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PART IV

COMPREHENSIVE ARTICLES ON SELECTED TOPICS

14: LONG RANGE WEATHER FORECASTING

BY

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FORECASTING MANUAL

Part IV - Comprehensive Articles on Selected Topics

14. LONG RANGE WEATHER FORECASTING

by

P. Jagannathan

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1. Introduction

1.1 The fundamental aim of meteorologists is to understand the atmospheric processes and then predict the future weather as much ahead as possible. Adaptation to the climatic environment, which means adjusting to the normal occurrences and withstanding the unfavourable extremes is an important feature which has helped survival of life. However, extreme climatic conditions are generally unfavourable, the worst consequences of which could be avoided or at least minimised if they could be predicted with adequate notice. Whether explicitly or not, a weather element is always built into all forward planning. In an age when we are concerned with large scale and long term plannings in several fields of human activity, e.g. agriculture, we are confronted with a series of questions relating to the future behaviour of the atmospheric environment, which amounts to a demand for climate forecasting.

1.2 Very useful information about seasonal changes can be provided from pure climatology; but a forecast worth the name should be something specific for the particular occasion. A long range forecast must be able to indicate how the weather over the extended period will differ from the climatic normal. As the climate of a region and season is a summary of all types of weather conditions which occur, long-range forecasts may have to attempt to describe the future weather in terms of the types of weather situations to be expected. The realization that the climate is not constant and invariant, makes the forecasting of future climate all the more important. Consistent with the several needs, the scope of long-range weather prediction has extended over a wide spectrum ranging from 5 days to periods of the length of months, seasons or more.

2. Basis of long-range forecasting

Long-range forecast of weather will have necessarily to depend upon the routine observations of the several phenomena, made over the entire globe. The number of atmospheric elements/parameters concerned is so enormous that to maintain an accurate record of their locations, their physical state and their changes is practically impossible. In comparison with the requirements for maintaining records of these elements, the observational network is very inadequate and over large areas of the globe it is totally absent. However, the institution of the World Weather Watch, with the satellite observations of clouds and radiation and several other techniques has improved the observational network. But even if the entire atmosphere is continuously surveyed by a much closer network of observatories, it would still be difficult to get a complete picture of what is happening at a moment. Sufficient understanding of the physics of the atmosphere is necessary before we can use the available data for making efficient long-range forecasts. In spite of these limitations, surprisingly enough, long-range forecast of weather enjoys considerable success and this is fortunately due to the fact that the atmospheric behaviour is fairly systematic. Firstly, the systems that produce most of the weather over the world, the cyclones and the anti-cyclones of the weather map are so large that a fine **mesh** of observations is not essential to detect them; a network of stations 300 km apart is quite adequate in most areas. Secondly, the formation, growth, movement and dissipation of these systems depend upon phenomena of a still larger scale, viz. the planetary waves found in the upper air currents between 700 mb and 100 mb levels. Another fortunate circumstance is that in many respects, the behaviour of the cyclones, anticyclones and planetary waves have common features in successive periods of time. Thus the meteorological time series are serially correlated and consequently the correlations between the average variations from the normal for a week or a month or a season are much larger than would be expected if the daily weather were randomly distributed.

3. Physical causes of climatic fluctuations

3.1 The observed statistical behaviour of the atmosphere suggests that there are forces external] to the atmosphere, which cause repetition of similar weather developments. Of these external forces may be mentioned, the complex geographical influences produced by mountains and the ocean-land contours, which are highly important in producing certain recurrent wind and weather patterns, the net result of which are noticeable in climatological statistics over a fairly long series of years. Besides, the individual years are markedly different from one another. As such, other external influences besides geographical must operate. Franz Baur of Germany and H.C. Willet of America have pursued the idea that variations in solar activity are the primary external] stimuli. Namias et al believe that thermal character of the earth's surface comprising of the continents and oceans, provide the principal means for quasi-periodically restoring certain wind and weather patterns. These surface variations result from abnormality effected by the prece-ding and contemporary atmospheric behaviour.

3.2 As long as our present knowledge as to how these external influences, terrestrial and/or extra-terrestrial, physically interact with the atmosphere is not adequate to formulate the cause-effect relationship for application in long-range forecasting, there is need for concerted study with large volume of observations.

