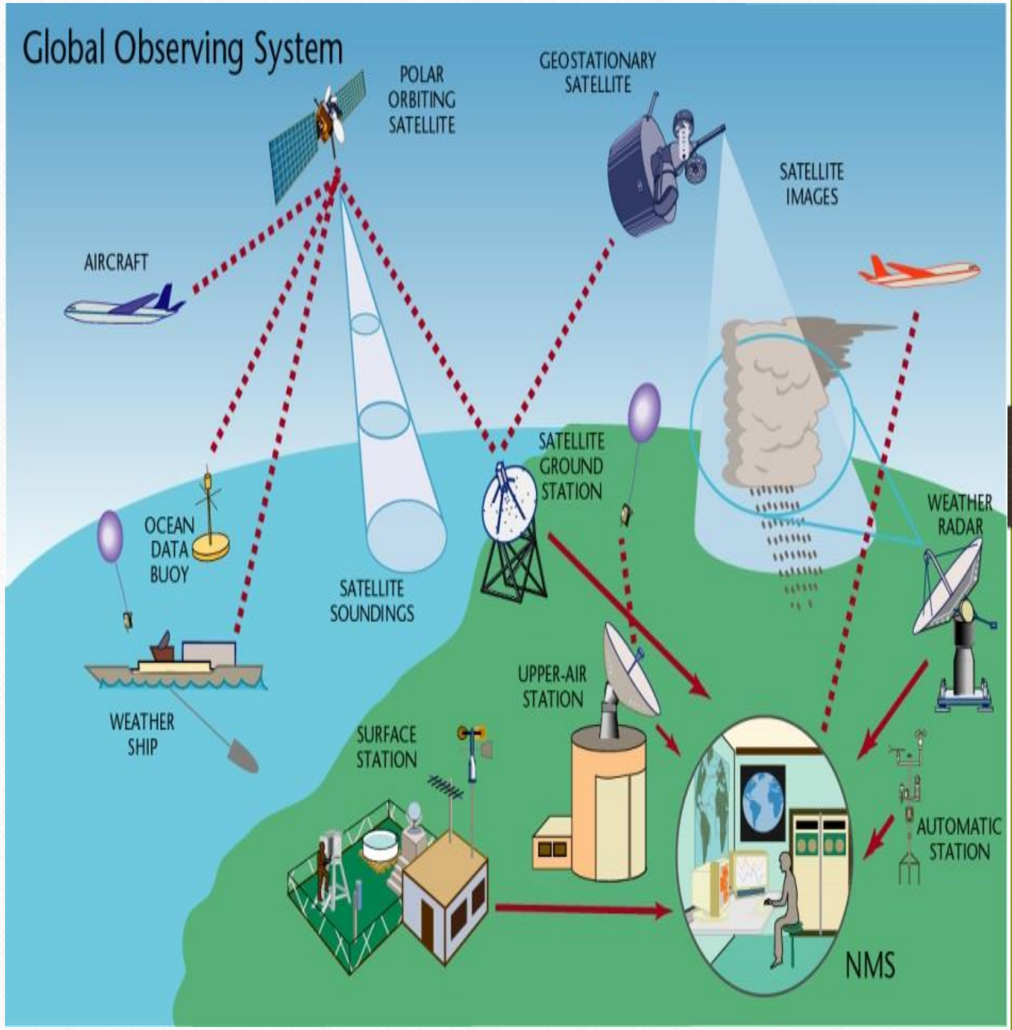
A Generic structure of different components of a NWP system

In a typical NWP system, broadly there are three compartments, viz., pre-processing unit, model and the post processing unit, as shown schematically below:



Input

Basic input for a NWP system is present values of 7 basic Meteorological parameters, viz.,three components of wind (u, v, w), pressure(p), temperature(T), density(ρ) and specific humidity(q). Present Values of those are mainly obtained from direct/indirect observation



Components

- Surface observations
- Upper-air observations
- Marine observations
- Aircraft-based observations
- Satellite observations
- Weather Radar observations
- Other observation platforms

Pre-processing

- In the pre-processing unit, observed data, available at unevenly spaced observing points, are subjected to different quality control checks, spatial and temporal consistency check and climatology check etc, followed by a sophisticated interpolation scheme to prepare values of the above variables at regularly spaced different grid points.
- It is most likely that grid point data, prepared in this way may contain errors, which is removed/minimised within a given tolerance limit and thus the initial values of the variables at grid points, i.e., initial conditions are prepared.

Model

- Here, using the initial conditions, prepared in pre-processing units, the following equations are numerically integrated forward with time.
  - $\frac{\partial u}{\partial t} = -\left[u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}\right]u - \frac{1}{\rho}\frac{\partial p}{\partial x} - 2\Omega(w\cos\varphi - v\sin\varphi) + \frac{uv}{a}tan\varphi - \frac{uw}{a} + \frac{\mu}{\rho}\nabla^2 u,$
  - $\frac{\partial v}{\partial t} = -\left[u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}\right]v - \frac{1}{\rho}\frac{\partial p}{\partial y} - 2\Omega(u\sin\varphi) - \frac{u^2}{a}tan\varphi - \frac{vw}{a} + \frac{\mu}{\rho}\nabla^2 v$
  - $\frac{\partial w}{\partial t} = -\left[u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}\right]w - \frac{1}{\rho}\frac{\partial p}{\partial z} - g + 2\Omega(u\cos\varphi) + \frac{u^2+v^2}{a} + \frac{\mu}{\rho}\nabla^2 w,$
  - $\frac{\partial T}{\partial t} = -\left[u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}\right]T + \frac{1}{c_v}\frac{dQ}{dt} - (\gamma - 1)T\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right)$
  - $\frac{\partial \rho}{\partial t} = -\left[u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}\right]\rho - \rho\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right),\ \frac{\partial q}{\partial t} = -\left[u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}\right]q$
  - $p = \rho RT$
- After integration, future values of the above variables at different grid points are generated, known as output.

Output & post processing

- These direct model outputs (values of 7 meteorological variables at future time steps) goes to the pre-processing unit for preparing balanced initial condition in the next cycle.
- However, these direct model output may be of very little use for the stake holders, rather, stake holder may like to have specific weather information, like, rainfall, visibility, divergence, vorticity, precipitable water content etc.
- In the postprocessing part of the NWP system, direct model outputs are post processed to generate products as required by the stake holders/users.