The Challenge of Weather Prediction

3. Old and Modern Ways of Weather Forecasting

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The previous articles of this series were:
1. The basic driving, November 1996.
2. Difficulties in predicting the weather, January 1997.

Introduction

In the last two parts we discussed the physical basis for weather forecasting and the practical and conceptual difficulties encountered when one tries to forecast the weather. In this concluding part, we shall trace the history of weather forecasting and describe its current status.

Traditional weather forecasting reminds us of meteorologists sitting with the weather charts spread in front of them and making forecasts based on their 'experience'. This experience is the knowledge gathered over years of observations and the background theory on weather. Given a background condition, a particular weather pattern, say a low pressure area, tends to evolve on the average in a certain way. This may be termed as mean or 'climatological' behaviour. Also atmospheric fluctuations have a certain amount of 'persistency'. In other words, once a low pressure is formed, it persists for a while. Forecasts made by meteorologists based on 'climatology' and 'persistence' and empirical knowledge about evolution of weather systems are known as synoptic forecasts. Before the advent of computers, this was the only method of weather forecasting. Upto 12 hours or 24 hours in advance, the meteorologists can actually make very good forecasts based on this technique. But beyond that this type of forecast is not useful.

Even with the approximations that must be made, the motion of the air is governed by a set of physical laws as described in Part I of this series. Therefore, if we knew the initial state and we could solve the equations, we could predict the future state. The first problem is that these equations are highly nonlinear coupled partial differential equations. It is not possible to arrive at analytic solutions. Thus, the only way to predict is using numerical techniques. The modern concept of numerical weather forecasting was born in the fertile mind of the Quaker mathematician Lewis Fry Richardson (1881–1953) during World War – I. Richardson was attracted by the success of spherical astronomy where the motion of the planets and the timing of the solar eclipse could be predicted years in advance. Although spherical astronomy deals with simple geometrical relations whereas meteorology has to struggle with an enormously complex mechanical and thermodynamical system, Richardson argued that it should be possible to proceed from an initial state of the atmosphere to a final state by a purely mathematical process. Richardson who served with an ambulance unit in France during World War I, worked through long nights and developed a step by step integration method for solving differential equations and in 1922 published one of the most remarkable books in meteorology, *Weather Prediction by Numerical Process*. Here he presented a set of equations that he thought described the physical processes governing the atmospheric phenomena together with a method for their approximate solution. Although the example worked out by Richardson in the book was a spectacular failure, this was the beginning of numerical weather forecasting. Richardson, with immense labour using his hand calculator, calculated the change of pressure at the surface over a period of six hours for an area in Europe and obtained an answer which was in error by at least two orders of magnitude. It must have required considerable courage to publish such a ludicrous result. We have reason to be thankful to him for this courage as this example brought to focus some of the intrinsic difficulties in solving meteorological equations!

Lewis Fry Richardson made the first attempt at numerically solving the atmospheric equations make a six hour forecast in 1922 using his hand calculator! His attempt, though a spectacular failure, showed the intrinsic problems in solving the meteorological equations.

During the next two decades not much progress took place in numerical weather prediction (NWP). In the late 40's Jule Charney (a pioneer of modern meteorology who was later a professor at the Massachussetts Institute of Technology) provided a theoretical basis to overcome the problems faced by Richardson.

The group led by Jule Charney at the Institute for Advanced Study, Princeton, made the first successful numerical weather prediction in April 1950, using the first ever built computer ENIAC.

