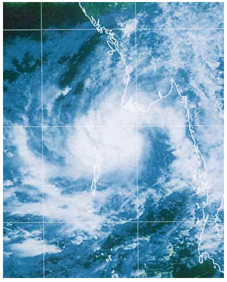


CHAPTER XII

METEOROLOGY AND ATMOSPHERIC SCIENCES

The growth of Meteorology and Atmospheric Sciences in the last fifty years in India is an outcome of many diverse features and has been shaped by circumstantial changes, not necessarily related to science, such as World War II or the partition of the country.

The Meteorological Department of India also referred to as the Indian Meteorological Department (IMD) has been for over 125 years, the premier Government Agency for all matters concerned with the weather and its application to other allied fields. Just prior to the War the IMD had seven Regional Meteorological Centres (RMCs). They were located at New Delhi, Mumbai, Kolkata, Chennai, Nagpur, Lahore and Karachi, the last two were later transferred to Pakistan. Its organizational set-up, primarily service-oriented, in reality has effectively helped to foster theoretical research in Meteorology.

One of the interesting features of meteorology is the wide variety of different disciplines that it covers under its umbrella. Thus, apart from weather prediction on different scales of space and time, it also covers subjects that are associated with natural hazards, such a, seismology (earthquakes), the hydrometeorology of floods and droughts, geomagnetism, and agricultural meteorology. These are the different facets of applied meteorology. On the other side, the theoretical aspects are concerned with the analyses of data, predictability on different scales, especially of the monsoons, rainfall variability, the coupling between the atmosphere and the oceans, tropical cyclones and meteorological instrumentation. For research on these different facets, different directorates have been formed under the IMD in recent years.

Considering the high frequencies of tropical cyclones, in the northern sector of the Bay of Bengal, a Storm Warning Radar was set up at Kolkata airport in 1954. To facilitate the rapid transmission of cyclone warnings and other data for operational use between principal meteorological centres of the world, a World Weather Watch Scheme was drawn up by the World Meteorological Organization (WMO) in the late 1950s. Under the aegis of this scheme, high-speed telecommunication links were set up between Moscow and New Delhi in 1961. These focal points for high-speed data exchange were named as the Northern Hemisphere Exchange Centres (NHECs) by the WMO and New Delhi was selected a centre for this purpose. Along with centres for the rapid exchange of data, a similar scheme was drawn up for establishing a set of Northern Hemisphere Analysis Centres (NHACs), and New Delhi was again selected by WMO to be a Principal Analysis Centre for the Northern Hemisphere in the early sixties. In addition to centres for Data Exchange and Analysis, a separate centre for the study of seismology was set up in 1961. A.N. Tandon, a distinguished seismologist, became the first Director of this new centre.

Around this time, space-based data collection platforms began to be introduced. This added a new

Meteorology in India

- The main progress in the post-war years have been in (a) Satellite meteorology, (b) Radars and (c) Computer simulation and models.
- Data are now available on water vapour in addition to other variables on real time. The network of coastal radars has been enhanced, and a MST radar provides valuable data on wave propagation in the upper atmosphere.
- A National Centre for Medium Range Weather Forecasts (NCMRWF) and an Indian Institute for Tropical Meteorology (IITM) have been established.
- A number of monsoon-related field experiments have been conducted, with Indian coastal research vessels over a marine surface.
- Studies on rainfall variability, and the impact of snow cover are in progress

dimension to meteorological data. The first Weather Satellite, Tiros-I, was launched by the United States in 1960. To analyse the data from this new source, two centres were set up, in Mumbai and Kolkata airports, in 1964. In 1970 and 1971, two additional directorates were set up for Meteorological Telecommunications and Satellite Meteorology and, in 1974, the NHAC became an Area Forecast Centre for meeting the requirements of South Asian countries for aviation meteorology.

In this manner, the first twenty-five years after the end of World War II, was a period of rapid expansion. The IMD was transformed into a major international centre.

