[In hundred days, from June to September, over seventy per cent of India's annual rainfall is recorded. A bad monsoon can adversely affect the annual food production of the country. The total grain production (135 *million annually) can be decreased by as much as* 15%. *But if the dates of onset and cessation of the monsoon and the total quantum of monsoon rain can be predicted, much of the loss can be offset by more efficient water management and by planning for the proper distribution of food grains. In this article Dr. P. K. Das reviews recent developments in Indian meteorology, identifying many areas where such developments can have an impact. He also describes how Indian meteorologists are trying to solve the problem of prediction using statistical methods and by modelling experiments.—Ed.*]

METEOROLOGY IN INDIA

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INTRODUCTION

THERE are two facets to the study of atmospheric sciences in India which, despite being closely related, are nevertheless distinct. First, we need a national agency for monitoring different aspects of the atmosphere on several scales of time and space. The Meteorological Department of India performs this function. This Department is now over a hundred years old and has the distinction of being one of the oldest scientific departments in the country.

The second important feature is concerned with the analysis of data and research. Specifically, the aim here is to use the data for anticipating changes in weather. This is achieved by applying the physical laws that govern fluid motion, especially in a turbulent medium, such as the atmosphere. Sometimes this is not possible by purely analytical tools and numerical methods have to be employed. We shall describe in a later section how mathematical models that are based on numerical algorithms can help us to understand the dynamic processes of the tropical atmosphere.

METEOROLOGICAL PREDICTION

It is appropriate to ask ourselves : what are the priorities for a national meteorological service for India? The question may be answered if we attempt a broad classification of the weather systems that affect us most. These are:

- monsoonal winds and rainfall extremes (droughts and floods);
- tropical cyclones and intense atmospheric vortices;
- the upper atmosphere and atmospheric waves;
- Ecological imbalances caused by human activity.

Opinions will inevitably differ on the above choice. We have left out, for example, the interface between meteorology and oceanography, or between meteorology and hydrology and these are certainly important. But, in this article, it is probably appropriate to confine ourselves to areas where the problem of prediction, in some form, is well defined. Moreover, a good part of the meteorological support to hydrology and oceanography is covered under monsoonal winds or under tropical cyclones.

Let us now examine the problem areas which we have identified. This will enable us to see the tools that are currently available to us and the outlook for the future.

Monsoonal Winds

Monsoonal winds arise from the same type of conditions that produce land and sea breezes. They are caused by uneven heating of the land and the sea.

The path of monsoon winds is, however, more complicated because of its much larger scale. When we consider the movement of air on the scale of the monsoons, we need to consider the rotation of the earth and the retarding influence of friction by the land and the sea by the overlying air.

By far the largest system, as far as India is concerned, is the summer or southwest monsoon.

The three principal prediction problems concerning the summer monsoon are:

- the total quantum of monsoon rain from June to September;
- the dates of onset and cessation of rainfall;
- the periods of lean and heavy rain within the monsoon season.

Currently, two distinct lines of approach are being followed for predicting the above features.

The first approach is built on statistics. We have over seventy years of rainfall data in the archives of the Meteorological Department. If we plot them as a time series and search for trends or periodicities by a periodogram or by a power spectrum, very few cycles are discerned which have real predictive value. We do not find any significant trends either, apart from a small region north of 13° N along the west coast of India where a slight increase is observed from the beginning of this century to around 1960.

A technique which appears to have some potential for further improvement is the Autoregressive Integrated Moving Average Process (ARIMA). It seeks to resolve a time series into a part that is determined by past history (autoregressive) and a part that is made up of a series of random shocks. The series determines by itself the sequence of random perturbations that best describes its future behaviour. The performance of ARIMA could be improved if we could discover a few 'leading indicators', or physical variables which have the most influence on the behaviour of the time series. Thus, in ARIMA we have the possibility of developing a technique that is a mix between statistics and physics. It has been used for long range prediction of monsoon rainfall for a given season.

The second approach to prediction aims at identifying those physical processes which are most important for monsoon rainfall. As a precursor to prediction, we attempt a number of experiments, in the nature of diagnostic studies, that seek to assess the impact of different parameters which might have a bearing on rainfall. Diagnostic experiments of this kind are best performed by designing suitable simulation models.

The basic equations for such models are based on the physical laws that govern fluid motion. We have a set of equations that express the conservation of mass, momentum and entropy under the influence of external body forces. The set of equations is then integrated with time, under appropriate constraints that ensure that the numerical solution will resemble to some degree an analytical solution of the problem. Suitable algorithms and computer capability for this purpose are now becoming available in India.