4. Methods of long-range forecasting

Statistical and synoptic methods together with qualitative reasoning form ~~xxxx~~ the basis of most long-range forecast methods practised. In these methods, it is assumed that the influence of the external factors is implicit in the meteorological time series. The statistical methods incorporate the coherence and persistence factors as well as other sequential properties which describe some of the interactions between remote locations on the earth. Attempts at long-range forecasting so far made, can be broadly divided into four categories, (i) periodicity approach, (ii) correlation approach, (iii) extended synoptic approach and (iv) the dynamical approach.

4.1 Periodicity approach

4.1.1 The study of periodic variations in weather has attracted many meteorologists. Much of the work done in long-range forecasting of weather by climatic cycles is based on the expected influences of the major planets. It is generally agreed that solar energy in the form of heat is the predominant factor in climate although the mechanism by which the solar energy is transmitted to earth and transformed into heat is still controversial. Considerable work has been done in many countries to discover relationships between the measure of solar constant, sunspot numbers, number of faculae and other solar characteristics on the one hand and the climatic features on the other. Tippenhover of Haiti believed in the 35 year cycle, which is the period that each of the most influential planets, Jupiter, Earth, Venus and Mercury take to attain the same heliocentric longitude. He used in addition sunspot cycle, lunar cycle and earth's magnetism in his forecasts. Janvrin Browne of Washington made use of the same planetary considerations besides a wide range of special data of physical geography and meteorology and issued forecasts for each geographical area of North American Continent. Inigo Jones of Crohamhurst Long-Range Weather Forecast Trust used an elaborate system of periodicity, which had spectacular accuracy on odd occasions. However, an extensive examination by Loewe failed to reveal any consistent merit in these forecasts.

4.1.2 Practically the periods relating to all planets, their multiples and sub-multiples have been exhausted in their application to seasonal forecasting. Failures were attributed to conflicting influences and the lack of sufficiently accurate records of weather. However, it should be mentioned that many periodic phenomena which were discovered were later found to be less pronounced. The sunspot cycle is another familiar period. It is well known that the upper atmosphere including the ionosphere is much more disturbed in periods of high solar activity than in years of quiet sun. However, the significance of weather changes near the surface is not yet well established. Recently some relationship between rainfall and phase of the moon is coming to light. But none of them is so thoroughly investigated as to be handed over to the weather forecaster.

4.2 Correlation approach

Statistical relations expressing the relationships between past and present weather on the one hand and the future weather in the same or other regions of the globe on the other, have been in use in various parts of the world particularly where large scale processes dominate the weather over wide areas. The correlation approach for seasonal forecasting was first introduced during the first decade of this century by Sir Gilbert Walker, who was Meteorological Reporter to the Government of India during 1904-1924. He applied it for forecasting monsoon rainfall in India. He also established forecasting formulae for the summer monsoon rains of Australia and winter temperature in Southwest Canada. Later attempts at seasonal forecasting by the correlation methods were made by Quayle, Treloar, Rimmer and Hossack in Australia. Treloar and Grant observed that there was a general decline in the multiple CCs when earlier relations were tested on the basis of all the available additional data. This drop in formerly high correlations may be mainly due to the fact that the CCs as selected had in general large sampling bias. Jagannathan (1960) made a critical review of seasonal forecasting in India and came to the same conclusions and further observed that factors beyond the second in importance rarely made further significant contributions to the forecast, largely due to the fact that the meteorological variables are highly correlated. Even though these results make one rather sceptical about the correlation approach for providing a basis for long-range forecasting of weather, the search for correlations among the meteorological elements in different parts of the world is very valuable in as much as it can improve the understanding of the functioning of the atmosphere.

4.3 Extended Synoptic approach

4.3.1 Franz Baur of Germany used 'broad weather situations' represented by a classification of surface mean pressure maps and developed a comprehensive system of extended forecast for 5 to 10 days. This selection of situations naturally reduced the amount of data to such an extent that accurate multiple regression computations had to be replaced by qualitative appraisal of contingency tables. However, the use of homogeneous samples must be regarded as a great advance over the regression procedure. The technique adopted is a grafting of an extension of the synoptic practice for the first five days on to the forecast derived from a combination of other methods in the second half of each 10-day period.