Recent Expansions

The next twenty-five years saw further expansion of meteorological services along with research and academic institutes. The number of cyclone warning centres was enhanced, and the number of upper air stations for probing the upper atmosphere was increased.

Of special significance was the creation of an Indian Institute for Tropical Meteorology (IITM) at Pune and a National Centre for Medium Range Weather Forecasts (NCMRWF) at New Delhi. The former was oriented towards research, while the latter was established to meet the increasing needs of weather forecasts for agriculture.

Courses of study in meteorology and atmospheric sciences were started at a number of universities and technical centres. New Centres for Atmospheric Sciences (CAS) were opened at the Indian Institute of Technology (IIT) at New Delhi, at Kharagpur in West Bengal and a Centre for Atmospheric and Oceanic Studies at the Indian Institute of Science (IISc) in Bangalore. A few universities, such as, the University of Calcutta, have introduced courses in meteorology within the department of physics.

The question which we need to ask ourselves at this stage is: What are the benefits in terms of research and applied science that have emerged out of this investment? And, what are the future targets that we must achieve? In this context, it is relevant to state that our progress in the last 50 years owes a great deal to the foundations laid by eminent scientists of an earlier generation.

The first Indian Director-General of Meteorology, S.K. Banerji, who succeeded Sir Charles Normand, an eminent British meteorologist whose work on the thermodynamics of the atmosphere was well recognized. Another eminent meteorologist from Britain was Sir Gilbert Walker. He gave up a senior academic position at the University of Cambridge to become the Director General of Meteorology in India. It was Walker who introduced the Indian mathematical prodigy, Ramanujam to G.H. Hardy at Cambridge. This led to his rapid recognition. Walker's outstanding discovery was thatt in the Southern Oscillation a see-saw pattern of pressure changes occur between the Pacific and Indian Oceans.

S.K. Banerji, an eminent seismologist, was the first to analyse the impact of topographic barriers on the Indian summer monsoon. Another eminent Indian meteorologist was K.R. Ramanathan, the first Indian to receive the IMO (International Meteorological Organization) prize from the WMO who did pioneering work on the upper atmosphere, especially on the height of the tropopause at low latitudes.

Several eminent meteorologists from India won recognition in the post-war period, and some were pioneers in their areas, P.R. Pisharoty and P. Koteswaram being prominent among them. Pisharoty is the second Indian to be awarded the IMO prize by the WMO, for his contributions which included the computation of fluxes of water vapour across the Indian Ocean. P. Koteswaram will be remembered for his discovery of the Easterly Jet Stream a narrow band of air moving from the east towards the west in the upper atmosphere prior to the arrival of the monsoon over India.

A positive feature of its research has been the ability of the IMD to manufacture its own specialist equipment to a large extent, in the two workshops it maintains in New Delhi and in Pune. Original contributions were made by L.S. Mathur and S.P. Venkiteswaran, and the Indian radiosonde stands as an example of the joint effort made by them.

Progress on both the theoretical and instrumental aspects of meteorology in India has been through collective effort by a team. This tradition is still maintained.

Seismology and Geomagnetism

These disciplines do not have much in common with meteorology, but it was an eminent seismologist who first created an interest in tropical cyclones. Around 1930, S.K. Banerji suggested that cyclones in the Bay of Bengal could be detected and tracked by the microseisms on the seabed. This idea was followed up by many seismologists, notably by A.N. Tandon in 1957 and his associates, but was eventually given up because the cyclones could not be detected by this technique until they were very near the coast.

