The Challenge of Weather Prediction

2. Difficulties in Predicting the Weather

B N Goswami

B N Goswami is with the Centre for Atmospheric and Oceanic Sciences at the Indian Institute of Science, Bangalore. After his PhD in Plasma Physics he was attracted to this field by the challenges in weather and climate prediction. His interests include understanding variability and predictability of all tropical phenomena including the monsoon.

Introduction

In Part I of this series, we mentioned that weather is a result of the motion of air caused by a balance between various forces. We have shown that this motion may be described by seven equations in seven variables. Some of these equations are nonlinear partial differential equations.

If we know the laws and the variables, why can't we make perfect forecasts even with a short lead time? There are many reasons for this. Let us understand a few of them.

Inaccurate Initial Conditions

Current meteorological observatory network consists of about 1000 observatories over land and island. Commercial ships, aircrafts and meteorological satellites supplement conventional meteorological observations specially over data sparse oceans.

To make the forecast for a future time, the initial state of the atmosphere over the whole earth at all heights must be provided as an initial condition. Routine meteorological observations are taken from observatories by releasing balloons that carry instruments to measure temperature and humidity. By radio tracking the balloons, velocities of wind are measured. As can be seen, these experiments are expensive. About half a million huge balloons are literally thrown away every year! Moreover, they are not automatic and require human involvement. Therefore, even on land these observatories are located only over well populated areas. Over the whole globe there are about 1100 such stations but only about 600 of these provide regular observations twice a day at noon and midnight Greenwich mean time as shown in *Figure 1*. There are other stations which make only surface measurements such as surface pressure, surface temperature, humidity and precipitation.

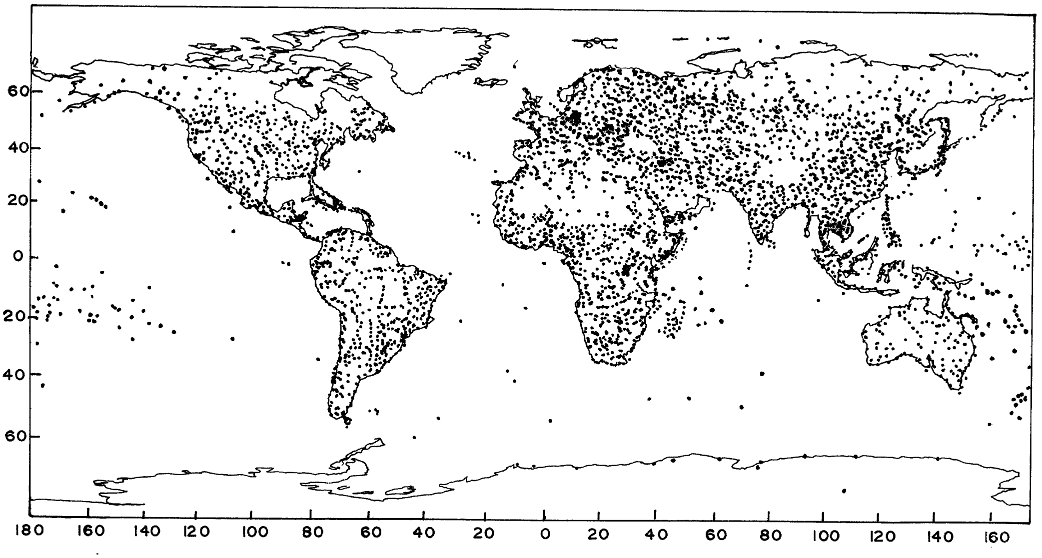

Figure 1 WMO's Regional Basic Synoptic Network: WWW (World Weather Watch) global observing system comprises 10,000 land stations, 900 of which make upper air observations, some 7,000 ships and 600 drifting buoys (Adopted from WMO Bulletin. Vol.45. January 1996).

As seen from *Figure 1*, there are very few upper air stations over the oceans that cover 70% of the earth's surface. Satellites are now providing some observations of wind and temperature profiles over the oceans. However, the signals received by the satellites are affected by the distribution of humidity and cloud cover. Therefore, information on wind and temperature derived from satellites suffers from a certain amount of uncertainty. Nevertheless, due to their large spatial coverage, this information is valuable in making weather forecasts. In addition to instrumental errors in the observations, the large data void regions lead to errors in the specifications of the initial conditions. This again leads to errors in prediction. As we improve our observational systems we can expect predictions to improve.

For an accurate description of the initial state of the atmosphere, ideally we need to make observations at each point over the earth, clearly a formidable task! In principle, the paucity of observations and the inherent instrumental errors in measurement give rise to errors in the specification of the initial state. As we improve the observing network, this error may be reduced but we may never be able to totally eliminate errors in the initial conditions!

