LONG RANGE FORECASTING OF SUMMER MONSOON RAINFALL OVER INDIA

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1. INTRODUCTION

The monsoon rains are perhaps the most important natural phenomena that sustain the large agrarian populations of Asia. On an annual time scale, there is a remarkable degree of regularity in the occurrence of the rainy season; however, there are large interannual variations in the amount of seasonal rain, its space-time variability and the timings of the onset and withdrawal of the rains. The agricultural production, the availability of drinking water and the generation of hydro-electric power critically depend upon these fluctuations. Because of the unique geographical location of India, the atmospheric circulation displays a spectacular annual cycle of rainfall in which more than 80% of the annual rain falls during the summer monsoon season comprised of the months June through September. Attempts to predict seasonal rainfall over India started more than 100 years ago. (The present paper is an outgrowth of a lecture given by one of the authors [J.S.] at an international conference held at New Delhi during April, 1986, to celebrate 100 years of long-range forecasting of monsoon rainfall over India). It is natural that considerable efforts have been made towards diagnosing the interannual variability and predicting the onset, withdrawal and total amount of monsoon rains. In this paper we shall confine our discussion mainly to the long-range forecasting of summer monsoon rainfall over India. However, in order to provide a suitable context to the prediction problem, we give below a summary of main conclusions drawn from various diagnostic studies on interannual variability of monsoon rainfall (Shukla, 1986; Mooley and Shukla, 1987).

a. Long term seasonal mean (June, July, August, September) rainfall over India is about 850 mm, its standard deviation is about 84 mm and the coefficient of variability is about 10%. The standard deviation of the percentage departure from normal rainfall for seasonal and monthly averages is about 13% and 25% respectively, and it reduces only to 21% if the seasonal mean is removed before calculating the standard deviation of the monthly percentage departure.

b. During the past century monsoon rainfall over India was more than one standard deviation above normal about 15% of the time and more than one standard deviation below normal about 18% of the time. For convenience we will refer to these years as excess rainfall years and deficient rainfall years, respectively. All the remaining years with the absolute value of the rainfall anomaly being less than one standard deviation would be referred to as the normal rainfall years.

c. During the excess rainfall years and the deficient rainfall years, the rainfall anomaly over most of India is of the same sign with the exception of northeast India where it is of the opposite sign and of small magnitude. This suggests that the spatial scales of the seasonal mean anomalies are quite large.

d. During the excess rainfall years and the deficient rainfall years, the monthly mean rainfall anomaly for each of the four individual months is generally similar to the seasonal mean rainfall anomaly. This is particularly true for the drought years. This suggests that the major anomalies of monsoon rainfall are not only of large scale but also persist for the entire season. However, for a large number of normal rainfall years there is a large month to month rainfall variability.

e. It is only during the excess and deficient rainfall years that significant anomalies of the global circulation are also observed.

f. It is reasonable to conjecture that intraseasonal fluctuations of monsoon rainfall are related to differences in the characteristics of the synoptic scale disturbances, quasi-periodic oscillations and interactions with circulation in the midlatitudes.

g. There appears to be a good potential for predictability of the large space-time average circulation and rainfall because they are related to the slowly varying global boundary conditions, and low-frequency planetary scale fluctuations. The degree to which the regional intraseasonal fluctuations can be predicted is uncertain because they appear to be caused by internal dynamical processes.

In the next section we present a historical review of the early efforts of Walker and his predecessors to predict monsoon rainfall. In section 3, we summarize the current efforts to search for possible relationships between monsoon rainfall and a variety of atmospheric circulation parameters. In section 4, we present an empirical method for predicting monsoon rainfall over India, and in section 5, we present concluding remarks and our opinions on the prospects for the future.

2. Historical Review

A large number of monsoon failures over India during the nineteenth century and the adverse impact of these failures on the economy ultimately led to the establishment of the India Meteorological Department in September 1875 for the improvement of meteorological observations in India and for study of weather and climate of India. Shortly thereafter, the country was struck in 1877 with severe drought over most parts of the country, resulting in intense suffering by the people. The government of India constituted the First Famine Commission to look into the Indian famines and suggest remedial measures. The Famine Commission collected valuable data for all past famines from 1770 and submitted a report to the government in 1880. After considering the report, the government took action on the recommendations of the commission. H. F. Blanford, the Meteorological Reporter was called upon by the government of India to take action for preparation of monsoon forecasts. Blanford (1884), who studied meteorological conditions in relation to the monsoon rainfall of India, concluded that Himalayan snow cover could influence climate and weather of the plains of India. He postulated that excessive winter and spring snowfall in the Himalayas and Hindukush delays the advance of summer monsoon and results in less rainfall during monsoon season. He also observed that droughts may be associated with high pressure in Mauritius, Australia and over a great part of Asia. He issued tentative forecasts of monsoon rainfall for the years 1883-85 on the basis of snowfall in the Himalayas. The success achieved by these tentative forecasts created a climate of confidence, and it was decided in 1885 that a monsoon forecast be issued routinely every year. The first regular forecast for India and Burma was prepared on

June 4, 1886, on the basis of general weather conditions over India and on snowfall in the Himalayas and Sulaiman range during January-May preceding the monsoon.

Sir John Eliot, who succeeded Blanford in 1887, included conditions over the whole of India as a predictor parameter, and in the next year he also included the conditions over the Bay of Bengal and the Arabian Sea. In 1888 and 1889, the forecast consisted of two parts — the preliminary memorandum issued in the third week of May and the final memorandum issued about the 9th of June. From 1890, the preliminary memorandum was dropped. The forecasts became more and more ambitious and the size of the forecast grew from 3 pages in 1886 to 22 pages in 1892. India experienced another great famine in 1899 which was not predicted and the newspapers made scathing comments on the forecasts. In 1902, the Government decided that forecasts should be issued only to the Provincial Governments as confidential documents. However, in 1906, the Government decided that forecasts of (i) monsoon rainfall, (ii) August-September rainfall and (iii) winter (December-February) rainfall be prepared regularly and after approval by the Government be published in the Gazette of India supplement.

Sir Gilbert T. Walker, a Senior Wrangler at Cambridge, succeeded Eliot in 1904. Walker knew that an accepted theory of general circulation was necessary for putting seasonal prediction on a scientific basis. He argued that in the absence of such a theory statistical studies can be pursued since the results of such studies are likely to give clues to a possible physical basis. He commenced studies of statistical relationships, both concurrent and antecedent, between Indian weather and world weather. His studies on world weather confirmed two pressure oscillations — North Atlantic (between the Azores high and Icelandic low) and North Pacific (between the North Pacific high and the Aleutian low). His search for global predictors for forecasting Indian monsoon rainfall brought out the important result that the oscillation suggested by Hildebrandson (1897) and confirmed by Lockyer and Lockyer (1904) as a pressure see-saw between the Indian Ocean and Argentina is a very large-scale phenomenon. For the first time Walker called this phenomenon the Southern Oscillation. He described this oscillation as a tendency for air to be removed from the Pacific areas for accumulation in and around the Indian Ocean and vice versa. As mentioned by Normand (1953), the most remarkable of Walker's results was the discovery that the June-August Southern Oscillation Index had a correlation coefficient of 0.8 with the same index for the following winter season (December-February) and only 0.2 with that for the preceding winter.