The principal body forces that a simulation model seeks to incorporate are:

- solar and terrestrial radiation,
- orographic barriers,

— clouds and conversion of moisture to *precipitation.*
— influence of oceans and frictional forces over land and sea.

An ideal model should be able to incorporate all external forces, but this is not yet possible because our understanding of the physics of the monsoon is still incomplete. *There are limitations of data over oceanic* regions and over mountains, which introduce further constraints.

Meteorological services which have access to large computers are currently experimenting with models on a global scale or General Circulation Models. For certain types of motion which have a regional interest it is more convenient—in terms of computer memory and cost—to design a model that covers a *limited part of the atmosphere or a* Regional Model. The question of devising suitable boundary conditions along the lateral *sides of a regional model is important,* because it is not yet clear whether it is logical to pull out a slice of the atmosphere and to study it in isolation. There must be a two-way traffic between what happens over a selected portion of the atmosphere and what happens elsewhere.

Modelling experiments on the monsoon have made a beginning in India. In Figs. 1 and 2 we reproduce the response of a simple model after 8 days of simulated time. The model begins with an initial idealised monsoon (Fig. 3). Figure 1 shows the response when the initial state is disturbed by the mountains alone. They are the Himalayan barrier, the Western Ghats and the mountains of Burma and Ethiopia. *It is interesting to see that these mountains are not sufficient by themselves* to generate an elongated low pressure *zone along the southern periphery of the* Himalayas known as the monsoon trough. On the other hand, if we include a few components of radiation, such as, *(i) incoming solar radiation as modified by the reflectivity of the earth's surface, (ii) upward flux of sensible heat from* the surface of the earth and (iii) long-wave