4.3.2 Namias and his co-workers at the Extended Forecast Section of the U.S. Weather Bureau made a distinction between weak and strong circulations and the associated long wave patterns in the upper air. The strength of the circulation was measured initially by surface and later by 700 mb indices. The indices were calculated as the average pressure gradient computed for various latitude belts over large ranges of longitude. Primary predictions are usually made from pressure patterns for a subsequent period of 5 or 30 days

and this output is transformed into probabilistic temperature and precipitation patterns which are usually expressed in terms of departures from normal climatological expectancy. The basic working hypothesis which facilitates long wave ideas to be applied to forecasting is that the waves are more slowly variable and that their immediate behaviour is a little more amenable to forecasting. However, inferences can be made with fair degree of accuracy about speed and wave length of waves that already exist but nothing definite can be said about the time and place of formation of new waves or about intensification and dissipation of pre-existing ones.

4.3.3 When we come to the time scale of a season, some degree of order obtains in the evolution. Prediction of the average characteristics of the forthcoming season is done by a combination of synoptic, statistical and physical procedures. This method, according to Namias (1964), is partially objective ($\approx 60\%$); the other 40% consists of experience in practical long range forecasting and thus involves imagination and ability to draw reasonable inferences from suggestive objective indications.

4.3.4 In U.K., various methods are used for 30 day forecast. Many are still exploratory but the analogue concept appears to be the most useful. In this method a search is made in all the previous years (about 80 years) to find analogous situations. Occasions when weather conditions of the immediate past, mainly of the corresponding month for the same time of the year, most nearly resemble the current conditions, are chosen and their evolution on those occasions examined. The basic assumption is that similar situations are likely to develop in similar manner and so provide a valid basis for prediction.

4.3.5 Multanovsky and his associates initiated in the early thirties studies to aid in forecasting for periods of a week to a season in advance. The Russian approach is based on dynamic climatology, natural periods and natural regions and the genesis, development, migration and decay of high pressure cells. On the basis of the analysis of the general circulation characteristics of the atmosphere and the heat exchanges between the continents and the oceans, techniques for determining the spatial boundaries of the natural systems, synoptic areas and the time limit of the natural synoptic periods are determined.

4.4 Dynamical approach

4.4.1 In this method, beginning with the observed state of the atmosphere at a given time, the future state is predicted on the basis of a set of thermodynamical and hydrodynamical differential equations involving the first law of thermodynamics and Newton's second law of motion. Owing to the complexity of these differential equations, exact analytical solutions are not possible and even approximate solutions by numerical methods require the use of high speed large memory electronic computers. Studies on long-range forecasting using the dynamical approach were initiated in Russia in the early forties (Blinova, 1943). Further developments were made by Blinova, Dobryshman and others during the subsequent decade. In 1952, the Central Institute of Forecasting began making 40-70 days forecasts of anomalies of average monthly temperature for the Eurasian continent, by using simple dynamical methods. By 1961 monthly forecasts of certain weather elements were compiled systematically for the northern hemisphere. As considerable simplifications have to be introduced for facility of handling, the reliability of such forecasts was not superior to the qualitative synoptic forecasts. However, more comprehensive equations have now been developed which take into account heat flux and other phenomena as well as certain elements of the interaction between the atmosphere and the underlying surface. From Blinova's (1966) paper at the Colorado Symposium on Long-range Forecasting, it appears that in Russia extended and long-range forecasting by hydrodynamical methods taking into account weather and climate forming factors has been brought to the operational stage by the use of large memory, high speed electronic computers.

4.4.2 In U.S., numerical experiments with dynamical general circulation models have their origin in Phillips' (1956) work. The problems on long period time integration are being tackled intensively by Smagorinsky, Adem, Mintz and others.

5. Long Range Forecasting in India

India being mainly an agricultural country, the character of the monsoon is of prime importance for its economy. After the serious countrywide drought and famine in 1877, the Government of India's anxiety for the earliest possible information about the progress of the monsoon grew, as recommended in one of the Famine Commission's Report as early as 1880, which reads as follows :

"As at present, no power exists of foreseeing the atmospheric changes effective in producing the rainfall or determining beforehand its probable amount in any season, such as would admit of timely precautions being taken against impending drought, the necessity becomes the greater for watching with close attention, the daily progress of each season as it passes;... So far as it may become possible, with the advance of knowledge, to form a forecast of the future, such aids should be made use of, though with due caution".