However, as is clear, no matter how hard we try, some errors in the initial conditions may be unavoidable.

While the foundations of the first law of thermodynamics (temperature equation) and Newton's second law of motion (momentum equation) are solid, the rigorous calculation of the radiative and latent heating and frictional forces involve complex small scale processes demanding approximations and leading to errors in the formulation of the basic equations.

Grey Areas

In addition to errors in the initial conditions, there are some errors in the formulation of the equations themselves. Although the formulation of the adiabatic forces such as the pressure gradient, Coriolis and gravitation are well known, the formulation of the frictional forces and heating requires approximations leading to certain amount of inherent errors. As we mentioned earlier, the frictional forces involve the turbulent eddies. As these eddies have very small scales, it is formidable to resolve them in a weather prediction model. Therefore, one has to develop a model of how the small scale eddies influence larger scale circulation. This process is often known as *parametrisation*. This involves certain approximations leading to errors in the formulation. Similarly, heating by radiation depends in a complex way on moisture distribution, temperature and cloudiness. Approximations are used to represent these effects. Also, the equations are so complex that exact solutions are impossible. Again error producing approximations are made.

Even though many important problems of the atmosphere have been successfully attacked using these seven variables, exact solutions of these seven equations may still not give us the complete state of the atmosphere as there are other variables not described by these equations. For example, they do not tell us about the amount of ozone or aerosols (e.g., dust) present. These and other variables also affect the state of the atmosphere. While the radiative effects of ozone and aerosols may not be crucial for short range weather forecasting, they are quite important in determining the mean state of the atmosphere. If we want to understand the behaviour of ozone, we must add one equation for ozone concentration and another equation for ozone changes. Ozone can be affected by the concentration of other gases. So we need to introduce more equations. This illustrates that we have to make approximations at some stages and that a perfect model formulation for atmospheric motion is almost impossible. These small but unavoidable imperfections of the equations add another source of errors in the prediction of weather.

Large amount of latent energy release (used up) in condensation (evaporation) or freezing (melting) of water constitutes a major forcing for the tropical atmosphere. Exact calculation of these again involves many microphysical processes requiring approximations.

Water Makes the Weather Forecaster's Life Difficult

We know that life on earth would have been impossible without water. The equilibrium temperature of the earth(as calculated earlier) is such that water is the only substance that exists in all three states - gas, liquid and solid. To melt 1 gram of ice about 80 calories of heat are required (latent heat of fusion) while evaporating one gram of water requires 597 calories of heat (latent heat of vapourisation). These values are much larger than the latent heats of most substances. Conversely, when water condenses (freezes) it releases 597 (80) calories per gram. This heat transferred to the air represents an important source of energy. Thus thunderstorms, tornadoes and tropical cyclones all depend on the release of latent heat. Wherever precipitation takes place, condensation of water vapour and release of latent heat occurs. The tropical region receiving tremendous amount of rainfall, is a major source of heat for the atmospheric heat engine. Therefore, to be able to predict the weather correctly, we should be able to predict when and where precipitation occurs. This turns out to be the most difficult problem in meteorology. This is partly because precipitation usually occurs from individual clouds which have a typical horizontal size of about 10 kilometres. However, they can form only when the large scale environment is conducive (see *adjacent box*). In other words, again there is interaction between small and large scale processes. Moreover, condensation of water vapour into water droplets that fall down as rain involves numerous microphysical processes such as condensation nuclei, coagulation of small droplets into bigger droplets and others. In a large scale model explicit calculation of these processes is impossible. Again, we make certain approximations leading to errors in our model formulations. In

For example, clouds cannot form in the regions of large scale subsidence. Ascending motion in the equatorial region (as discussed in Part I) produces subsidence over subtropics inhibiting cloud formation. This is why major deserts of the world are in the subtropics.