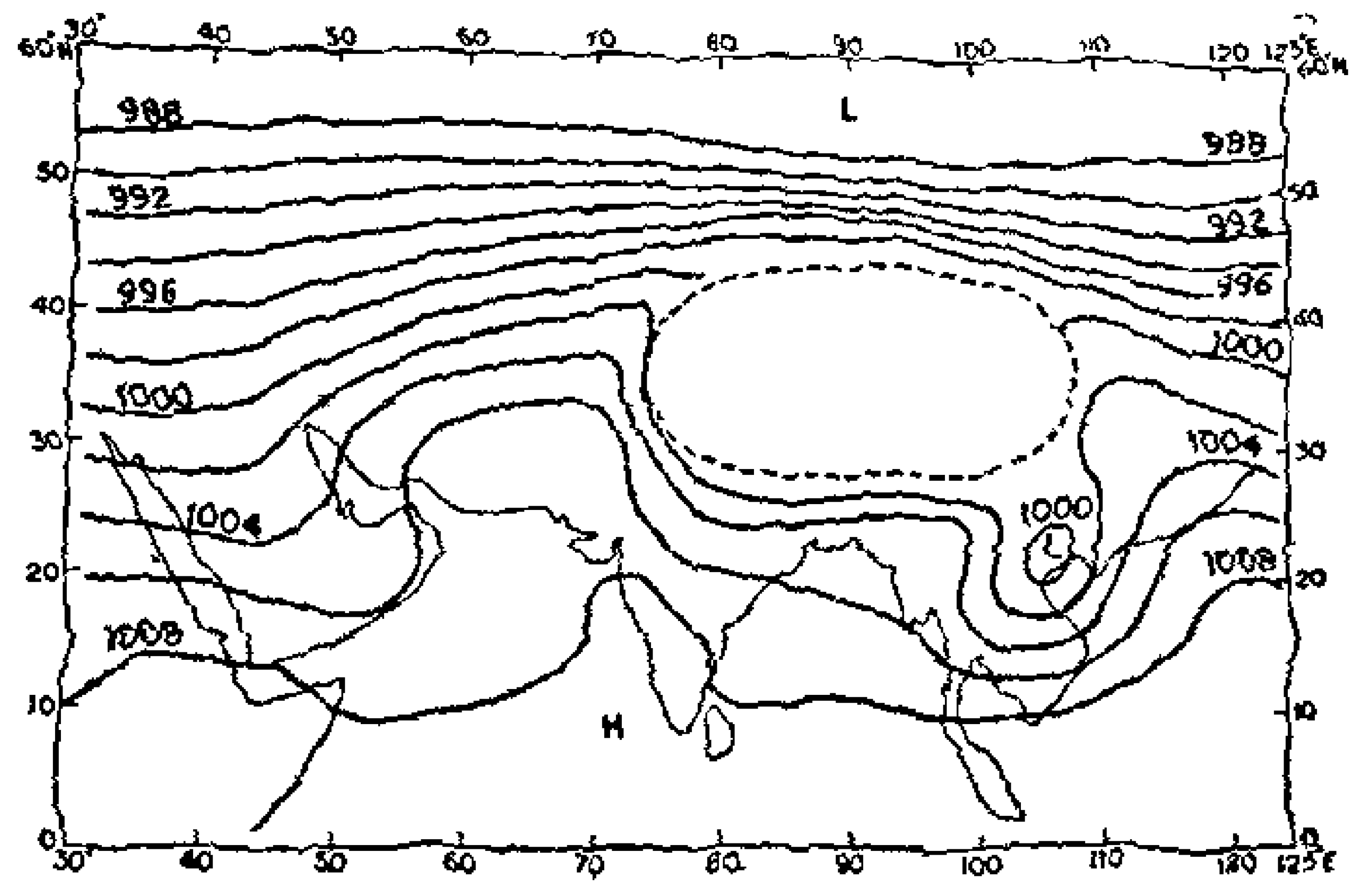

FIG. 1. *Model response (8 days) with mountains.* Figures represents millibars.

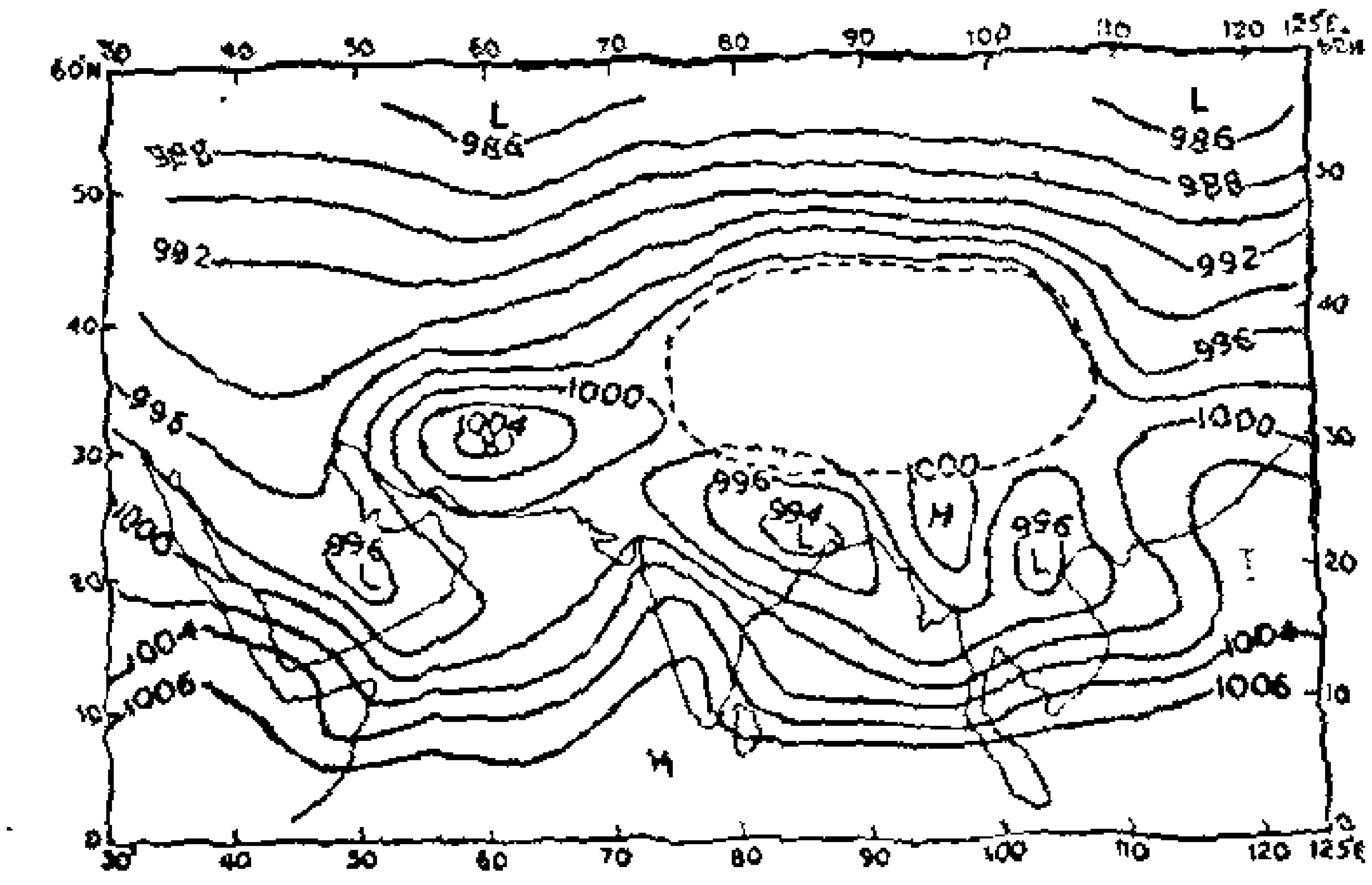

FIG. 2. Model response (8 days) with mountains and radiative heating. Figures represent millibars.