5.1 Long-range forecasts of rains

Blanford, the then Meteorological Reporter, was called upon to make attempts for estimating the prospective rains. He issued tentative forecasts from 1882 till 1885 utilising the indications provided by the snowfall in the Himalayas. The success achieved infused greater confidence and in 1885 it was decided that a monsoon forecast should be issued annually as a matter of routine and the first of the regular series of forecasts was given on 4th June 1886. The issue of regular series of seasonal forecasts is being continued till date. The first forecast was mainly based on the general weather conditions over India and on the considerations that heavy snowfall in the Himalayas and Sulaiman Range during the preceding January to May caused abnormal pressure conditions and was unfavourable for the advance of the monsoon over the whole of India and Burma. Sir John Eliot, Blanford's successor, utilised conditions over the whole of India as well as the adjoining seas. From 1892, forecasts for the latter part of the monsoon season viz. rainfall of the August-September and in December 1893, forecasts for the winter precipitation over the Northern and Central India were commenced.

5.2 Objective techniques

5.2.1 Walker realised the complexity of the problem and switched on to objective methods for getting quantitative and analytical relationships. In his early work, Walker noticed, that data for large areas tended to behave uniformly both within the area and in relation to the surrounding areas which pointed to the need for studying the global patterns even for forecasting local conditions. His studies confirmed that variations in the monsoon rainfall were connected with widespread and long-lasting changes in the pressure distribution over large portions of the earth's surface. He soon found that periodicities did not pay and supplemented the previous methods by working out correlation coefficients as objective measures of dependence. This new approach not only eliminated to a very large extent, personal bias inherent in the previous methods but also simplified the selection of factors considerably. His extensive work in this connection may be divided broadly into two categories :

- (i) Studies in relation to world weather, and
- (ii) Those connected with forecasting of monsoon rainfall in India.

These form the most important contributions from India to the subject of seasonal weather forecasting based on the correlation method that has so far been done.

5.2.2 The main objective criterion used by Walker was the correlation coefficient between the forecasted element and the various factors. Factors found significant are taken up for further analysis. Finally only those factors, which have the least "intercorrelation coefficients" between themselves are included so that the multiple correlation coefficient is maximal with the minimum number of independent factors.

The forecast formula is set in the form

$$R = C_1F_1 + C_2F_2 + \dots + C_0$$

where R is the anticipated departure from normal of seasonal rainfall and F_1, F_2, \dots are the departures of the different factors utilised, C_1, C_2, \dots are the regression coefficients and C_0 is a constant. He introduced many statistical refinements and separated out the forecast areas into more homogeneous zones. Further refinements were later introduced by Normand, Savur and others.

5.2.3 Every year, five seasonal forecasts are issued. The date of issue of these forecasts and other details connected with them are given by Raghavendra and Roberts (1973).

5.3 Statistical routine

5.3.1 The first statistical procedure before the year's forecasts is prepared, is to test the performance of the individual factors as also the forecast formula. This test which was introduced by Normand (1932) is made on the basis of correlation coefficients between the several pairs derived with data of recent past and not included in the evolution of the forecast formula. The test CCs are compared with the previous CCs (i) for determining the significance of the individual factors and (ii) for specifying the order of reliability of the factors. If the test CCs are significant and their signs are same as those of the CCs used in the evolution of the regression formula, the relationships are regarded as real. The occasion is also utilized for selection of fresh factors for replacing insignificant factors.

5.3.2 As soon as the data for the forecast become available, the individual contributions of factors to the calculated forecast departure are worked out and the factors classified according to their contribution. These are published in the forecast memorandum to indicate to the reader, the intensity and reliability of the influences.

* However, it should be mentioned that the method adopted suffers from two defects in that (i) it assumes that the standard deviations are additive and (ii) that all the factors contribute equally to the variation.

5.3.3 The calculated value of the departure is utilised for setting up confidence limits for anticipated value of the element (rainfall or precipitation*) for the specified "chance of success". Usually a four-to-one chance of success is aimed at so that the forecasts in the long run may be correct on 80% of the occasions.