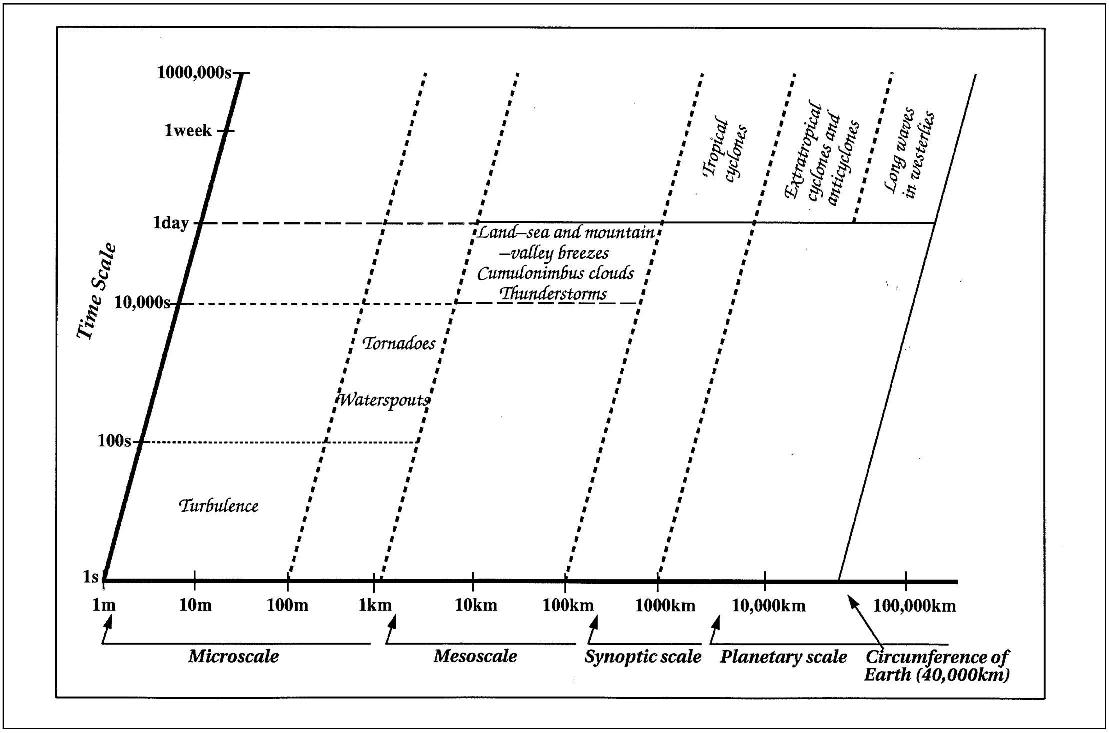

Figure 2 Horizontal and time scales of atmospheric motions.

fact, the interaction between the small scale cumulus cloud and the large scale environment is not yet fully understood.

Multiscale Interactions

The atmosphere is a giant laboratory in which phenomena with a wide range of time and space scales coexist as shown in *Figure 2*. There are phenomena ranging from turbulent eddies with a horizontal scale of a few meters and time scale of few seconds to large weather disturbances (e.g., depressions and tropical cyclones) with a horizontal scale of about 1000 km and time scale of about a week. In addition there are larger scale phenomena such as the meridionally narrow cloud bands extending thousands of kilometres in the east-west direction often seen in cloud pictures, known as the *intertropical convergence zone* (ITCZ), with horizontal scale of about 10,000 km and time scale of weeks to months.

Existence of multiple scales from turbulent eddies (L-1m) to tropical cyclones (L-1000km) in the atmosphere and the fact that one scale of motion depends on the other makes it hard to models.

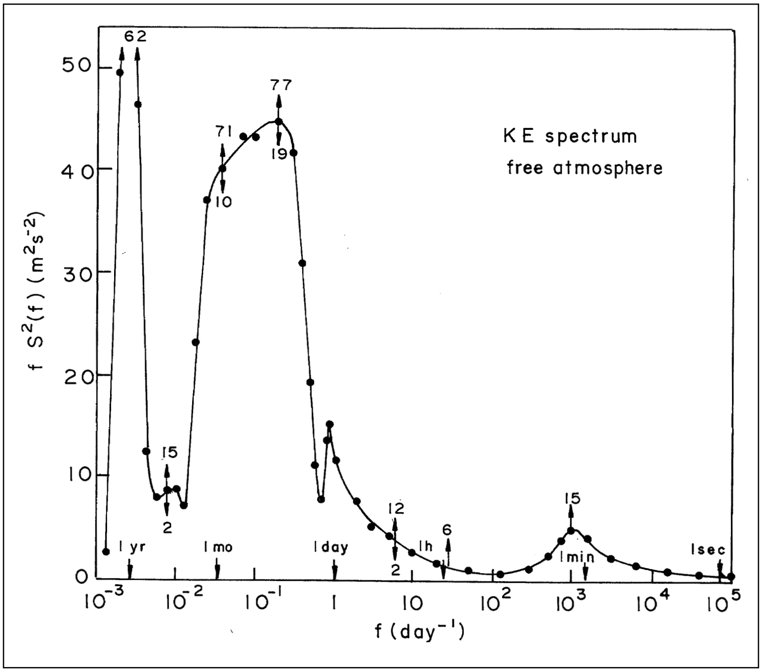

Figure 3 Spectrum of kinetic energy in the free atmosphere between 10^{-5} and 10^3 days. The abscissa axis is in units of $f\,S^2(f)$ where f is the frequency and $S^2(f)$ is the explained variance (Adopted from* Vennichenko. *Tellus. Vol. 22. pp 158-166, 1970).