of counter *radiation, in a simple form,* directed downwards due to clouds, then the *response of the model suggests that the monsoon* trough can indeed be generated (Fig 2). This is an important result because *it suggests that the mechanical effect* of mountains is not the only important factor for generating monsoon rainfall.

Towards the end of 1972, a series of catastrophic events over different parts of the world drew the attention of scientists to the *possibility of tele-links between what happens* to the monsoon over India and events in *other parts of the world. The monsoon of* 1972 was poor, and an unusual spell of lean rainfall over the Sahel region led to widespread drought that year. An abnormal belt of warm waters off the coast of Peru in the *western Pacific severely depleted the fishing* industry of that country.

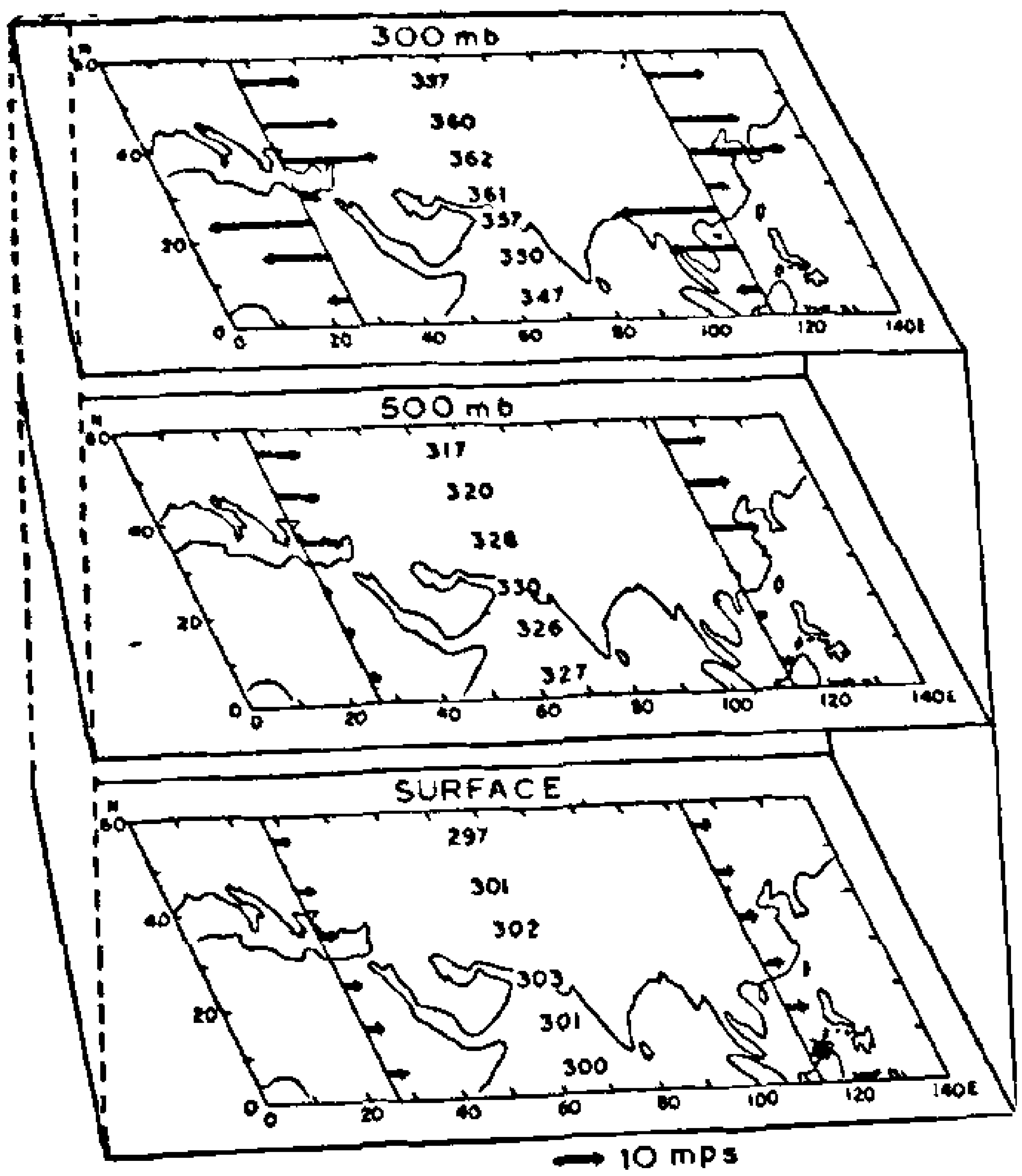

FIG. 3. Idealized initisl state foi monsoon model; Figures represent temperatures and arrows represent wind direction.