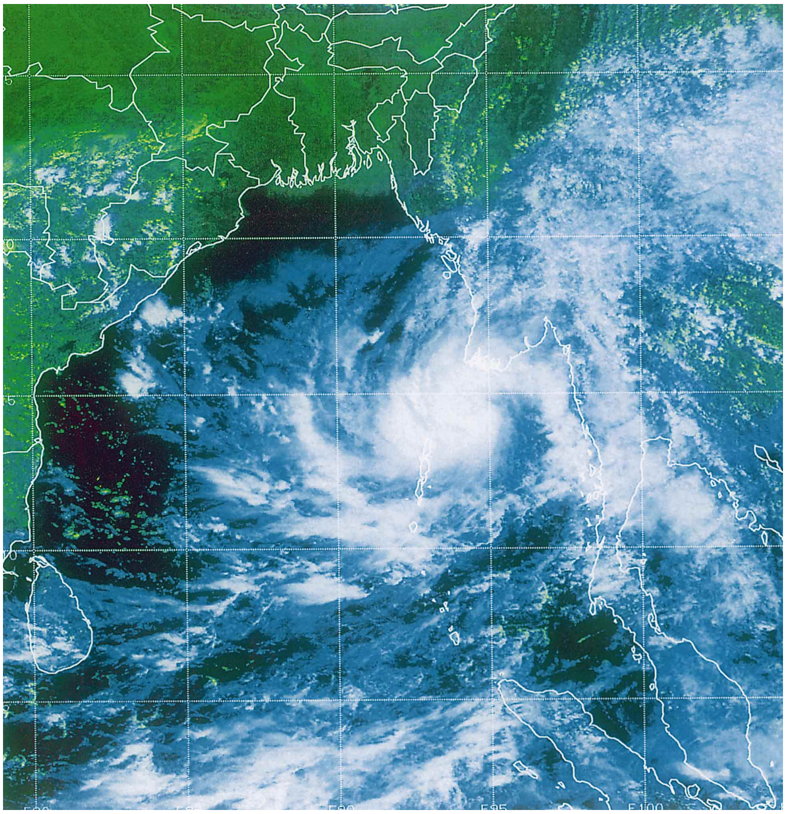
But work along similar lines continued, and recent advances in geomagnetism have helped us to understand the upper reaches of the atmosphere. S.K. Mitra's book *The upper Atmosphere* is now a classic on the propagation of waves in the upper atmosphere. A centre for research on geomagnetism at Colaba (Mumbai) had distinguished scientists like S.L. Malurkar and B.N. Bhargava who worked in this field.The recent book *Earth's Magnetic Field* by Girija Rajaram and P.R. Pisharoty, 1998, describes valuable links between geomagnetism and the upper atmosphere.

Satellite Meteorology

(a) The principal Indian achievements in the last three decades have been in three sectors:(i) satellite meteorology, (ii) weather radars (iii) computer simulation and numerical models for prediction. The achievements in satellite meteorology were an outcome of close collaboration with the Indian Space Research Organization (ISRO) when India began receiving the earth's images through its own geosynchronous satellites (INSAT Series) from 1982. In the early years, the imageries were received through different channels in the visible and the thermal infrared bands of the electromagnetic spectrum. But, very recently another satellite has been launched with two meteorological payloads: a Very High Resolution Radiometer (VHRR), and a Charged Coupled Device (CCD) camera. The VHRR payload provides imageries in two channels, while a third channel is used to measure the water vapour content of the atmosphere. The current resolution varies from 8 to 12 km. The data consist of the following meteorological variables:

I. Cloud Motion Vectors,
II. Sea Surface Temperatures (SST),
III. Estimates of Precipitation,
IV. Outgoing long wave radiation, and
V. Aerosols

The data provided gives valuable information for weather prediction, especially for the study of tropical cyclones and associated clouds. The information on aerosols is also important because



Spirals round the cyclone centre.

of their role in the condensation of vapour within clouds.

The estimates of precipitation from satellite cloud imageries is likely to reveal more details on cloud transformation, and interactions between clouds in the near future. It is also interesting to recall that the D.N. Sikdar, a scientist with the IMD who migrated to the University of Wisconsin in the USA, had been one of the earliest in the team of scientists in the USA, who embarked on this project. Estimates of precipitation are based on measurements of the rate of change in a cloudy area, from satellite-derived imageries. Extension of this technique to multiple clouds, or clouds that interact with each other will open up further research possibilities. This will be of interest to India because of the substantial damage caused by thunderclouds.

Satellite imageries are also turning out to be very useful for detecting biomass burning and forest fires in different parts of the country. This is a natural hazard about which not much is known at present.