However, if we examine the kinetic energy in different scales of motion in the atmosphere (*Figure 3*), we notice that except for the annual cycle due to external solar forcing, the large scale weather disturbances with time scales of a few days are the most energetic. The primary aim of weather prediction is therefore to predict the large scale weather disturbances (in meteorology called synoptic disturbances) correctly. However, the biggest hurdle is that these weather disturbances owe their very existence to smaller scale processes. For example, the tropical cyclone owes its existence and strength to the condensation of a large amount of water vapour. The water vapour is produced by evaporation and sucked into the cyclone by frictional convergence due to small scale turbulent eddies. As the moisture goes up, it forms a large number of cumulonimbus clouds, individually having a horizontal scale of about 10 km. These individual clouds organise themselves into spiral bands having a horizontal scale of several hundred kilometres. Although the small scale processes are not energetic themselves, without them the large scale systems cannot

The primary aim of weather prediction is therefore, to predict the large scale weather disturbances correctly.

be sustained. Therefore, there is continuous interaction going on between the small and large scales.

However, it is almost impossible to model all the scales of motion together. There are two major problems. First, the physical laws governing the evolution of some of these small scale turbulent processes are not well known. Therefore, even if we wanted to model them in detail we will have to make certain approximations. The second problem is technical in nature. If we want to resolve all the scales of motion, upto let us say 2 meters, we have to solve the same equations over the entire globe with a grid spacing of at least 1 meter. This means there will be about 5 x 10^{15} points over the entire globe. Then we have to consider at least 20 vertical levels. Thus the seven equations will have to be solved in about 10^{17} grid points in every time step! This is a formidable task even for the fastest supercomputer in the foreseeable future!

Thus, the large scale models of the atmosphere cannot resolve the small scale eddies. But their effect on the larger scales must be taken into account in some way. As I mentioned earlier this is the problem of *parametrisation* of the sub-grid scale processes. To be successful, we must understand clearly how the small scales influence the large ones. There are some major lacunae in our understanding in this field. Over the last three decades great strides have been made in parametrisation of rain formation and its effect on the large scale environment and formulations of evaporation and frictional forces. However, there is a lot more to be done in this area.

Even if the equations governing the atmospheric motions were known exactly, due to the intrinsic nonlinearity of the system, weather prediction would be limited to about two weeks in advance.

Chaos and Limit on Deterministic Predictability

Suppose that the uncertainties in the formulation of the governing equations were not there and that the model of the atmosphere represented by the seven equations was perfect, could we then predict the atmosphere indefinitely in advance? E N Lorenz of Massachussetts Institute of Technology showed in 1965 that even if the equations are perfect, infinitesimal unavoidable errors in the initial conditions can make a forecast differ significantly from the observations (actual future state of the atmosphere) within a period of about two weeks. Such a divergence of a forecast from observation is characteristic of all *nonlinear* systems and is known as *deterministic chaos*. Lorenz's original work has opened up a whole new field of research on deterministic chaos. Lorenz's original estimate using a rather simple three variable model was later confirmed using much more complex models of the atmosphere. Thus, even if the model was perfect, intrinsic nonlinearity of the atmosphere would restrict our ability to predict the weather to about two weeks. This limit of deterministic predictability is different in different nonlinear systems. It depends on the instabilities present in the system and the nature of the nonlinearity of the system.

While these intrinsic problems may never allow the weather forecaster to make perfect forecasts, as we shall demonstrate in the third and concluding part of this series, tremendous progress has been made in weather forecasting over the past four decades.

Suggested Reading

- **Nigel Calder. *The Weather Machine.* The Viking Press. New York. p 144, 1974.**
- **John M Wallace and Peter Hobbs. *Atmospheric Sciences: An Introductory Survey.* Academic Press. San Diego, California. p 467, 1977.**
- **Richard A Anthes, John J Cahir, A B Fraser and Hans A Panofsky. *The Atmosphere.* (Third Edition) Charles E Merrill Publishing Company. Colombia, Toronto, London, Sydney. p 532, 1981.**
- **A Miller, J C Thompson, R E Petterson and D R Harayau. *Elements of Meteorology.* Charles E Merrill Publishing Company. Colombia, Toronto, London, Sydney. p 417, 1983.**
- **J P Peixoto and A H Oort. *Physics of Climate.* American Institute of Physics. p 520, 1992.**
- **N Kumar. *Deterministic Chaos: Complex Chance Out of Simple Necessity.* University Press (India) Limited. Hyderabad. 1996.**

Address for Correspondence
B N Goswami
Centre for Atmospheric and
Oceanic Sciences
Indian Institute of Science
Bangalore 560 012, India
email:
goswamy@cas.iisc.ernet.in
Fax: (080) 334 1683