As a result, research on a "Southern Oscillation" which was first suggested by Sir Gilbert Walker in 1924 has been revived. The Southern Oscillation is an inverse statistical correlation in sea level pressure between India-Indonesia and the eastern half of the south Pacific Ocean (Fig. 4). Thus, good rainfall over India and Indonesia appears to be linked with abnormal low pressure off the eastern coast of South America. The reasons for this oscillation are not well understood, but research is in progress to investigate this phenomenon with mathematical models. This could improve our understanding of droughts and poor monsoons in some years.

Tropical Cyclones

A large part of the eastern coast of India is devastated by tropical cyclones each year. A recent cyclone which hit the Andhra coast near the village Chirala in November 1977 led to over 10,000 fatal casualties. Improvements in our early warning system are thus a matter of vital importance to the country.

The principal prediction problems which we encounter are:

- transformation of an ensemble of cloud clusters into a tropical cyclone.
- rapid changes in the track of a cyclone as it approaches the coast, especially its recurvature.
- the rise in sea level, or the storm surge, as a consequence of the cyclone.

If we look at the structure of clouds over the Indian Ocean, as seen by the cameras of a weather satellite, a wide variety of cloud clusters will be generally seen. But, the interesting feature is—in some months of the year—that some of the clusters seem to suddenly merge and transform themselves into a giant whirlpool. This then becomes a tropical cyclone. We still do not understand by what process of selective growth this transformation is brought about. Some have expressed the view that this represents a form of instability, when some clouds grow at the expense of others and transform themselves into a cyclonic vortex. On the other hand, others feel that disturbances, or atmospheric waves, which move from the east to the west are responsible for converting a cloud cluster, under suitable conditions into a tropical cyclone. The entire tropical belt extending from the north Pacific Ocean, the China Sea and the Indian Ocean adjoining the Gulf of Thailand and the Bay of Bengal seems to be a favourite ground for spawning tropical cyclones.

If the formation of a cyclone is imperfectly understood, still less is known about why changes occur in a cyclone's track. Cyclones often change their track very rapidly. As they approach the coastline, they often recurve and begin to move in an entirely different direction. This makes it difficult to design an adequate early warning system, unless the behaviour of the cyclone is monitored at frequent intervals.

Numerical models have not yet had much success in predicting the formation or the track of tropical cyclones. But, success has