Weather Radars

In the last two decades, the detection of oncoming cyclones has become much more easier due to a close network of coastal radars. These radars operate on a wavelength of 10 cm, and have a range of about 400 km.

Radars operate on a system of transmission and reflection of radio waves from an object. The radiation from a radar antenna is polarized. In some radars it is possible to measure the reflectivity of an obstacle which could be in the form of a raindrop or a cloud. The horizontal motion of drops in the sampled volume of air leads to shifts in the frequency of the reflected signal. A Doppler radar measures this for the detection of cyclones.

The Mesosphere-Stratosphere-Troposphere (MST) Radar

A radar which is meant for studying wave propagation in that part of the atmosphere which extends from the troposphere to the stratosphere and, finally, to the mesosphere is referred to as the Mesosphere, Stratosphere, Troposphere or MST radar.

An MST radar became operational at Tirupati in 1994 and an extensive scientific programme has been drawn up for it, including one for studying cloud drop-size distributions in the troposphere and programmes for the study of equatorial waves in the atmosphere. Quantitative estimates of the vertical fluxes of momentum are needed to study the long and short period oscillations in the equatorial middle atmosphere. Measurements of such fluxes have been recently conducted by a combination of the MST radar, high-altitude balloons and sounding rockets. The data are needed for studying the propagation of Kelvin (long period) and Rossby gravity (short period) waves.

Considering the recent developments in radar meteorology, a precipitation sensing radar installed on an Earth orbiting satellite is likely in the near future. The properties of waves emanating from the satellite and the radar will be one of the main problems for study in such a venture.

Computer Simulation and Mathematical Models

Numerical Weather Prediction (NWP) is based on a model of the atmosphere which is integrated in small time-steps. This was started by the IMD during the early 1960s with a third generation computer. Today, there are three centres where NWP is in operation; at the Indian Meteorological Department, the NCMRWF, Delhi, and IITM in Pune.

A Limited Area Model is used by the IMD, while NCMRWF uses a global model. The outputs from the IMD Model are largely oriented for meeting the requirements of civil aviation at the principal airports in India. On the other hand, the outputs from the NCMRWF are oriented for meeting the requirements of agriculture. They place the greatest emphasis on rainfall forecasts for 3 to 5 days duration. The work at the IITM at Pune is also research oriented. Work in this area had started with a third-generation computer but today the latest CRAY Computer is in operation at NCMRWF.

The major areas of uncertainty, on which research is in progress, are summarized below

Initial Conditions: The mathematical equations that predict atmospheric motion are very sensitive to the initial conditions with which the integration is commenced. Even very small changes in the initial conditions could lead to wide variations in the final output. Consequently, the best initial conditions are determined by using variational principles. Experimental forecasts are first made for small intervals of time, with an ensemble of initial conditions that differ only slightly from each other. The one that minimises the error between the observed and predicted values of the relevant variables are then selected as the best initial conditions. This process is referred to as the initialization of the prediction model.

Parameterisation of Clouds and Aerosols.

The NCMRWF Model uses a scheme that was first introduced in 1947 by Arakalwa and Schubert, with a few modifications. The scheme is based on (a) the release of thermodynamic energy and (b) changes in the water content of clouds. The model's specification of clouds changes with different scales of motion. In addition, a cloudy atmosphere is a multi-phase system. The aerosols and the liquid cloud, and the interactions between the two for different scales of motion have not yet been quantified. These could be important for studies on climate variability.

The Planetary Boundary Layer (PBL)

This is the region above the earth's surface, of approximately 1-km depth, where the effects of friction and heat flux from the ground are predominant. Uncertainties arise because it is difficult to quantify the ground features, especially in the vicinity of mountains.

The motion within a boundary layer is turbulent. The balance between the production and dissipation of the kinetic energy of turbulent motion has been recently worked out, although different views exist on how to quantify the dissipation function.