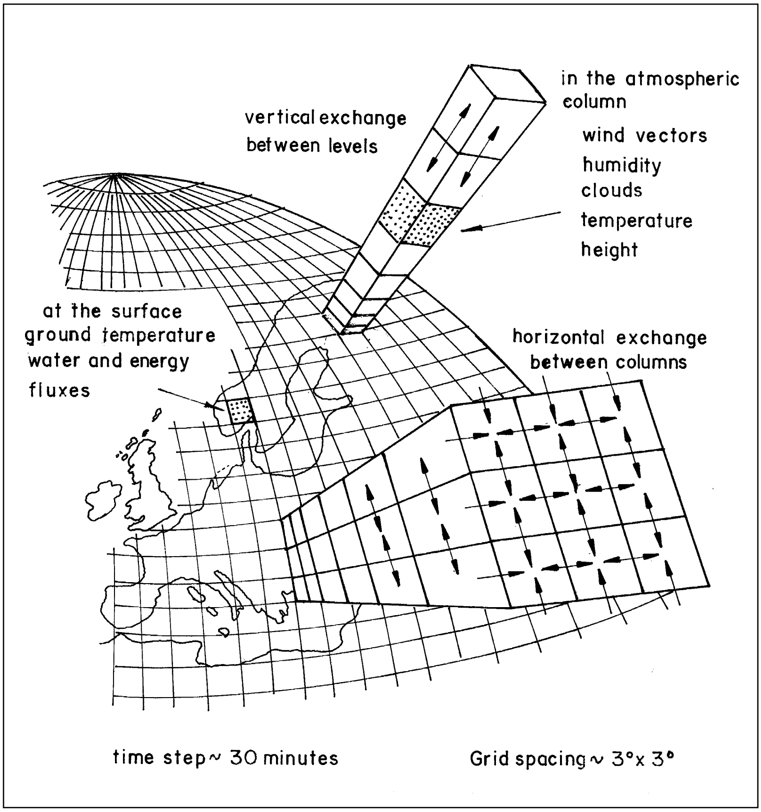

Figure 1 A cartesian grid for solving the meteorological equations .

Meanwhile, the first electronic computer ENIAC (Electronic Numerical Integrator and Computer) was being built at Princeton. Professor John Von Neumann at the Institute of Advanced Studies in Princeton recognised the enormous potential of this machine and organised a group with Jule Charney, R Fjortoft and a few others to conduct numerical forecasts of the atmospheric system. Using the simplified equations proposed by Charney (known as the *barotropic vorticity equation*) the first successful numerical forecast was produced with the ENIAC in April, 1950 for a level in the middle troposphere (500 hPa) supposed to represent the total behaviour of the atmosphere. Thus the era of numerical weather prediction was finally launched. Although the integration of the barotropic vorticity equation was made in a relatively small domain in the middle latitude (about 5000 Km x 5000 Km) only, a forecast of 24 hours took 36 hours of the computer time!

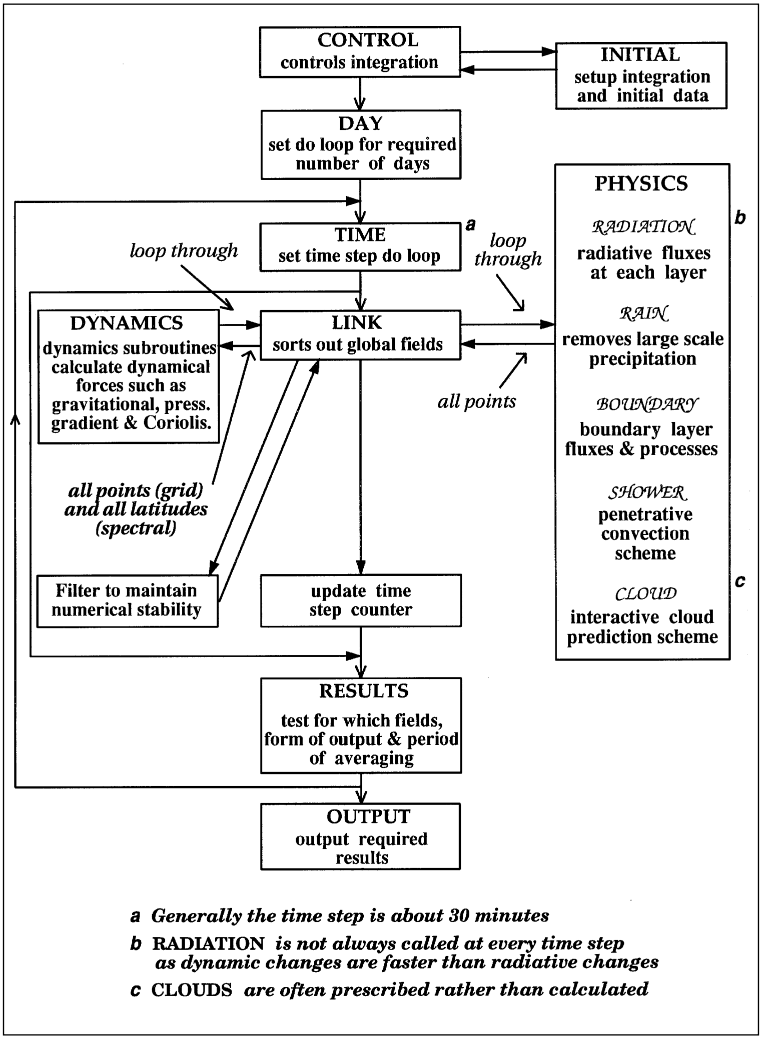

Figure 2 *Generalised flow diagram of a general circulation model.*

In a modern weather forecasting centre such as the one we have in New Delhi (National Centre for Medium Range Weather Forecasts), the basic equations are solved over the entire globe as shown in *Figure 1*. The method of solving illustrated in this figure is known as finite difference technique in which the equations are solved at a set of equi-spaced points. The other technique, more commonly used in recent times, is known as spectral technique. In this technique the variables are expressed in terms of a set of orthogonal basis functions (spherical harmonics) and equations expressing the evolution of the