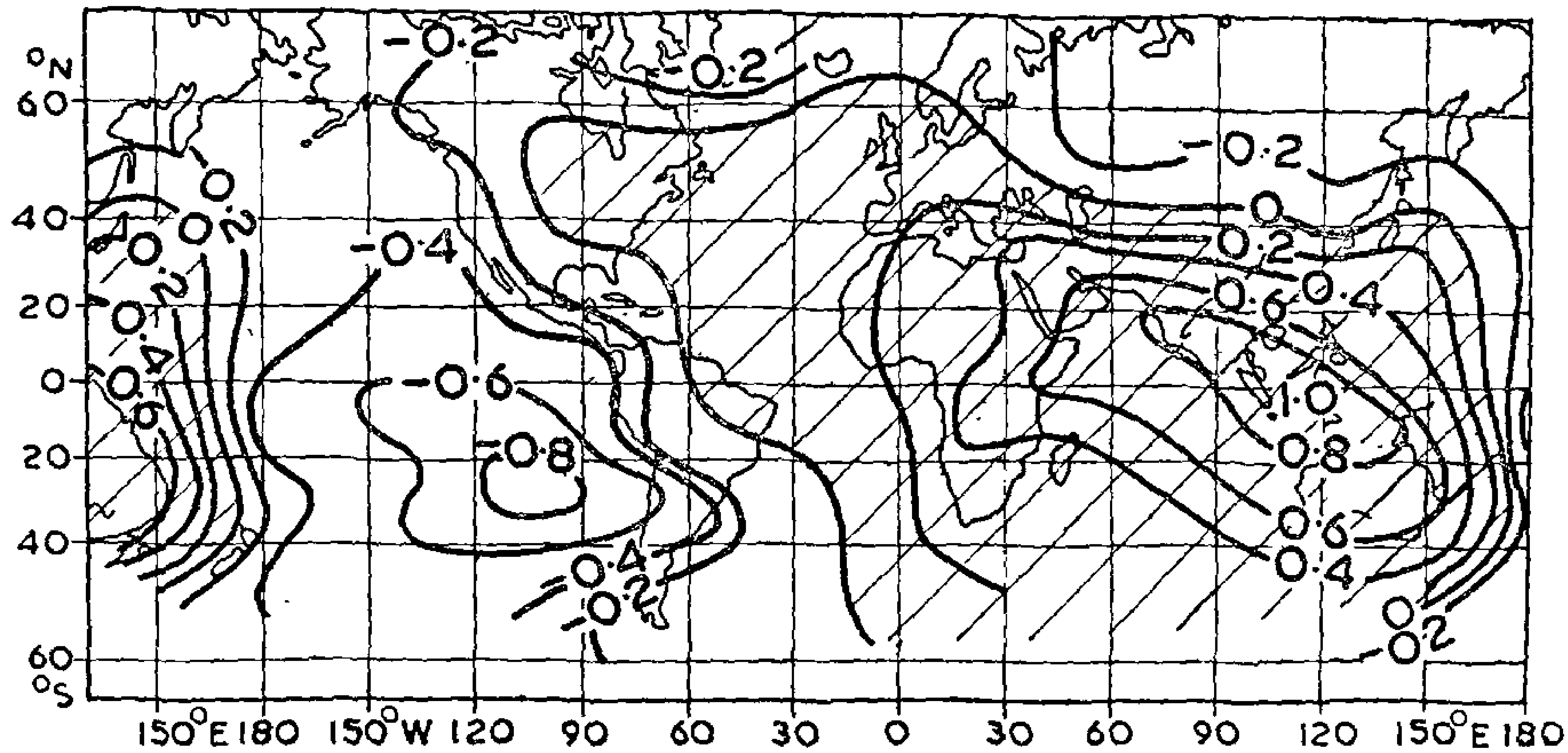

FIG. 4. The southern oscillation; figures represent correlation coefficients.

been achieved in forecasting storm surges with numerical models.

A storm surge represents a rapid rise in sea level as a consequence of water being driven towards the coast by the action of cyclonic winds. Most of the devastation due to coastal inundation is brought about by the storm surge.

Numerical models of the storm surge are based on the *shallow water equations*, which are integrated with respect to time. As input to these models we need to know

— the coastal geometry and the cyclone track.
— seabed bathymetry.
— cyclonic characteristics and wind speed.
— wind stress and seabed friction.

Unfortunately, none of these features is well documented, because realistic data are difficult to obtain. In particular, there are certain features of the winds round a cyclonic vortex of which our understanding is fragmentary. Contrary to general belief, cyclonic winds are not symmetric around the storm centre, nor do they follow any simple variation with radial distance from the centre of the cyclone. As the kinetic energy of the storm is finite, there is a central calm region known as the "eye" round the storm centre. Just beyond the eye, the fiercest winds are encountered. The difficulty in incorporating such features in a model is lack of data on the dimensions of the eye.

Similar difficulties are encountered when we try to estimate the retarding influence of seabed friction. For many years empirical drag coefficients have been used, but these are not satisfactory in very shallow waters. More recently, the dissipation of turbulent energy has been considered. This uses a similarity hypothesis for dissipation at the sea floor. At this stage, more research on these lines is needed to determine the effect of seabed friction on the surge.

Tropical cyclones belong to a genre of atmospheric vortices which occur on different scales of length and time. Thus, in addition to cyclones, we often encounter vortices on a smaller scale which are not so spectacular, but are equally intense. The "nor'westers" of eastern India, "Andhis" of North India and tornadoes are examples of meso-scale vortices. A feature which is common to such vortices is the dominance of the centrifugal force due to the rotation of the air. On many occasions this could be sufficient to make the pressure rise with height, instead of decreasing with height as may be expected from hydrostatic considerations.

THE UPPER ATMOSPHERE AND ATMOSPHERIC WAVES

Improvements in probing techniques have revealed many intreesting features in the upper reaches of the tropical atmosphere.

The central problem here is to ascertain what the coupling mechanism between the lower and the upper atmosphere (30–100 km) is. Observations suggest several types of oscillatory motion in the upper atmosphere. They are:

— a quasi-biennial oscillation.
— semi-annual oscillations.
— propagation of planetary waves, such as, Kelvin waves and mixed Rossby-gravity waves.