For including the boundary layer in a model, the turbulent fluxes are correlated to the gradients of the mean motion to the eddy diffusivities. A recent experiment compared the outputs from the NCMRWF Model by two different formulations of eddy diffusivity. In the first experiment, the conventional form of eddy diffusivity was used with an empirical dependence on atmospheric stability, while the second experiment employed a correction factor for large scale eddy stress. It was observed that the latter approach yielded better results.

Radiative Effects

At present, the models developed by (a) the Geophysical Fluid Dynamics Laboratory and (b) the NASA / Goddard Space Centre in USA are adopted to quantify the impact of radiation. These models consider the absorption by each line of the electromagnetic spectrum. This has the advantage of considering the wavelength separation of direct solar radiation and the long wave terrestrial radiation. Of course, the major difficulty here is the problem of quantifying the role of clouds. As the temperature profile of the atmosphere and the distribution of clouds change with time, the radiative fluxes need to be calculated at different atmospheric levels and at frequent intervals of time. For long wave terrestrial radiation, the absorption at different wavelengths is complicated. Consequently, a line by line integration yields the best results.

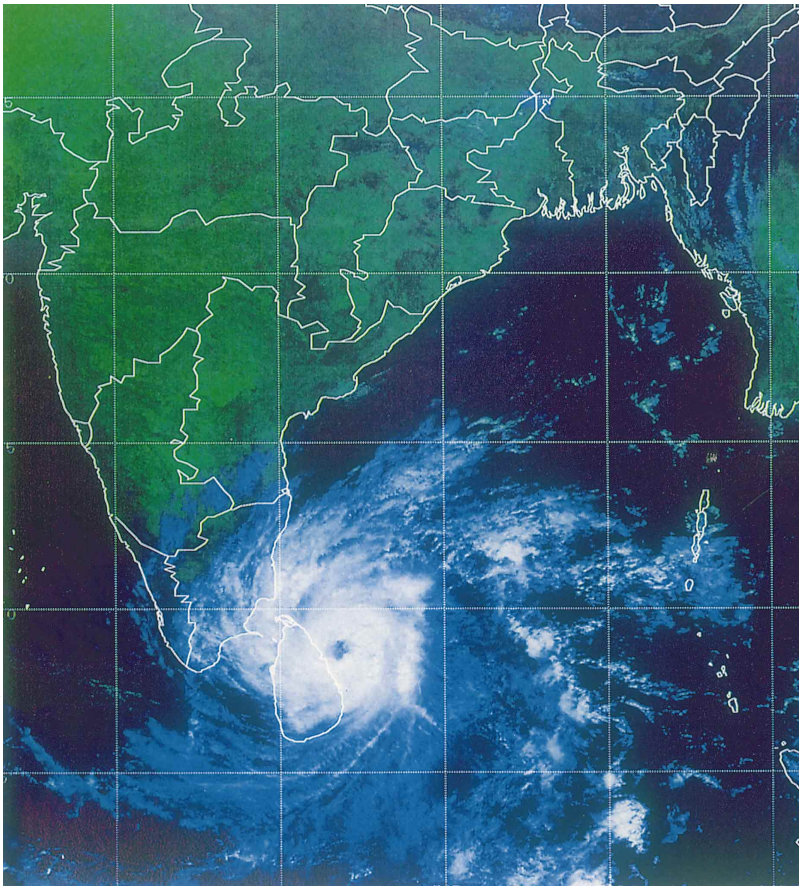


Photo: IMD and NCMRWF, New Delhi

A peep into the eye of the storm.

Walker Cells in a Steady Monsoon: A Walker Cell is an east-west oriented pattern of wind circulation in which the ascending limb of the cell is at its eastern end and the descending limb is located at the western end. The cell is named after Sir Gilbert . An early study of the monsoon in the 1960s had revealed a Walker cell type of circulation between the eastern and western parts of northern India during the summer monsoon months. Ascending motion over northeast India implies cooling because the air moves from higher to lower pressure. Consequently, to maintain a steady monsoon we need a warming mechanism to balance the cooling. This could be produced by the latent heat of condensation associated with the heavy rainfall of the summer monsoon. By the same reasoning, descending motion over northwest India, especially over Rajasthan, would imply a cooling mechanism to balance the warming due to descending air. The view has been put forward that the required cooling could be provided by the heavy dust load of the atmosphere over the semi-arid regions of Rajasthan. The required cooling due to scattering of light is about 1.6°C/day. There are a few uncertainties in this picture, because a steady monsoon is difficult to come by Reid Bryson, from the University of Wisconsin in the U.S.A., had brought a team of scientists to make actual measurements of cooling rates from an aircraft. Their observations showed results that were fairly close to the cooling rates prescribed by theory. More observations of this nature are needed in future because they could throw light on the causes of desertification over Rajasthan.