Walker (1910) developed regression equations with the predictors: snow accumulation over the Himalayas at the end of May, South American pressure (mean of March, April and May), May Mauritius pressure, Zanzibar rain for April and May, for forecasting monsoon rainfall over India and Burma. During 1907 and 1908, this regression equation was used only as a guide to the inferences drawn from the current forecast method in use. The issue of official forecasts based on Walker's regression equation commenced from 1909. The objective approach of Walker's forecast method helped in the deletion of detailed discussions about the behavior of the factors and their anticipated influence on monsoon rainfall and thereby considerably reduced the size of the forecast memorandum.

Walker also examined the relationship between solar activity, as measured by the annual value of the mean sunspot number, and meteorological parameters at many stations. Based on his empirical studies, Walker was apparently convinced about the reality of the solar-weather relationship, but he concluded that sunspot numbers play only a minor role in influencing the seasonal weather over India.

Up to 1915, the monsoon forecasts were being issued for the whole of India and Burma. Thereafter, Walker divided the country into four fairly homogeneous divisions on the basis of correlation with the predictors, and forecasts for these divisions were being issued till 1922 when the areas were again revised. On partition of India in 1947, the areas were changed. In 1961, the areas were changed again. Fig. 1 shows the subdivisions of India.

After several revisions of the predictors and divisions of India, Walker (1924) developed in 1924 the following regression equations for forecasting the normalized anomaly of monsoon rainfall over Peninsular (ΔRP) and Northwest India (ΔRNW).

$$\Delta RP = 0.20P_1 - 0.32P_2 - 0.24P_3 - 0.22P_4 - 0.26P_5 - 0.12P_6 \quad (1)$$

$$\Delta RNW = 0.04P_1 - 0.14P_4 - 0.48P_5 - 0.30P_7 - 0.24P_8 - 0.06P_9 \quad (2)$$

where the predictor parameters are,

P_1 = normalized anomaly (i.e., anomaly divided by standard deviation) for April and May South American Pressure (mean of Santiago, Buenos Aires and Cordoba)

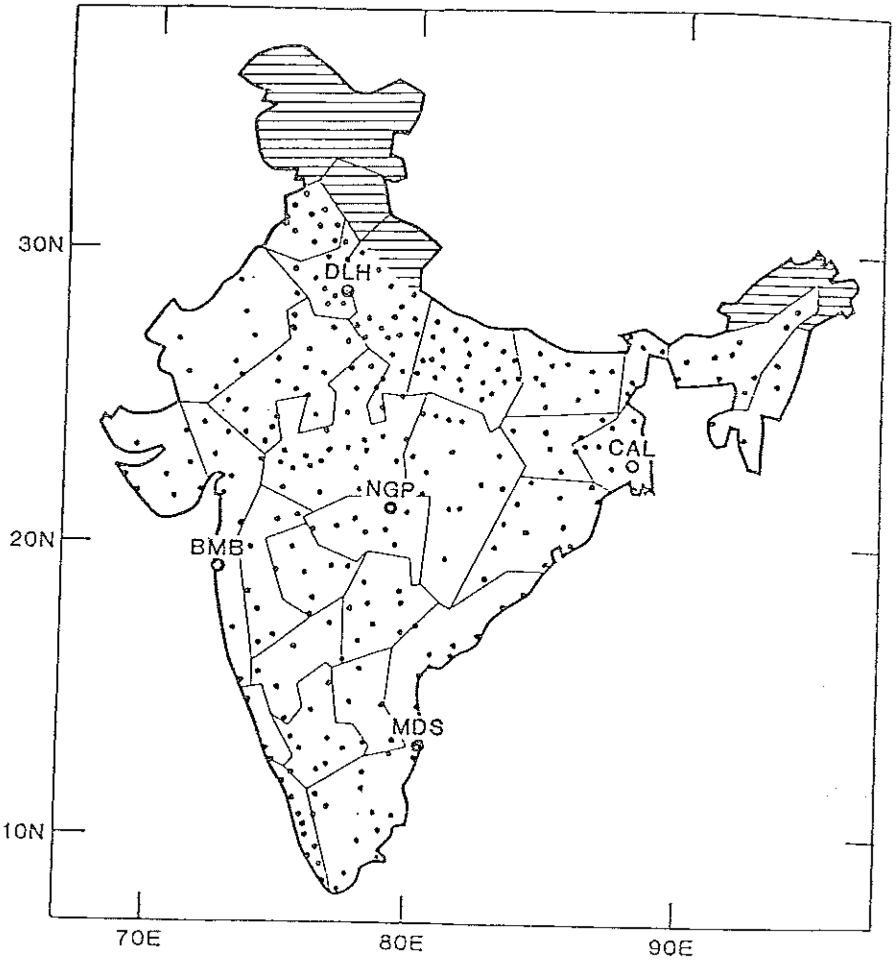

FIG. 1. Locations of the stations and the subdivisions for which rainfall is averaged. Hatching indicates the hilly regions not included in the averaging.

P_2 = normalized Zanzibar May rainfall anomaly
P_3 = normalized Java rainfall (October-February) anomaly.
P_4 = normalized Cape Town pressure (September-November) anomaly
P_5 = normalized South Rhodesian rainfall (October-April) anomaly
P_6 = normalized Dutch Harbor temperature (December-April) anomaly
P_7 = normalized anomaly of snow accumulation over the western Himalayas by the end of May

P_8 = normalized anomaly of Dutch Harbor temperature (March-May)
P_9 = normalized anomaly of equatorial pressure.

Equatorial pressure = 1/3 [1/2 Seychelles Pressure (February + March) + 1/4 Batavia Pressure (January-April) + 1/3 Port Darwin Pressure (March-May)]

Walker (1924) has mentioned that the multiple correlation coefficient between monsoon rainfall and the predictors used is 0.76 for peninsular as well as northwest India monsoon rainfall.

Until 1955, the predictors used in the regression equations for forecasting monsoon rainfall were from the surface or sea level. In 1956, Calcutta and Bangalore upper level winds were introducled as predictors in the regression equation for forecasting Peninsular monsoon rainfall, and Agra-Gwalior and Calcutta upper level winds in the regression equation for forecasting northwest India monsoon rainfall.

For the first time, Jagannathan and Khandekar (1962) examined the relationship between contour heights of different isobaric surfaces up to 400 mb at Indian radiosonde stations for the months March through May and Indian Peninsular monsoon rainfall, based on the data for 1944-58. They showed that the height and thickness between two pressure levels for some locations are useful predictors. Utilizing these predictors, they obtained three regression equations based on all data up to 1958 and verified for one independent year 1959. The three regression equations gave forecast departures of Peninsular rainfall as 7.5, 7.9 and 6.1 inches against the actual departure of 11.2 inches.

At present, the India Meteorological Department gives its long-range forecast in seven categories, large defect ($\leq$ 50% of normal), moderate defect (50% to 74% of normal), slight defect (75% to 89% of normal), normal (90% to 110% of normal), slight excess (111% to 125% of normal), moderate excess (126% to 150% of normal) and large excess ($>$ 50% of normal) (Thapliyal, 1981). Normand (1953), Jagannathan (1960) and Rao (1964) have reviewed the seasonal forecasting of monsoon rainfall in India.

Ramdas *et al.* (1954) evolved a regression equation for forecasting the date of establishment of the summer monsoon over Travancore-Cochin (the present Kerala state), south Kanara, Ratnagiri district and Colaba district. They used April Seychelles rain, mean westerly wind component over Agra (or average of Delhi and Gwalior) from 1 to 3 km during the first half of May, April Darwin pressure, Cochin pressure minus Jaipur pressure in April, October-April south Rhodesian rainfall and April Rhodesian rainfall as predictors. The regression equations were developed on the basis of all available data up to 1950. They have not given any verification on independent years 1951-54. However, on the basis of the general indication of the behavior of the predictors, they have inferred for these independent years whether the onset over the west coast (which covers all the four areas) would be about the normal date, not far from the normal date, later than a particular date or earlier than a particular date, and have tried to verify such general forecasts for the west coast.