5.3.4 In the particular year, if the calculated value of the departure is ' σ ' assuming that the deviation of the actual departure (which will be known only after the event) from this value will be distributed according to the normal law of error with zero mean and variance $\sigma^2 = \sigma_y^2 (1 - R^2)$ forecasts for a P% chance of success are prepared in each of the following three forms :

- (i) The actual departure A will lie between $C - \epsilon_1$ and $C + \epsilon_1$
- (ii) The actual departure A will be less than $C + \epsilon_2$
- (iii) The actual departure A will be more than $C - \epsilon_2$

where ϵ_1 and ϵ_2 are obtained from the probability integral

$$P = (2\pi)^{-\frac{1}{2}} \sigma^{-1} \int_{-\epsilon_1}^{+\epsilon_1} e^{-x^2/2\sigma^2} dx = (2\pi)^{-\frac{1}{2}} \sigma^{-1} \int_{-\epsilon_2}^{+\epsilon_2} e^{-x^2/2\sigma^2} dx = (2\pi)^{-\frac{1}{2}} \sigma^{-1} \int_{-\infty}^{+\infty} e^{-x^2/2\sigma^2} dx$$

σ_y is the variance of the forecasted element; R is the multiple correlation coefficient; P is the chance of success aimed at, usually 80%.

* Winter precipitation 'p' over northwest India is defined as $p = \gamma + 0.4S$ where γ is the departure of rain in NW India obtained as the mean of the monthly departures weighted according to the area and S the winter snow of western Himalayas in coded scale. Information of snowfall consists of reports from high stations as to the quality and quantity of snow that has fallen on certain days, or the thickness of snow in certain high passes or the lowest altitude to which snowfall has reached. These are inevitably inaccurate and incomplete. This fragmentary information is pieced together by adopting a system of coding.

- + 3 - Large excess
- 3 - Phenomenally little snow
- + 2 - Much above/below normal
- + 1 - Above/below normal

The divisional mean snowfall for each month is worked as the average of the coded snowfall. The snowfall for western Himalayas in each of the three months January to March is worked out as the average for the three divisions Kashmir, Himachal Pradesh and Uttar Pradesh and the monthly figures are added. This figure is multiplied by 0.4 to get the rain equivalent.

The monthly departures from normal of rainfall of state rain gauge stations are averaged for finding out the divisional or sub-divisional means. The divisional or sub-divisional mean departures are weighted in proportion to their respective areas and the rainfall series worked out.

5.3.5 The criterion adopted for choosing the type of forecast to be issued in the particular year is that the forecaster's "chance of success" is appreciably greater than the "climatological probability" which is termed the "Intelligent Layman's chance of success". Obviously, forecast

Form (i) will be preferred if C is very small,

Form (ii) if $C + \epsilon_2$ is negative, and

Form (iii) if $C - \epsilon_2$ is positive.

5.3.6 An example of the forecast is given below :

Summary of forecast

August - September rainfall for the year 1936

" The monsoon rainfall of August and September will not be less than 94% of the average in the Peninsula nor less than 83% of the average in Northwest India."

5.3.7 From the monsoon forecast of 1949, the forecasts are being expressed in 'popular language' using such terms as "normal", "slightly above normal" etc. to make the forecasts more intelligible to the public. An example is given below :

Summary of forecast

Monsoon rainfall for the year 1950

" The monsoon rainfall during June to September 1950 is likely to be normal or slightly below normal in the Peninsula and not far from normal in the Northwest India."

5.4 Verification of Forecasts

5.4.1 The validity of the forecasting technique lies in the success of the forecasts based on the technique. Thus to justify the technique and to determine the economic value and usefulness of the forecasts, an adequate verification with the actual realised event should have to be carried out. The requisite for a proper verification is objectivity which ensures that no element of judgement is brought into the comparison of the forecast with the subsequent observation. Another important objective of verification is the analysis of forecast failures with a view to determine their nature and to find possible causes for such failures. Further it facilitates a search for indications of forecasting difficulty which can help locate the synoptic situations under which forecasts are most likely to go wrong.

5.4.2 At the end of each of the months to which the forecast relates, a chart showing the rainfall of the month in the various sub-divisions is prepared. Due to the fact that the data from the several State raingauge stations will not be available, these are based on the data of the observatory stations alone and serve to watch the progress of the rainfall during the season. After the season, as soon as the data of all the State raingauge stations are available, the departures are calculated for each sub-division and for the area as a whole, weighted in proportion to the areas of the sub-divisions. A comparison of the forecast with a statement of the actual rainfall of the season in question is issued. Walker (1922) published a verification of his forecasts based on a few of his formulae.