Oceanic Circulations: Tropical Cyclones

The advent of weather satellites and coastal radars have greatly improved our ability to detect and trace the path of cyclones in the Bay of Bengal and the Arabian Sea. Cyclones are more frequently observed in the post-monsoon months of winter. Next to earthquakes, tropical cyclones are the worst natural hazards in our country. However, improvements in our warning systems over the last fifty years has brought about a declining trend in the number of casualties, albeit with some exceptions, such as the Orissa Cyclone of 1999. The principal prediction problems in this field are: (i)prediction of formation and the path of cyclones, especially their recurvature near the coast; (ii) sudden changes in the intensity of cyclones, and (iii)Storm surges.

A scheme devised by U.S. scientist Dvorak in 1975 is used to classify cyclones according to their intensity. The classification is based on the characteristics of cyclones as seen on satellite imageries; especially on the enhanced infrared imageries. They provide an indication of the future movement of the cyclone. This is possible for intense cyclones whose intensity exceeds a threshold value. Similarly, another scientist from the IMD has pointed out that an increase in the surge of convective clouds is often the precursor of a cyclone in the Bay of Bengal. Another feature of a cyclone is multiple eye formation. The mechanism for multiple eye formation is not yet clearly understood. It is believed that the maximum angular momentum of winds rotating round a cyclone is often not reached at a single value of the radial distance from the cyclone centre. This could lead to the formation of two or more eye walls. The formation of multiple convective rings has been utilized by scientists from the Centre for Atmospheric Sciences at the IIT in New Delhi to suggest an interaction between two eye walls which could influence the path of a cyclone. It has been observed that low values of the Outgoing Longwave Radiation (OLR) are associated with the formation of cyclones because of an increase in cloudiness. This provides an indication for the formation of cyclones.

Considerable progress has been achieved by Indian scientists in designing prediction models for forecasting the amplitude of storm surges. This is a sudden rise in the sea level when a cyclone hits the coast. Monograms, prepared by different scientists, are now available to predict the surge amplitude from the observed features of a cyclone. Two of the unsolved problems in this area are (i) interactions between a surge and the tidal elevations, and (ii) the interactions between a surge and river discharges. These problems involve nonlinear mathematics, but research has made a beginning by expanding the dependent variables in terms of a small parameter.

Rainfall Variability and Ocean Atmosphere Interactions

Indian meteorologists have often experienced periodic changes in the rainfall generated by the summer monsoon. The reasons for such variations are still not clear. To improve our understanding of the role of oceans in causing such variations, a number of scientific expeditions have been arranged in the past two decades.

Two major expeditions were arranged in 1977 and 1979. The expedition of 1979, the larger of the two, was named the Monsoon Experiment (MONEX). It was a part of the Global Atmospheric Research Programme (GARP), that was organized, jointly, by the WMO and the International Council for Science (ICSU). MONEX revealed many features, that were not realized earlier. By tracking the path of constant level balloons, for example, it was possible to see that the origin of the monsoon winds lay in the southern hemisphere.

An Indian Ocean Experiment (INDOEX) was organized during the winter of 1998, with the aim of determining the radiative forcing by aerosols. An interesting result showed high values (40 w/m^2) of radiative cooling by aerosols, which had not been observed before.