Montgomery (1940a,b) who reviewed the work of Walker examined the stability of the predictors used by Walker (1910, 1922, 1924) in the preparation of forecasting formulae for monsoon rainfall, by computing the correlation coefficients between monsoon rainfall and these predictors for later periods and comparing these correlation coefficients with those obtained by Walker. Among the predictors used by Walker in his 1924 formula for forecasting of monsoon rainfall for Peninsular India, Montgomery (1940b) found that South American pressure, Dutch Harbor temperature and south Rhodesian rainfall have maintained their original correlation, and have thus exhibited stability. In this connection, it may be mentioned that the lengths of periods over which the correlation coefficients for the predictors for forecasting Peninsula monsoon rainfall have been compared are very dissimilar, the periods used by Montgomery (1940b) being much smaller.

Jagannathan (1960) studied the stability of the different predictors used by the India Meteorological Department in the regression equations for forecasting the monsoon rainfall over Peninsular and northwest India over different decades of the period 1881-1960. According to him none of the predictors showed stable correlations over all the decades of the period. It may, however, be mentioned that a decade is perhaps too small for studying the stability of a relationship. The mean, standard deviation and covariance and consequently the correlation coefficients for 10-year periods are subjected to high random sampling fluctuations. In view of this, fading of the relationship, or change of the relationship from direct to inverse and vice versa could be due to random sampling fluctuations. On the basis of study by Jagannathan (1960), American pressure, Dutch Harbor temperature and Bangalore 6 km wind have shown good stability.

Montgomery (1940b) carried out verification of Walker's (1922, 1924) formulae for forecasting monsoon rainfall for the Peninsula. Using Walker's formulae, he computed the forecasts for the later periods 1920-

36 and 1924-36 and as a measure of verification of these forecasts he computed the correlation coefficients between the forecast and actual rainfall. For the 1919 and 1924 formula the correlation coefficients were 0.21 and 0.12. These small and nonsignificant correlation coefficients showed that the earlier good relationship was not sustained for later periods. Walker (1922, 1924, 1933) himself verified his forecasting formulae. He computed a forecast of All-India rainfall for the later periods 1909-21 and 1909-27 by using the "1908 forecast formula", and then computed correlation coefficients between forecast and actual rainfall. The correlation coefficients for these periods are 0.55 and 0.56, suggesting fairly good stability in the later periods. He also verified the two "1924 forecast formulae" for northwest India and Peninsula for the later period 1924-36. In all, there were 18 forecasts — 9 for northwest India and 9 for the Peninsula. According to Walker, forecasts should be issued only when there is a 4 to 1 chance of success. In 8 of these forecasts, this condition is satisfied but in 2 cases only the sign of the forecast departure is correct. On a careful scrutiny by Walker (1933) of the forecasts issued before the monsoon seasons of 1905-32, two-third were correct. However, the verification of such general forecasts is subject to uncertainty.

Normand (1953) verified the monsoon forecasts issued during the period 1931-48, 16 each for the Peninsula and northwest India for the whole season, and 14 for the Peninsula and 15 for northwest India for August-September rainfall. Of these 61 forecasts, 10 were wrong. On pure chance, the numbers of forecasts estimated wrong on the basis of a normal distribution, and on the basis of actual distribution for 1931-48 are 23 and 17, respectively. The number of the wrong forecasts allowable on the 4 to 1 standard was 12. Thus the regression forecasts have done much better than chance forecasts, but only slightly better on the 4 to 1 standard. However, the period 1931-48 is not quite typical in that it has experienced relatively less droughts. It was also found that the proportion of wrong forecasts for the worst monsoon years was 66 percent, which is large. Considering all these points, Normand posed the question, "Are the relationships, though real, now so small that they are of insufficient value for the issue of useful forecasts?" Finally, Normand (1953) expressed the hope that persistent patterns of flow in the middle or upper troposphere may prove to be of prognostic value, but lacking a background of theory we will still have to depend on statistical methods. As mentioned in Section 3, the development during the last decade, as hoped by Normand, has brought out the April ridge at 500 mb as a middle tropospheric flow parameter characterized by some persistence and well-related to the Indian monsoon rainfall. However, we have yet to understand the physical mechanisms that produce statistically significant empirical relationships between monsoon rainfall and other circulation features.

3. Current Research

In this section we have summarized the results of several investigations that have appeared during the last 10 years. The current approach is not different from the one used by Walker more than 75 years ago in that empirical relationships are sought between monsoon rainfall and global circulation features; however, the choices of predictor parameters are different. We have divided this section into the following subsections to present separate descriptions of various predictor parameters.

- 3.1 Mid-tropospheric circulation over India
- 3.2 Boundary conditions at the Earth's Surface
  - 3.2.1 Snow Cover
  - 3.2.2 Sea Surface Temperature
- 3.3 Southern Oscillation
- 3.4 Surface Temperature over India
- 3.5 Surface Pressure over the Northern Hemisphere
- 3.6 Upper Air Flow over India

3.1 *Mid-Tropospheric Circulation over India*

The tropospheric circulation over India is characterized by the subtropical ridge, which can be identified at and above the 500 mb level along 75°E in the monthly mean wind charts. As observed from the normal charts (India Meteorological Dept., 1972), based on the data for 1951-65, the 500 mb ridge along 75°E is located at 11.5°N in January, 15°N in April, 28.5°N in July and 20°N in October (Fig. 2). The seasonal shift is largest from April to July, the period covering the transition from summer to the monsoon season. However, the mean seasonal shift from January to May is only 4-5° of latitude. Thus, during the onset and establishment of the monsoon during June and July, the normal 500 mb ridge location undergoes a rather large and rapid shift. At 200 mb level, the mean ridge shifts from 4°N in January to about 10°N in April and shifts

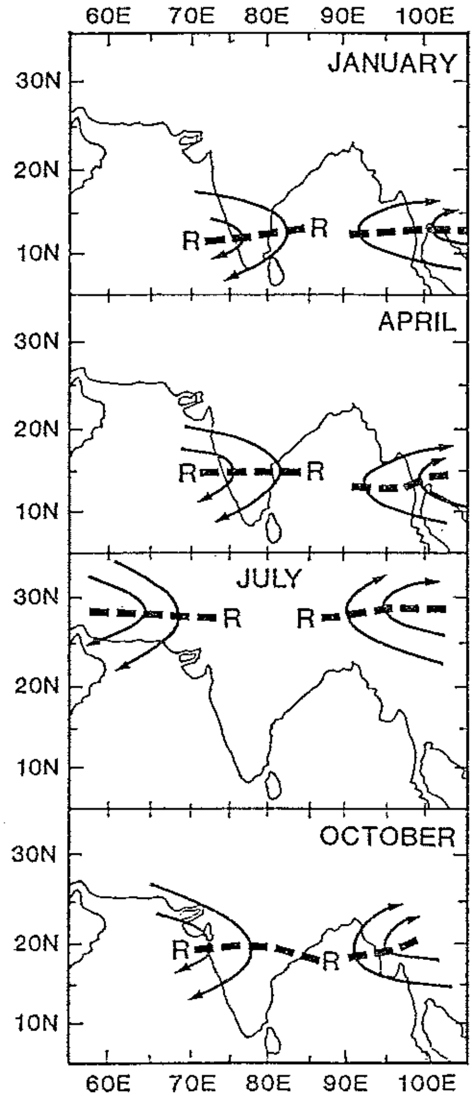

FIG. 2. Schematic representation of the climatological monthly mean circulation and location of the ridge (R) at 500 mb during January, April, July and October. Based on actual streamline maps published by the India Meteorological Department (1972).

further northward to 15°N in May and to 25°N in June. The shift in the 200 mb ridge is thus not regular. Moreover, due to paucity of wind observations at 200 mb in the earlier portion of the period, these normal charts do not adequately represent the ridge at this level. Since the observational coverage is much better at 500 mb level, it has become customary to use the ridge at 500 mb as a possible predictor parameter.