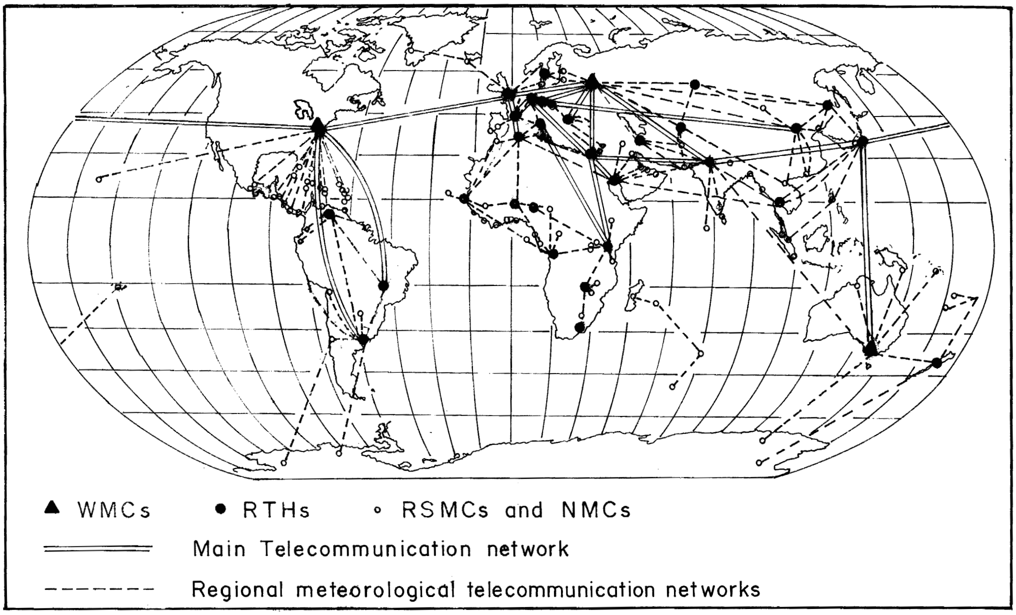

Figure 3 The Global Teleconnection System (GTS) (Adopted from WMO Bulletin, Vol. 45, January 1996).

amplitudes of these basis functions are solved. The flow chart in *Figure 2* shows how this integration is carried out. The grid spacing shown in *Figure 1* and *Figure 2* is somewhat outdated. Most state of the art models now use 1° x 1° grid spacing or better. They divide the atmosphere into 20 layers or more in the vertical. This gives us about 1.3 million points for the seven variables! In addition the calculation of the forcing functions such as radiation and cloud formation and release of latent heat requires very complex calculations. With all these constraints, the forecasts for tomorrow and days beyond must be produced today or else it will not have any value! This is why the weather forecasting centres require super computers.

Solving the equations in a super computer is only part of the story. A major effort is required to specify the initial state. The initial state comes from all those weather observations mentioned in Part II of the series. Currently, in addition to about 900 upper air stations, about 10,000 surface meteorological stations, 7000 merchant ships and 600 drifting buoys send their routine weather