Yet another recent experiment was the Bay of Bengal Monsoon Experiment (BOBMEX) in 1999. This experiment was part of the Indian Climate Research Programme (ICRP), with a main focus on the marine boundary layer over the southern Bay of Bengal. The experiment collected valuable data on convection and its associated energy transformation in the atmosphere, somewhat similar to the observations made over a warm pool of water over the west Pacific Ocean. A second experiment similar to BOBMEX is now being planned for the Arabian Sea to study convective processes over a warm pool of water on the southern sector of the Arabian Sea. It could yield useful information for predicting the onset of the summer monsoon.

ENSO Linked Rainfall Variability

ENSO stands for combination of the El Nino (EN) and the Southern Oscillation (SO). The Southern Oscillation was discovered by Sir Gilbert Walker who found that the inter-annual fluctuations over the Indian and Pacific Oceans were inversely related to each other. Thus, when high pressure exists over the Pacific, it was low over the Indian Ocean, and *vice versa*. And, as high (low) pressures imply low (high) rainfall, the Southern Oscillation represents a rainfall oscillation. *El Nino*, is a Spanish word which means a male child. It is used in meteorology to denote, a sudden spread of warm waters off the coast of Peru towards the east. This is referred to as an ENSO event. The summer monsoon rains are unusually deficient in the ENSO years, although the relation between an ENSO event and poor monsoon rains is not established.

The link between rainfall over the equatorial regions of the Pacific and Indian Oceans is now a topic of considerable research interest. Scientists in China attribute this to similarity in air sea interactions between the two oceans. But, interestingly, experiments with ocean atmosphere coupled models suggest that an increase in sea surface temperatures (SST), such as an ENSO event, could induce oscillations in another basin. The models start with two adjoining oceanic basins separated by a narrow strip of land. This mimics the Pacific and Indian Oceans with a land strip dividing the two. The results suggest that warming in one ocean will induce oscillations over the other.

Global Warming and Rainfall Variability

The global mean temperature records show a general warming trend, of about 0.3 to 0.6°C in the last hundred years. (IPCC, WMO, 1992). Opinions differ, but it is difficult to assess whether this constitutes a signal in the time series, or whether it is a part of the natural variability of the temperature time series.

This is particularly so because temperature and rainfall appear to move in opposite directions. In China, for example, the summer monsoon rain became weak in the 1920s when there was rapid global warming. A similar situation prevails over India. Thus, there has been a rapid increase in the combined land, air and sea temperature from 1970 onwards, but the trend observed in summer monsoon rains has been one of decrease. Opinions are also divided on whether there has been any significant increase or decrease in the number of depressions or cyclones from 1970 onwards. There are also uncertainties regarding the models that predict global warming because of the negative feedback from clouds.

Despite the difficulties of climate predictions, attempts are being made to predict the quantum of rainfall during the monsoon season. This is based on a statistical regression equation which links the predictand (monsoon rains) with several predictors. The prediction used to be for the whole country, but is now made for separate regions where the rainfall pattern is homogeneous. This technique needs improvement for it is not clear, for example, how much of the variance of rainfall is explained by the regression model, or whether the predictors are independent of each other. Unfortunately, due to the wide limits of tolerance, predictions for a normal monsoon are made year after year. This does not agree with facts. But, an interesting possibility has recently emerged. It has been suggested that 'breaks' in monsoon rains could be predicted by improved regression equations.

Snow Cover Influence on Monsoon Rains

The interesting possibility of a link between the Himalayan snow cover and summer monsoon rains is a research project of much interest to Indian meteorologists. Hitherto, the project was hampered by lack of data, but this position has improved considerably after the advent of satellites and improvements in radar technology. The recent developments in this field have been described in a book, *The Himalayan Environment*, brought out by scientists from the Centre for Atmospheric Sciences at the IIT, New Delhi. The principal impact of snow is linked with its high albedo, or reflection power for solar radiation. This provides a negative feedback which could be of the order of 15 walts/m^2, to the earth's radiation budget. The presence of clouds could increase the negative feedback. And, interestingly, this is of the same order as the negative feedback from aerosols. These features need to be considered in the design of mathematical models to simulate the airflow over the Himalayas.