Interannual variability of the ridge during April through July

The Monthly Weather Report in the India Weather Review, published by the India Meteorological Department, includes a monthly 500 mb wind flow chart for India and neighborhood for the years 1948-67. The mean monthly locations of the 500 mb ridge along 75°E for the months April through July for each of the years 1948-67 were estimated from these flow charts by Shukla and Mooley (1986). From these mean locations of the ridge, the mean, standard deviation (S.D.) and the extreme locations of the ridge for the period 1948-67 have been obtained for the months April, May, June and July. These are given below. It should be noted that the ridge could not be located in June in 8 years, and in July in 2 years.

	April	May	June	July
Mean	15.7°N	18.6°N	23.1°N	28.3°N
S. D.	2.3°	2.4°	2.5°	2.4°
Northernmost location	19.5°N	24.5°N	26.5°N	31.6°N
Southernmost location	11.0°N	14.8°N	18.0°N	23.7°N

It can be seen that the range of variation of the ridge is about 8°-9° of latitude. The extremes are generally observed to lie within two standard deviations from the mean.

Relationship of the 500 mb ridge with rainfall

Banerjee *et al.* (1978) showed for the first time that the cube-root of the percentage of Indian meteorological subdivisions with normal or above normal monsoon rainfall (i.e., $\geq$ 81% of the normal) is significantly correlated with the latitudinal position of the subtropical ridge along 75°E on the 500-mb mean circulation chart of April. They obtained the regression equation between these two parameters for the period 1950-

70 and verified the same on the independent years 1939-49 and 1971-75 and found that the mean error for the number of subdivisions with normal or above normal rainfall was 6 percent. They also showed that at 500 mb level, the normal northward seasonal movement of the ridge axis from January to May was regular and organized. Mooley *et al.* (1986) have pointed out that the Indian Meteorological subdivisions vary largely in size, by more than one order of magnitude, the ratio of the largest to the smallest being about 13. Therefore, in a particular year, when all except five subdivisions have normal to above normal monsoon rainfall, it may appear to be a normal rainfall year; however, if the five subdivisions with deficient rainfall happen to be large, they could cover 30% of the country. In view of this, the number of subdivisions with normal to above normal monsoon rainfall cannot be considered to be a satisfactory measure of the monsoon rainfall over the country. The percentage area of the country with normal to above normal monsoon rainfall might have been a relatively better measure of monsoon rainfall over India than the percentage of the number of subdivisions with normal to above normal monsoon rainfall. Mooley *et al.* (1986) have shown that the relationship of the Indian monsoon rainfall with the location of April 500 mb ridge is positive (correlation coefficient = + 0.71) and highly significant and that even over periods as small as 20 years, the relationship is stable and consistent. They have also shown that ridge location south of the normal by more than one standard deviation is a much better indicator of deficient monsoon rainfall (i.e., normalized rainfall anomaly ≤ -1.0 S.D.) than ridge location north of normal by more than one standard deviation, of excess monsoon rainfall (i.e., normalized rainfall anomaly of ≥ 1.0 S.D.). They developed a regression equation on the basis of data for the period 1939-80 and verified it for the independent years 1981-84. Estimates for 1982 (a drought year) and 1984 (a near-normal monsoon rainfall year) were very close to actual rainfall, and those for 1981 (a near-normal activity year) and 1983 (an excess rainfall year) deviated from the actual rainfall by + 7.6% and − 15%. However, the verification sample was rather too small to judge the efficacy of the regression relationship. Mooley *et al.* (1986) also examined the relationship between monsoon rainfall of each of the subdivisions and the location of the ridge on the basis of data for the period 1939-80, and found that the rainfall for the subdivisions mostly north of 12°N and west of 84°E is positively and significantly related. It may be mentioned that the monsoon rainfall series used by Mooley *et al.* (1986) is based on monthly rainfall from a fixed network of 306 evenly distributed rain gauge

stations for the period 1939-80 and about 250 rain gauge stations for the period 1981-84.

Thapliyal (1981, 1982) showed on the basis of data for 1944-73 that the relationship between monsoon rainfall in Peninsular India and the April 500 mb ridge is highly significant. He developed an Auto-Regressive Integrated Moving Average (ARIMA) model for forecasting monsoon rainfall for the Indian Peninsula, with April 500 mb ridge as the leading indicator. For forecasting Peninsular monsoon rainfall, using data for 1939-76, he obtained an expression which involves rainfall of the preceding thirteen years and changes in the ridge location from the current year to the preceding year for the preceding five years. He obtained forecasts of Peninsular monsoon rainfall for the years 1977-80 by ARIMA as well as a regression model and found that error by the ARIMA model was smaller than that by the regression model in each of these four years. It may, however, be mentioned that the sample size for verification was rather too small.

Intra-seasonal relationships among 500 mb ridge locations

Over the period 1948-67, correlation coefficients have been obtained between the April ridge location and the May through July ridge locations and between May and July ridge locations. These are, cc (April, May) = 0.63, cc (April, July) = 0.55, cc (May, July) = 0.47. The first two correlation coefficients are significant at 5% level and the third is very close to significance at 5% level. The correlation coefficient of 0.55 between April and July ridge locations suggests the persistence in the ridge location from April through July.

The years with normalized monsoon rainfall anomaly with absolute value larger than 1.0 have been classified as years of deficient (negative) or excess (positive) monsoon rainfall and 500 mb ridge locations have been

Years of deficient monsoon rainfall	Ridge location anomaly (°lat.)			Years of excess monsoon rainfall	Ridge location anomaly (°lat.)		
	April	May	July		April	May	July
1951	−3.0	−3.8	−0.8	1956	3.8	5.9	2.7
1965	−0.7	−2.5	−4.4	1961	1.8	0.3	1.7
1966	−1.7	0.4	−3.7				
Mean	−1.8	−2.0	−3.0	Mean	2.8	3.1	2.2

examined for such years for the months April, May and July. The anomaly of the ridge locations during these years and in these months is given below.

Thus, the mean anomaly of the ridge location in each of the months April, May and July is negative/positive for years of deficient/excess monsoon rainfall and the difference between the two means is 4-5° of latitude which is about twice the S.D. of the monthly ridge location. In addition, in each deficient rainfall year the ridge anomaly is generally negative and relatively large, and in each excess rainfall year the anomaly is positive and relatively large. Thus in these years, the anomaly in April ridge location is found to persist through July.

Indian monsoon rainfall in years of low/high latitude April ridge location

As an illustration, Fig. 3 shows the April 500 mb ridge location for 1951 and 1956, which were respectively years of deficient and excess monsoon rainfall.