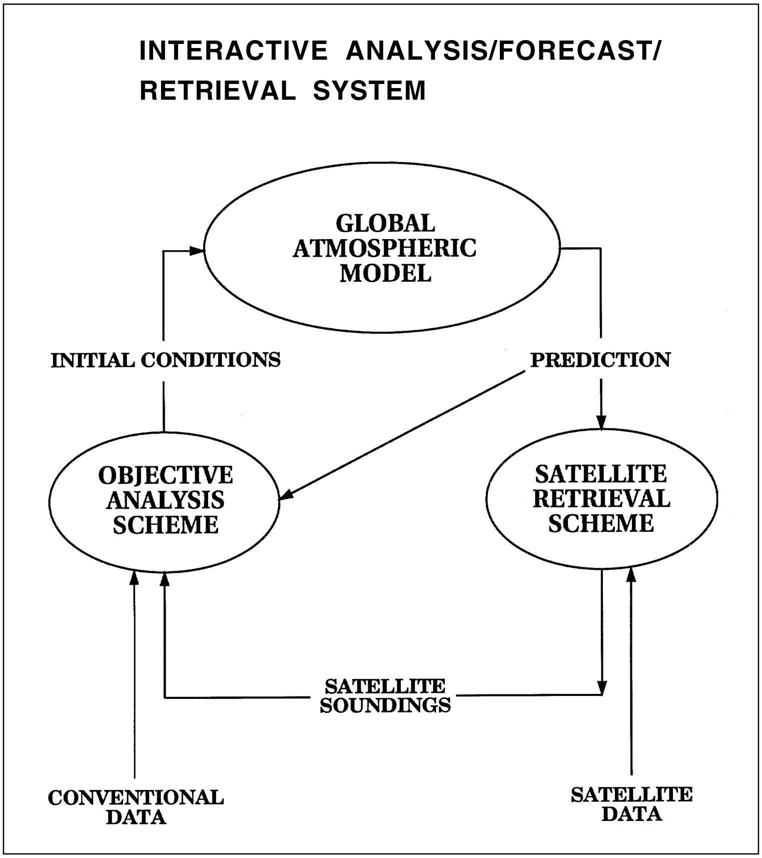

Figure 4 Schematic diagram of an interactive analysis/forecast/retrieval system.

reports. These are passed around the globe through 'hot lines' called the Global Teleconnection System (GTS) as shown in *Figure 3*. Most NWP centres have facilities to receive these data.

In addition to these, weather observations by several aircrafts and satellites are also passed on through the GTS. Since these are different types of information and at non-uniform space and time points with relatively large data void regions, a system has to be evolved to generate data at regular grid points required by the model. This, known as *Objective Analysis Scheme* uses a certain objective interpolation scheme to fill up the data void regions. In principle, this initial condition must exactly satisfy the governing equations. However, due to observational errors as well as the interpolation over the data void regions, the initial observations normally do not satisfy the governing equations.

Due to tremendous advance in computer technology, better understanding of the physical processes and better acquisition of data (through conventional means and satellites) have increased the skill in the middle latitude forecasts at least six fold since 1950. In contrast, the tropical forecasts have improved by only about two fold since then.

This imbalance is seen by the model as an initial error which grows rapidly with the integration of the model. To reduce this initial 'shock' a short forecast by the model is used as the first guess and the differences between the observation and the first guess are minimised using an objective minimisation technique. This procedure generates an initial state for the forecasts that is in approximate balance with the model equations. Before doing all this the system must also carry out some quality control checks on the data. Similarly, getting the meteorological parameters from satellite observations requires a set of calculations called *Satellite Retrieval Scheme*. A schematic diagram of the interactive analysis/forecast/retrieval system is shown in *Figure 4*. This procedure is quite involved and requires almost as much, if not more time on the computer as the actual numerical integration of the computer model.

NWP has never looked back since the first numerical forecasts in April, 1950. The tremendous advance in computer technology allows us to solve more complex models over a global domain. Moreover, specification of initial conditions has steadily improved through better observation, data collection and communication techniques and availability of satellite observations. In addition, our understanding of the physical processes responsible for the weather changes has also steadily improved. As a result, today, operational NWP centres are capable of making successful forecasts of the large scale circulation features in the middle latitude about 6-7 days in advance. By large scale circulation features we refer to wind conditions or temperatures over thousand kilometres or higher spatial scales. However, even in middle latitude, prediction of rainfall is somewhat less successful. Similarly, if we want the forecast for a specific small town, it is less skillful. In the tropics, the skill of the forecast for even the large scale circulation features is currently only about 2-3 days while the skill for precipitation forecasts is even poorer. This is because in the middle latitudes, rainfall is rather passive. The circulation forces upward motion that condenses the moisture and produces rain. In the tropics, rain plays a much more active role. It actually dictates the type of circulation we should have. As a result, to improve the tropical forecasts we must improve our knowledge of how the rains form in the tropics and how they interact with the circulation. The challenge of the day is therefore, to push the skill of tropical forecasts from the present 2-3 days to let us say 5-6 days through better understanding and formulation of the relevant processes. Every one day improvement in the averaged forecast skill can save us crores of rupees !

Better understanding of how clouds are formed and organised in the tropics holds the key to improving the tropical weather forecasts.

Before concluding, let me add a few words on climate forecasting. By climate, we refer to the average state of the atmosphere such as the monthly or seasonal mean. Thus, climate forecasts must be made at least one season in advance. From the discussion on the limit to weather forecasts, it is clear that even if we have a 'perfect' model and 'near perfect' observations, the skill of weather forecasts will be limited to about two weeks at best. Does this mean that there is no hope for climate forecasts? Fortunately, the answer to this question is no. This is because, so far we have considered the atmosphere in isolation from the ocean. Oceans have large thermal inertia. On time scales of a season or longer the oceans can modulate the mean condition of the atmosphere. Therefore, even though weather is not predictable beyond two weeks, the climate may be predictable beyond a season! This will be the subject of a future article.

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Suggested Reading

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