The quasi-biennial oscillation is a feature of the lower tropical stratosphere with an average period of about 26 months. It suggests an alternating sequence of easterly and westerly winds, with a maximum amplitude near the equator. Theoretical work, with the help of models, suggest that this oscillation is driven by waves which originate in the troposphere but propagate vertically. Examples of such waves are (i) Kelvin waves and (ii) mixed Rossby-gravity waves. Kelvin waves propagate eastward with a horizontal wavelength of 30,000 km. Their importance arises from the fact that they appear to be the only source for pumping eastward momentum into the stratosphere. On the other hand, the mixed Rossby-gravity waves have a shorter horizontal wavelength of 10,000 km, and they propagate westwards. They represent a source of westward momentum into the stratosphere. Much of the current theory behind the quasi-biennial oscillation is concerned with the interaction between the mean motion in the stratospheric regions, and the vertical propagation of Kelvin and mixed Rossby-gravity modes.

The mechanics of the semi-annual oscillation has not yet been satisfactorily explained. Theoretical work suggests that tidal motion in the stratosphere would not be sufficient to provide the necessary source of momentum for an oscillation of this nature. Current research tends to emphasize the role of Kelvin waves, but of shorter period, for the eastward phase of this oscillation.

What excites the Kelvin waves or the mixed Rossby-gravity waves in the troposphere? Both these wave types propagate energy and momentum into the equatorial stratosphere, but the precise mechanism by which these waves are generated is not understood. In this context, it is interesting to conjecture that the Indian summer monsoon might act as a source for such waves. Here is a region of the earth where heavy precipitation is released in a comparatively short period of about hundred days. It is not unreasonable to assume that the considerable amounts of latent heat that are released by this precipitation could induce oscillations in the stratosphere. Future research in this aspect could bring out interesting results.

ECOLOGICAL IMBALANCES

Much concern has been expressed in recent years over an increase in the carbon dioxide content of the atmosphere as a result of human activity. Carbon dioxide tends to act as a "greenhouse" for the atmosphere. It allows solar radiation to pass through but absorbs the long wave radiation emitted by the earth very strongly in a small band around 18 microns. The view has been expressed that this increase in carbon dioxide might result in a decrease in monsoon rainfall.

The welfare of plant and animal life depends on the way certain elements, such as, nitrogen, oxygen, carbon and sulphur are cycled through the soil, air and water. This includes all the carbon that is stored in the oceans, in the atmosphere and in the biomass (agricultural land and forests). Fossil fuels (coal, oil and gas) contain considerable amounts of carbon. It has been estimated that hundreds of gigatons of carbon dioxide are exchanged annually between the oceans and the atmosphere and between the biomass and the atmosphere. While estimates differ, recent figures suggest that nearly 5 gigatons of carbon dioxide are transferred annually to the atmosphere through burning fossil fuels.

Of the 5 gigatons of carbon released, nearly one-half remains in the atmosphere, while the other half is partitioned between the ocean and the biomass. The mechanism by which this partition takes place is not clearly understood.

Numerical models have been developed to assess the impact of an increase in atmospheric carbon dioxide. These experiments suggest that the carbon dioxide concentrations that might be reached around 2050 A.D. would increase the global average surface temperature by 1–3° C. The increase in temperature would be greater in the polar regions and the higher latitudes than in the tropics because of the higher reflectivity of ice.

It has been argued that the temperature difference between the poles and the equator is an important feature that helps to drive weather systems. A consequence of increasing this temperature contrast might drive the monsoonal winds further southwards, so that they do not reach India at all. While such conjectures need not be a cause for immediate alarm, they do suggest the need for further modelling experiments. Impact studies to determine the effect of increasing carbon dioxide in different latitudinal belts are clearly needed.

A wide variety of problems exist in our country where numerical experiments could yield useful results. We have referred to the "greenhouse" effect of carbon dioxide. There are similar problems concerned with the release of toxic gases from chimney stacks in highly industrial regions.

Many industrial regions release large quantities of sulphur dioxide, which is harmful not only for human beings but also for plants and vegetation. If we consider an elevated point source, such as a stack, which is pumping sulphur dioxide into the atmosphere, then it is possible to devise models that will tell us what should be the correct height of the stack to ensure that the gas (SO_2) is dispersed most rapidly. In Fig. 5 we reproduce the results obtained by a model designed by the Meteorological Department, to show the concentrations downwind from a stack releasing sulphur dioxide at the rate of 1 ton an hour. There are interesting possibilities of further experiments of this kind in our country, because if we are to minimise air pollution we must ensure that the harmful effects of toxic gases are reduced to the bare minimum by the suitable design of chimney stacks, and by considering the meteorology of the region.