We have classified the years in which the April ridge was located south/north of the mean position by more than one standard deviation as years of low/high latitude ridge location. The years of low latitude ridge location are 1941, 1951, 1952, 1963, 1966, 1968, 1972, 1974, 1979 and 1982 and those of high latitude ridge location are 1942, 1946, 1947, 1956, 1964, 1967, 1969 and 1975. Indian rainfall for the two bimonths (June-July, August-September) and the same for the low/high latitude ridge location years falling within the period 1939-78 are given below:

Years of low latitude ridge	Indian rainfall mm		Years of high latitude ridge	Indian rainfall mm	
	June-July	Aug-Sept		June-July	Aug-Sept
1941	389	358	1942	502	471
1951	411	331	1946	501	415
1952	453	352	1947	414	531
1963	401	472	1956	556	437
1966	416	343	1964	467	475
1968	436	334	1967	442	436
1972	311	356	1969	430	416
1974	389	374	1975	480	503
Mean	401	365	Mean	474	461

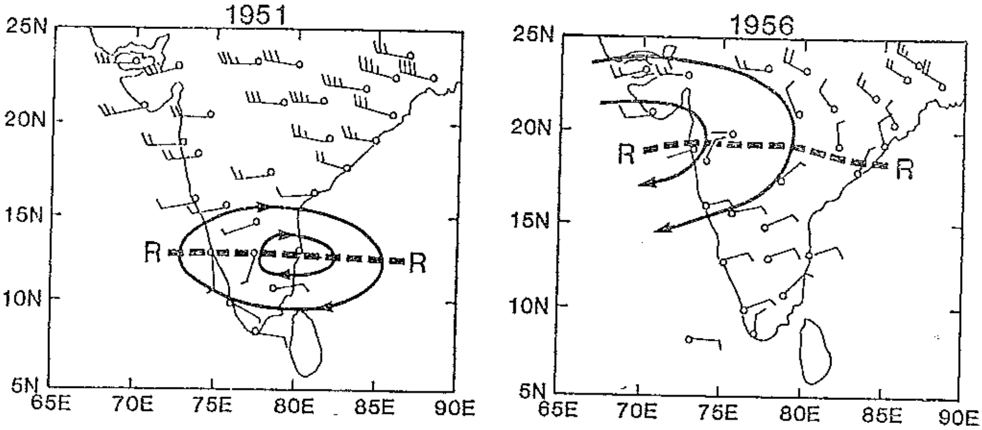

FIG. 3. Monthly mean (April) winds at the Indian upper air stations at 500 mb for the years 1951 and 1956.

Mean rainfall amounts for the two halves, June-July and August-September, for the period 1939-78 are 443 and 432 mm respectively.

These rainfall values show clearly that (i) the mean for each half of the monsoon season is much higher for the years of high latitude ridge location than that for low latitude ridge location; (ii) in most of the years of low/high latitude of the ridge location, the rainfall anomaly is negative/positive for both halves of the monsoon season. This suggests that low/high latitude location of April ridge is an indicator of low/high rainfall in each half of the monsoon season, apparently through persistence of the anomaly of April ridge location through July.

Possible physical basis for influence of the ridge location on rainfall

As mentioned before, the mean 500 mb ridge undergoes an annual oscillation of about 17° of latitude. The ridge demarcates the westerly circulation regime to the north from the easterly tropical regime to the south. During January, the westerly circulation regime at 500 mb reaches its southernmost position. As the season advances, the westerly circulation regime shifts north. The anomaly in the magnitude of this northward shift of the westerly circulation could therefore result either from the anomaly in the characteristics of the mid-latitude westerly flow, or from anomalous tropical heat sources. Anomalous snow accumulation over Eurasia and anomalies in incoming/outgoing radiation could also affect the ridge position. A rather large negative anomaly of the ridge location in April or May could be associated with colder tropospheric conditions whose persistence through July could adversely affect the establishment and activity of the monsoon. This apparent relationship between the anomaly of the April 500 mb ridge and the anomaly of the Indian monsoon rainfall appears to be quite complicated, and in the present stage of our inadequate knowledge of these factors and their interactions it is not possible to offer any explanation for the observed relationship.

3.2 *Boundary Conditions at the Earth's Surface*

3.2.1 *Snow Cover*

Blanford (1884) utilized the winter and spring snowfall in the Himalayas to predict the subsequent summer monsoon rainfall over India. The inverse relationship between snow cover and rainfall which was suggested by Blanford and later used by Walker gave consistent results during the period 1880-1920; however, for the following 30-year period the relationship was either weak or opposite, and after 1950 the India Meteorological Department dropped this parameter as a predictor.

Hahn and Shukla (1976) utilized a short series of satellite-derived snow cover over Eurasia for 9 years (1967-1975) and showed that the original suggestion by Blanford for inverse relationship between winter-spring snow cover and monsoon rainfall was strongly supported by satellite-derived snow cover data.

Dickson (1984) further extended this study by including data up to 1980 and found that the correlation coefficient for the period 1967-1980 was only − 0.59 compared to − 0.74 for the period 1967-1975.

The physical mechanism responsible for this relationship is not clearly understood. It has been conjectured that excessive snow cover could contribute towards a weaker summer monsoon intensity in two ways: colder tropospheric temperatures over Eurasia could delay the establishment of meridional temperature gradients, or wetter soil could dissipate most of the solar heating for evaporation rather than heating of the continental land masses. There is some evidence that during the years of excessive snow cover, the mid-tropospheric ridge over India is to the south of its normal position during the spring season.

3.2.2 *Sea Surface Temperature*

Angell (1981) used seasonal Sea Surface Temperature (SST) anomaly time series for the eastern equatorial Pacific (0-10°S and 90°W-180°W) for the period 1868-1977 to examine the relationship between SST and Indian monsoon rainfall. He found a highly significant inverse relationship (correlation coefficient = − 0.62) between Indian monsoon rainfall and the SST anomaly two seasons later. He also observed that in 20 years during the period, SST anomaly during an El Niño season, was at least 0.8°C.

Mooley and Parthasarathy (1984) examined the sea surface temperature (SST) over the eastern equatorial Pacific Ocean (0-10°S and 90°W-180°W) in relation to the Indian monsoon rainfall for the period 1871-1978. They utilized the seasonal anomaly series which they obtained from Angell (1981). In addition to computing the lag/lead correlation coefficients for the whole period, they computed these for the two halves of the period to find out whether the relationships exhibited any stability. The correlation coefficients obtained by them are given below.

SST Season		CC for Period	
	1871-1978	1971-1924	1925-1978
DJF (−2)	0.08	+0.02	+0.13
MAM (−1)	−0.22*	−0.29*	−0.17
JJA (0)	−0.47**	−0.46**	−0.52**
SON (+1)	−0.60**	−0.66**	−0.55**
DJF (+2)	−0.58**	−0.65**	−0.52**

* Significant at 5% level.
** Significant at 0.1% level.

The figure after the season indicates the number of seasons before (if negative) or after (if positive) the monsoon season. It can be seen that the relationship between SST for the concurrent and the succeeding two seasons and Indian monsoon rainfall is highly significant and stable, but for the preceding MAM season, the relationship is much weaker and is not stable. SST in the DJF season preceding the monsoon season has no relationship with Indian monsoon rainfall.

Association between Indian monsoon rainfall and El Niño events

El Niño is an anomalous oceanic and meteorological event involving the sudden appearance of abnormally warm surface water off the Peru-Ecuador coast (equator - 12°S). The warm water spreads westward to the central Pacific Ocean. The event generally starts around March or April, and may last for one year or more and attains maximum sea surface temperature in late December. The Southern Oscillation is closely linked to this event and the two are referred to as ENSO event.