Montgomery (1940) verified Walker's formulae with data upto 1936 and concluded that inspite of its early very encouraging performance, the formulae had broken down completely in the 15 years (1921-36). Out of the 8 different factors involved in these formulae, the relationships with four were negligible for recent years, one had reversed its sign, and the other three had stood the test of time.

5.4.3 Jagannathan (1960) while reviewing the system of forecasting techniques in India introduced a skill score 'S'.

$$S = \left[1 - \frac{\sum_{i=1}^N (E_i - P_i)^2}{\sum_{i=1}^N (E_i - p_i)^2} \right] \times 100$$

Where N is the total number of forecasts prepared.

E_i = 1 or 0 according as the forecast is successful or not,

P_i = is the probability expected on the basis of the forecast formulae, and

p_i = is the corresponding climatological probability.

If S is positive, the forecasting technique can be considered to have given more information than the climatological knowledge, while if it is a negative the reverse is the case. The skill scores calculated* for the 5 series extending from 1932 to 1958 are :

(i)	Monsoon rainfall - Peninsula	4.5
(ii)	Monsoon rainfall - Northwest India	-23.0
(iii)	August-September rainfall - Peninsula	- 0.1
(iv)	August-September rainfall - Northwest India	-4.9
(v)	Winter precipitation - Northwest India	-35.3

He concluded that the forecasting factors used for monsoon (June - September) rainfall over Peninsula alone could be said to have justified their use; the other forecasts, in particular those for monsoon rainfall over Northwest India and winter precipitation over Northwest India have not conveyed as much information as available from the climatological knowledge.

5.5 Nature of subsequent work

5.5.1 Search for new factors has been continued. However, as long as the physical processes involved in the relationships are not adequately understood, a blind search for fresh correlations cannot be rewarding. In fact, many of the failures of the forecasts, could be attributed to the changes in the character of the influence exerted by the factors utilised.

* In this analysis it should be mentioned that the forecasts issued during the different years even though they were not based on the same forecast formulae have been pooled together. As such the results brought out relate to the system of forecasting technique and not to the individual formula.

5.5.2 It is well known that the rainfall is very variable both in space and time. The year to year variation in the total amount and the pattern of distribution over the different periods of the season are larger in most parts than the total rainfall of the season over the whole area. In view of the potential value of the forecasts of the character of the rain in the different parts of the country, Indian Meteorologists have been engaged in studies in this direction.

5.5.3 Iyer and Satakopan (1942) prepared regression formula for forecasting monsoon rainfall in different sub-divisions of the Peninsular India. Ramdas et al (1954) evolved techniques for predicting the date of establishment of the monsoon on the west coast of India.* The forecasts prepared on this basis were being issued to the forecasting offices to serve as guide. Jagannathan and Khandekar (1962) utilizing upper air data collected over India, evolved regression equations for predicting monsoon rainfall over the Peninsula. The thermal state of upper atmosphere over North India in March seems to be a good predictor for subsequent south-west monsoon rain over the Peninsula. The higher the mean temperature of the air column above 1.5 km in March over North India, the greater the subsequent monsoon rainfall in the Peninsula. The values for April and May do not show similar features. However, the conditions in May over the Peninsula show inverse relationship with monsoon rainfall. With a view to ultimately evolve appropriate forecasting techniques, several attempts are being made to find the physical causes for the distinguishing patterns of rainfall distribution in the different parts of the country.

5.5.4 Further, numerical studies on general circulation with particular reference to monsoon and the ancillary studies of integration over long time periods by the use of large memory high speed electronic computers are being actively pursued. It is hoped that these will be helpful in the evolution of useful techniques in long-range forecasting.

6. Conclusion

6.1 The importance of long-range prediction has gained new significance in view of the need for scientific planning in several fields of human activity. There are indications that the need for long-range forecasting will increase in the years to come. Long range forecasting which was largely practised as a subjective quantitative procedure has changed during the past few decades into an exact physico-mathematical science.

6.2 In the correlation approach, many relationships, all of them rather weak, are combined to provide a prediction. It is now recognized that search for correlations, without good physical reasoning to guide is too hazardous, as most often they turn out to be accidental coincidences of no prediction value. There are other limitations to the correlation approach. When an analysis is made with a sample of data, the results of the analysis and the conclusions relate only to the sample of data considered; inferences and extrapolations to anticipate the future behaviour will naturally depend largely upon the persistence of the formal relationships postulated on the basis of the limited data. The statistical behaviour of large scale weather patterns has not been consistent over long periods of time due to climatic fluctuations. How well we can incorporate all the long period fluctuations in the statistical model will determine the degree of success of the forecasts.