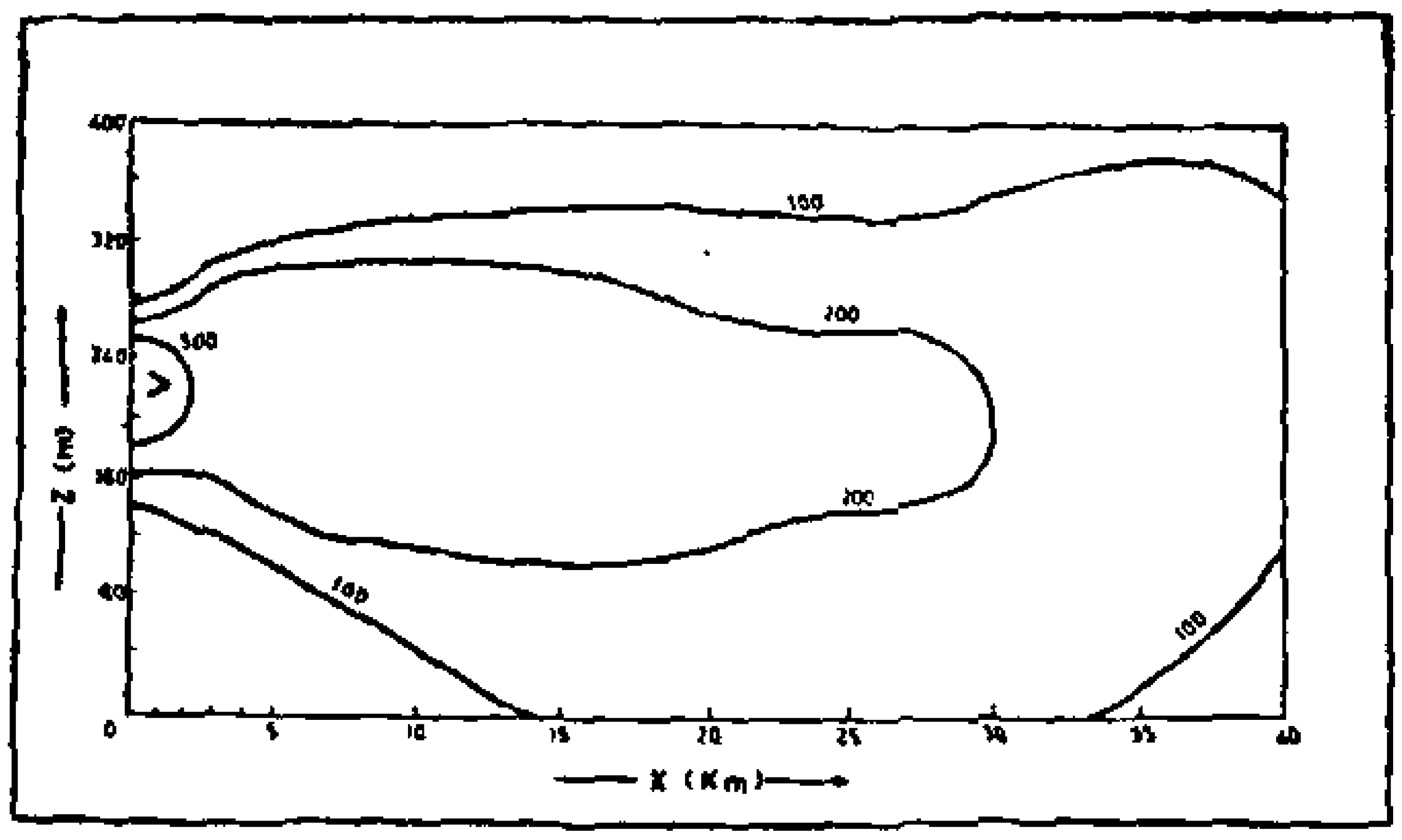

FIG. 5. Dispersal of toxic gases from a chimney stack. Figures represent concentrations in micrograms per cubic metre. Concentrations were obtained by a computer model. X represents distance downstream from point of emission and Z is the altitude above the surface.

CONCLUSIONS

The aim of this article was to attempt a review of current developments in Indian meteorology. Our objective was to identify a few areas, where the logical use of our atmospheric resources could help the economy of the country. Just as we regard the minerals, the forests and the rivers as our natural resources, it is but logical to regard the atmosphere also as a natural resource, because it provides the rainfall needed for our agriculture and indeed, for our sustenance. The complex nature of atmospheric motion need not be a cause for despair because, as we have seen in the last decade, better observations and monitoring facilities, coupled with the application of scientific reasoning, could well lead to a situation where we will be able to understand and anticipate the behaviour of the atmosphere.