Using the Line Islands Precipitation Index (LIPI) as indicator of El Niño events during the period 1922-74, Sikka (1980) brought out a general association between El Niño events and deficient rainfall. But as mentioned by Rasmusson and Carpenter (1983), since LIPI has a tendency to peak near the end of the El Niño year, they listed all El Niño events as occurring during pairs of consecutive years. As a result of this ambiguity in identification of the years of El Niño events, the degree of correspondence and lead/lag relationship could not be fixed.

Rasmusson and Carpenter (1983) examined Indian monsoon rainfall with reference to warm episodes (El Niño events) during the period 1875-1979. They took years of El Niño as those listed by Quinn *et al.* (1978) during the periods 1875-1920 and 1939-1947, and for the remaining periods, i.e., 1921-38 and 1948-79, when they had adequate surface marine data, they determined the years of El Niño events from these data. Their study showed that during 21 out of 25 El Niño years, Indian monsoon rainfall was below the median rainfall, and in 19 years it was below the mean rainfall.

Mooley and Parthasarathy (1983) examined the association between Indian summer monsoon rainfall and El Niño during the period 1871-1978. They considered 22 El Niño events — severe and moderate — as categorized by Quinn *et al.* (1978). They used two categories of rainfall, the first with rainfall in standard units (i.e., normalized anomaly) ≤ -0.84, calling this category as "Drought", and the second with rainfall > -0.84, calling this category as "No Drought". By considering "Drought" and "No Drought" as two categories of rainfall and "El Niño" (severe and moderate) and "No El Niño" as two categories of El Niño events, they prepared 2×2 contingency tables for India and for the different Indian meteorological subdivisions. They tested these contingency tables for significant association by applying Chi-square test. The association between drought and El Niño is found to be significant (at 5% or above) for India and 19 subdivisions mostly located west of 80°E. They also found that the worst drought years in the history of Indian drought, viz., 1877, 1899, 1918 and 1972, were severe El Niño years. Out of 22 El Niño (moderate and severe) years, in 17 El Niño years Indian monsoon rainfall was below normal, in 4 El Niño years the normalized anomaly of Indian monsoon rainfall was between +0.52 and 0.92, and in one El Niño year the rainfall was very close to normal.

Parthasarathy and Mooley (1985) examined the average monsoon rainfall of India for severe, moderate, weak and very weak El Niño events as classified by Quinn *et al.* (1978) during the period 1871-1980 and found that mean rainfall increased with the decrease of intensity of El Niño. They also showed through a student's t-test that the difference between the means for the 22 El Niño years (moderate and severe) and the remaining 88 years was significant at 0.1% level and brought out the influence of El Niño events on Indian monsoon rainfall.

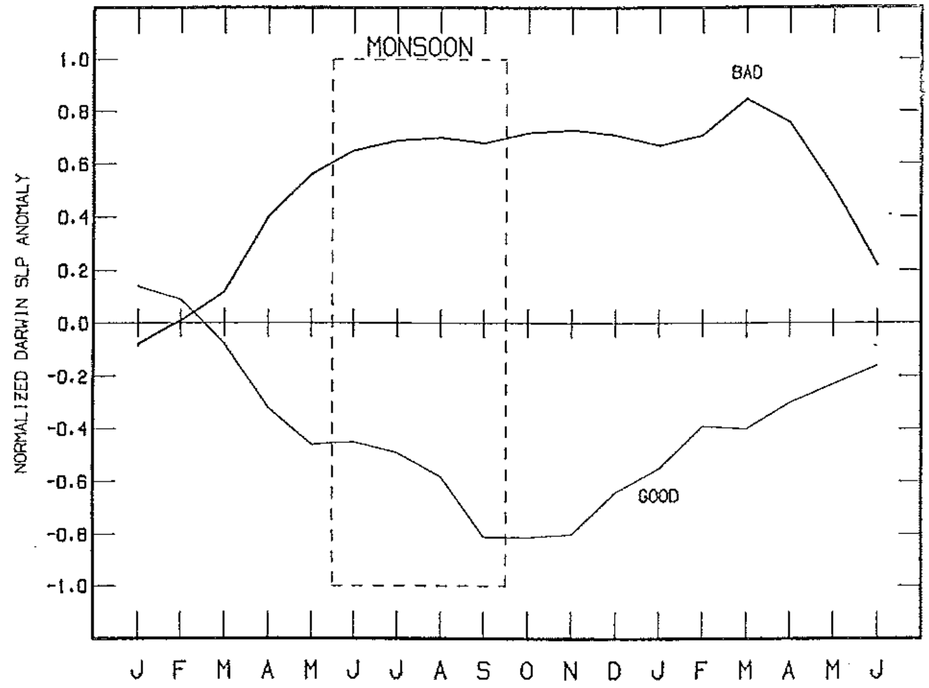

FIG. 4. Composite of normalized Darwin pressure anomaly (three-month running mean) for good monsoon rainfall years and bad monsoon rainfall years.

3.3 *Southern Oscillation* (*SO*)

As described in the section entitled Historical Review, the basic relationship between the Southern Oscillation and Indian monsoon rainfall was utilized by Walker as two of the predictor parameters (P_1 and P_9) in equation (1) which represent the two nodes of SO. However, in a recent study Shukla and Paolino (1983) found that the mean Darwin pressure anomaly during the spring season preceding the monsoon season composited separately for all the drought years and flood years were not very different from each other (see Fig. 4). The winter to spring tendency of the Darwin pressure appeared to be a more useful predictor for summer monsoon rainfall over India. Figure 4 gives composite Darwin sea level pressure anomalies for deficient rain years (1899, 1901, 1904, 1905, 1911, 1918, 1920, 1928, 1941, 1951, 1965, 1966, 1968, 1972, 1974, 1979, 1982) and excessive rain years (1892, 1893, 1894, 1916, 1917, 1933, 1942, 1947, 1956, 1959, 1961, 1970, 1975, 1983).

We have also examined the stability of correlation between Darwin pressure tendency and Indian rainfall, and it is found that this relationship is statistically significant for the entire record length; however, during the past 50 years the correlation coefficient is considerably higher than that for the previous years.

3.4 *Surface Temperature over India*

Mooley and Paolino (1986) have examined the surface maximum and minimum temperature over India during the pre-monsoon months March, April and May in relation to Indian monsoon rainfall. They found three areas for which temperature is significantly related to the Indian monsoon rainfall. These three areas are: south Gujarat and adjoining parts of Maharashtra and of Madhya Pradesh (area A), north Tamilnadu coast and adjoining parts, (area B), and south Gujarat State and adjoining parts of southwest Madhya Pradesh (area C). The mean monthly April minimum temperature for areas (A) and (B) and mean monthly May minimum temperature for area (C) are significantly (5% or over) related with Indian monsoon rainfall. The best relationship (cc = 0.60) is between Indian monsoon rainfall and mean monthly minimum temperature during May over south Gujarat and adjoining parts of southwest Madhya Pradesh (area C). This area is apparently located east of the Intertropical Convergence Zone (ITCZ) over the Arabian Sea and the anomalous thermal conditions over this area possibly represent the anomalous thermal conditions over the Arabian Sea ITCZ.

Bhalme and Mooley (1980) found that the mean heights of the 200 mb surface were much below (above) normal over the belt 15°-30°N along 70°E during drought (good monsoon) years, suggesting colder (warmer) upper troposphere. Verma (1980, 1982) showed a good association between cooler (warmer) upper troposphere over north and northwest India and poor (good) summer monsoon rainfall. He also found that a cooler (warmer) upper troposphere in May generally persists during the monsoon season. However, for later years, i.e., after 1977, we did not find good association between upper tropospheric temperature and Indian monsoon rainfall.