6.3 As purely internal factors controlling the evolution of weather patterns should not lead to statistical inconsistencies, the changes are probably due to variable action of external physical controls. The emphasis is now shifting towards a better understanding of the physical controls of general circulation and its fluctuations.

* Discontinued since 1971.

6.4 The work done so far has highlighted the need for concerted research for enhanced knowledge in the field of general circulation on the one hand and climatic fluctuations on the other, and these are fundamental for the establishment of a valid theory of climate. As a preliminary to long-range forecasting, the global aspects of the general circulation, in particular the tropical and sub-tropical circulations have to be adequately understood. As the evolution even of the extra-tropical atmosphere, beyond a few days depends on the evolution of the tropical atmosphere, long-range forecasting in its theoretical and practical development, demands developments in tropical meteorology.

6.5 The dynamical approach to long-range forecasting appears to be most promising. While the inertial properties of the dynamical equations are most relevant in weather developments over one or two days, the influence of the dynamical properties wanes as the scale of time increases to a month or a season, when the thermodynamical influences associated with the energy sources and sinks are the most relevant. It is known that significant ocean temperature anomalies persisting for decades or longer introduce anomalous atmospheric circulations. Thus in long-range forecasting, the other boundary conditions will have to be taken into account and the atmosphere-ocean-continent complex will have to be treated as a whole.

6.6 At present, highly simplified models are constructed and numerically solved in order to determine the primary mechanisms in the atmosphere, which give its characteristic time and space scales and the limits of variability of these scales. An understanding of this is vital as it helps to account for the way in which the solar energy is ultimately used by the atmosphere and for indicating the methods the atmosphere finds most efficient for heat transfer. Once, one can account for the gross characteristics of the general circulation, then it is reasonable to ask more specific questions regarding the details of the evolution such as are required for long-range forecasting. Before this can be done, considerable progress will have to be made in understanding the mechanism of the contributory physical processes such as the release of latent heat, exchange of momentum, heat and water vapour between the atmosphere, continent and oceans, internal sensible heat exchanges, including convective transfer, the heat transport within the oceans and radiative transfer. It is not yet known, how well we have to understand these processes in order to adequately take them into account in general circulation and long-range forecasting models.

6.7 Concerted efforts are being made in the fields of dynamical and physical meteorology, theory of general circulation and computation technology, in which significant progress and advancement has taken place in recent years. The numerical simulation of the general circulation by Smagorinsky, Mintz and others has opened up new dimensions in forecasting. The synthetic atmospheres have revealed features like jet streams, fronts, tropopause, cyclones etc. Studies on the energy exchange over the northern hemisphere, by Wien Nielsson, Murakami and others, confirm several important deductions from the numerical models. Apparently a good understanding of the physical processes leading to the existence of such phenomena is near at hand. Thus numerical modelling appears to be a powerful medium of diagnosis where controlled experiments could be performed. This shows great promise of success which is bound to have a profound impact on the dynamical approach to long range forecasting.

6.8 From the rate at which the energy of the general circulation is generated and dissipated it is apparent that the root cause for the long term weather anomalies should be sought from outside the atmosphere itself, for example the variations in the ocean and land surface, and the variations in the solar radiations.

6.9 Significant meso-scale differences may occur in certain localities, which cannot be involved in the large-scale dynamics and the statistical studies of local and distant interrelationships with and without time-lag will still be very

useful. Statistical studies are needed for determining interactions between ocean and atmosphere or between troposphere and stratosphere.

6.10 Long-range weather forecasting is acceptedly the most difficult problem according to Von Neumann (1960). The absence of a single satisfactory approach to the problem suggests the combination of statistical, synoptic and dynamic methods as the only practical solution for quite some time.

6.11 The daily forecasts aim at considerable precision and detail, while in long-range forecasts, attempts are made to indicate only the general character of weather over the period. In assessing the reliability and utility of these long-range forecasts, it is important to realise that they differ markedly in both character and technique from the short-range forecasts.

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Note : The author has given a "Bibliography of papers which have a bearing on Long-range forecasting in India" as an appendix to the publication "Seasonal Forecasting in India - A review" (1960) - IMD Special Publication. The reader interested may refer to that publication.

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