3.5 *Surface Pressure over the Northern Hemisphere*

Hemispheric analyses of seasonal mean sea level pressure (SLP) were used to investigate relationships with monsoon rainfall. These fields were available for a long period of record and are of good quality. The period of record used for the SLP is from Dec. 1924 through Nov. 1977.

Correlation coefficients were computed between seasonal SLP and Indian monsoon rainfall for seasons preceding, during, and following the monsoon. Maps of correlation coefficients showed a continuity of pattern from one season to the next, but did not show any statistically significant persistent patterns. The correlation map for summer SLP anomalies one year before the monsoon showed a large negative pattern significant above the 5% level off the east coast of North America. We do not know if this relationship has any physical significance. The correlation map for spring SLP anomalies immediately preceding the monsoon showed an area of statistically significant positive correlation in the North Pacific, south of 30°N.

An empirical orthogonal function (EOF) analysis was performed on the seasonal SLP data, in the hope that certain dominant patterns of SLP variability, as isolated by the analysis, might be related to the Indian monsoon. The coefficient time series for the dominant EOFs in each season were correlated with the all-India monsoon rainfall time series, but no significant correlations were found.

We have also examined SLP at selected stations in India, Pakistan, Bangladesh and Sri Lanka, with periods of record from 20 to 85 years, and their relationships with monsoon rainfall. Correlation coefficients were computed between monthly and seasonal station SLP time series and

India monsoon rainfall. Our motivation was to see if relationship between monsoon rainfall and SLP at the Indian stations is as strong, or even stronger than Darwin SLP. It was found that for none of the Indian stations were the correlation efficients as high as that for Darwin.

3.6 *Upper Air Flow over India*

Joseph (1978) examined the meridional flow in the upper troposphere over India during May, June, July and August and found that during years of large-scale monsoon failure the meridional flow in the upper troposphere during June through August was southerly, and that during May in such years, southerly meridional flow over India at the 150 mb level was stronger than that in other years. Utilizing this persistence of upper tropospheric flow associated with monsoon failure, Joseph *et al.* (1981) developed relationship between a meridional wind index (Vm) and Indian monsoon rainfall. This index is the mean of the meridional winds at Madras, Bombay, Nagpur, Delhi and Srinagar for May at the 200 mb level. This index had a highly significant correlation coefficient of −0.89 with Indian monsoon rainfall for the period 1964-78. They used the Indian monsoon rainfall series constructed by Parthasarathy and Mooley (1985). They developed a regression equation between Indian monsoon rainfall (R) and (Vm) which is given by $R = 92.55 - 3.15\,Vm$, where R is in cm, Vm in m. sec^{-1}, southerly meridional wind is taken as positive. Joseph (1983) verified the regression equation for the independent years 1979-82. The percentage errors of the forecast rainfall for these years were, −6.0, −9.7, +3.3 and 5.3 respectively. Mooley and Shukla (1987) examined the relationship between mean April 500 mb ridge along 75°E and the meridional index for May, Vm, of Joseph *et al.* (1981) and found the correlation coefficient between the two parameters to be −0.73 for the period 1964-78. The relationship is inverse and is highly significant. Thus, the meridional wind index, Vm, and April 500 mb ridge are not independent. With the April 500 mb ridge as predictor, the forecast of monsoon rainfall can be prepared earlier and hence it is more useful than the mean May meridional wind index, Vm.

Thapliyal (1979) has shown that the circulation features at the 50 mb level in January during westerly and easterly Quasi Biennial Oscillation (QBO) years are very different and that they can provide useful guidance for forecasting Indian monsoon rainfall. But in view of the fact that drought is also seen to follow both easterly and westerly phases of QBO in January, it is difficult to use these circulation features as predictors for monsoon seasonal rainfall in any individual year.

Kung and Sharif (1980) developed a regression equation for prediction of the date of onset of the summer monsoon over the Kerala coast from 700 and 100 mb circulation parameters. They considered geopotential heights, temperature, kinetic energy, zonal and meridional wind components at the 700 and 100 mb levels (in all, 10 predictors) over the point, 12.4°N, 76.5°E on the Kerala coast, for April. They used data for the period 1958-78. They obtained the dates of monsoon onset over Kerala from the India Meteorological Dept., and data for geopotential heights and temperatures at 700 and 100 mb from the National Meteorological Center's octagonal grid data archived at the National Center for Atmospheric Research (NCAR). The wind components were approximated by the computed geostrophic components. On experimentation, they found that the addition of the zonal wind component at 100 mb and the meridional wind component at 700 mb did not improve the fit of the regression equation. In view of this, they deleted these two parameters. The standard deviation of the observed date of onset is about a week. The error in the forecast of date of onset exceeded one S.D. in 4 years out of 19 years. The largest error of 17 days occurred in 1972, actual onset being much later than the forecast date of onset.

In another study, Kung and Sharif (1981, 1982) considered the additional predictors, 700 mb January zonal wind and 700 mb March temperature over Australia, April Indian Ocean temperature over the area 10°-20°N and 60°-70°E and developed regression equations for forecasting the monsoon onset date over Kerala and for forecasting monsoon rainfall over Central India, using data for 1958-77. According to them, forecasts of the onset date had an average accuracy of 5% and forecasts of rainfall over Central India had an average accuracy of 6%.

4. AN EMPIRICAL PREDICTION SCHEME

In this section we have summarized the results of Shukla and Mooley (1986), who have presented a multiple regression equation to predict seasonal rainfall over India. They have suggested that since the two most important circulation anomalies that influence the Indian monsoon rainfall appear to be the Southern Oscillation and the latitudinal location of the 500 mb ridge, and since there is no significant correlation between these, they should be used as predictors in a linear regression equation.

Based on data for the period 1939-1984, they have developed a regression equation:

$$Y = aX_1 + bX_2$$

where Y = Normalized rainfall anomaly for India for the summer monsoon

X_1 = Normalized anomaly of the location of the 500 mb ridge during April along 75°E

X_2 = Normalized anomaly of January to April change in Darwin sea level pressure.

Table 1 gives the values of seasonal rainfall, latitudinal location of ridge and Darwin pressure change for the 46 year period used in that study. Table 2 gives the regression coefficients (a) and (b) for the successive 30 year periods. Table 2 also gives correlation coefficients between monsoon rainfall and the two predictors. Regression equations are developed for each 30 year period and utilized to predict rainfall for two independent years, one immediately preceding and one immediately succeeding the 30 year period. The results of independent verification for 32 years are shown in Figure 5. Actual rainfall is along the abscissa and the predicted rainfall is along the ordinate. The two dotted lines represent ± 5% of the actual rainfall. It can be seen from this Figure that prediction of droughts is especially better. The root mean square error is 35.8 mm, which is only 4.2% of the mean rainfall. The root mean square error for the climatic mean to be the forecast each year would have been 82 mm, which is 9.6% of the mean rainfall.

The multiple correlation coefficient is 0.82, which means that only 67% of the variance is explained by these two predictors. While a regression equation on this level of explained variance might provide some useful guidance in operational forecasting of monsoon rainfall, it is clear that a substantial percentage (33%) of variance remains unexplained, and therefore it will be necessary to investigate other factors which might be related to the summer monsoon rainfall over India.

5. Prospects for the Future and Concluding Remarks

From a practical standpoint, there are two aspects to the problem of monsoon prediction:

— Prediction of seasonal mean rainfall
— Prediction of space-time variability of rainfall

There appear to be statistically significant relationships between monsoon rainfall and anomalies of planetary scale circulation and boundary

Table 1 - Indian Monsoon rainfall, April 500 mb ridge location along 75°E and Darwin Mean Sea Level pressure (SLP) change from January to April (1939-84).

Year	Rainfall (mm)	Ridge (°N)	Darwin SLP Change (mb)	Year	Rainfall (mm)	Ridge (°N)	Darwin SLP Change (mb)
1939	788.9	14.0	4.4	1963	855.2	13.5	2.6
1940	850.2	15.3	5.0	1964	919.9	18.3	1.8
1941	729.0	11.2	2.8	1965	706.8	14.0	4.9
1942	958.3	17.5	1.8	1966	735.2	13.5	2.4
1943	866.1	16.0	2.5	1967	858.6	17.5	5.7
1944	921.3	14.5	3.0	1968	753.7	12.5	5.6
1945	907.3	16.7	3.8	1969	829.3	17.3	5.1
1946	901.3	17.3	4.1	1970	939.4	15.8	1.8
1947	942.3	18.0	2.1	1971	885.8	16.7	2.2
1948	872.4	14.5	1.7	1972	653.2	11.0	4.8
1949	901.8	17.0	2.8	1973	911.6	16.7	1.7
1950	874.9	17.0	3.0	1974	746.9	13.5	4.8
1951	736.9	12.0	4.1	1975	960.1	17.5	1.3
1952	791.7	13.5	3.6	1976	854.7	17.0	4.8
1953	919.7	17.0	2.0	1977	880.5	14.0	3.4
1954	885.3	16.5	2.8	1978	908.0	14.0	1.9
1955	929.9	15.5	0.6	1979	746.0	12.5	3.7
1956	979.5	17.5	3.5	1980	881.0	15.0	3.8
1957	784.3	16.0	3.0	1981	842.0	17.0	4.8
1958	886.3	17.0	0.4	1982	736.0	11.3	3.8
1959	938.1	16.0	2.8	1983	959.0	14.5	0.3
1960	839.4	16.7	2.0	1984	835.0	14.8	3,0
1961	1017.0	15.0	1.9				
1962	806.9	14.8	4.7	Mean	857.1	15.3	3.0
				S.D.	82.2	2.0	1.3

TABLE 2 - Values of regression coefficients a(1) and b(2); multiple correlation coefficients mcc (3); cc for rainfall and ridge location only (4); and cc for rainfall and Darwin pressure tendency only (5) for the successive 30 year periods and the whole 46 year period.

Period	(1)	(2)	(3)	(4)	(5)
1939-68	0.624	−0.294	0.77	0.71	−0.49
1940-69	0.607	−0.333	0.75	0.68	−0.47
1941-70	0.594	−0.361	0.76	0.67	−0.50
1942-71	0.522	−0.389	0.72	0.62	−0.52
1943-72	0.577	−0.368	0.77	0.69	−0.55
1944-73	0.576	−0.370	0.78	0.69	−0.56
1945-74	0.603	−0.369	0.81	0.73	−0.59
1946-75	0.588	−0.387	0.83	0.74	−0.63
1947-76	0.577	−0.406	0.83	0.73	−0.64
1948-77	0.551	−0.412	0.81	0.70	−0.63
1949-78	0.524	−0.434	0.80	0.68	−0.64
1950-79	0.540	−0.425	0.81	0.69	−0.65
1951-80	0.542	−0.413	0.80	0.69	−0.64
1952-81	0.524	−0.439	0.79	0.66	−0.63
1953-82	0.544	−0.429	0.80	0.68	−0.62
1954-83	0.513	−0.487	0.79	0.63	−0.64
1955-84	0.513	−0.487	0.79	0.63	−0.64
1939-84			0.82	0.71	−0.58

conditions. The most significant association is found with the El Niño-Southern Oscillation phenomena and the mid-tropospheric circulation over India. This is indeed encouraging because if the fluctuations of seasonal mean were merely the consequences of interannual variability of the intraseasonal variability, the problem of monsoon prediction would have been reduced to predicting the intraseasonal fluctuations themselves.

In order to make further progress it would be essential to understand the relationship among the synoptic scale, intraseasonal variability and planetary scale circulations which appear to influence the seasonal mean rainfall. There have been several suggestions that eastward propagating 30-60 day oscillations might play an important role in determining the intraseasonal fluctuations of monsoon rainfall over India. This deserves further investigation. It is quite likely that a suitable phase relationship between the Southern Oscillation (2-4 years) and 30-60 day oscillations

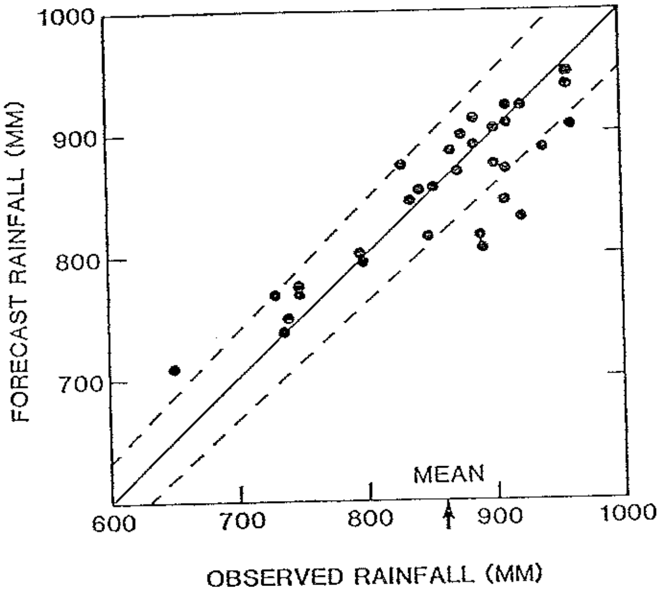

FIG. 5. Observed and forecast rainfall (mm) for 32 years of verification. The arrow indicates the long term mean rainfall (753 mm). The dashed lines represent the ± 5% of the solid line.

might provide important insight into the mechanisms of intraseasonal and interannual variability of monsoon rainfall over India.

On a day-to-day basis, the rainfall fluctuations are associated with synoptic scale disturbances (lows, depressions) and fluctuations of the monsoon trough; however, it needs to be investigated if planetary scale circulation anomalies (which are apparently related to seasonal mean monsoon rainfall) influence the statistics of these synoptic scale disturbances. If this were found to be the case, prospects for long range forecasting of monsoon would be quite good.

Another important question from a practical standpoint is the predictability of monthly and seasonal rainfall anomalies over smaller spatial regions. We have examined the multiple correlation coefficients between seasonal rainfall over each of the 30 subdivisions of India, Southern Oscillation tendency, and 500 mb ridge location. We find that the multiple correlation coefficient is considerably less for subdivisions than for all India rainfall. This suggests that the relationships between planetary scale circulation anomalies and seasonal mean rainfall over India do not necessarily hold for anomalies over smaller regions and that it would be necessary to gain a better understanding of the mechanisms of intraseasonal variability at regional scale before we could attempt to predict rainfall anomalies over smaller regions of India. At this time we do not have any clear evidence that it would be possible to predict rainfall anomalies over smaller regions empirically.

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PONTIFICIAE ACADEMIAE SCIENTIARVM SCRIPTA VARIA
69

STUDY WEEK
ON:

PERSISTENT METEO-OCEANOGRAPHIC ANOMALIES AND TELECONNECTIONS

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EDITED BY
CARLOS CHAGAS and GIAMPIETRO PUPPI

ABSTRACT

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