Empirical Prediction of the Summer Monsoon Rainfall over India

J. SHUKLA AND D. A. MOOLEY*

Center for Ocean-Land-Atmosphere Interactions, Department of Meteorology, University of Maryland, College Park, MD 20742

(Manuscript received 3 July 1986, in final form 22 September 1986)

ABSTRACT

We have examined 46 years (1939–84) of observed data to study synoptic and statistical relationships between the summer monsoon rainfall over India, the Southern Oscillation, and the midtropospheric circulation over India.

The change in Darwin pressure from January to April and the latitudinal position of the April 500-mb ridge along 75°E are taken as two quasi-independent predictor parameters to develop a regression equation to predict the summer monsoon rainfall. Verification of predictions on independent data shows that the root-mean-square error for predicted rainfall is 36 mm, which is less than half of the standard deviation (82 mm) and only about 4% of the mean rainfall (857 mm).

Since the observations needed to define the predictor parameters would be available well before the monsoon season, and since the performance of the empirical prediction formula is reasonably good, this method can be of some possible use for long-range forecasting of seasonal mean rainfall over India.

1. Introduction

Several years ago it was suggested that the anomalies of space-time averaged monsoon circulation and rainfall are potentially predictable because of the influence of the slowly varying boundary conditions at the earth's surface and the related low frequency atmospheric fluctuations (Charney and Shukla, 1981; Shukla, 1981). Recognition of the existence of planetary-scale, low-frequency fluctuations, of which the El Niño–Southern Oscillation-monsoon phenomenon is a prime example, and reasonable numerical simulations of the observed circulation anomalies (Nihoul, 1985) have provided some hope that there may be a physical basis for dynamical prediction of monthly and seasonal mean atmospheric anomalies. Presently there is considerable effort underway to demonstrate the feasibility of dynamical prediction of monthly and seasonal averages using complex general circulation models of the atmosphere and oceans (WMO, 1986).

It is also desirable that statistical and empirical techniques for long-range forecasting on monthly and seasonal scales be developed and continuously refined to produce operational long-range forecasts. In fact, it is quite likely that a suitable combination of dynamical and statistical techniques would be the most appropriate way of producing operational long-range forecasts.

Diagnostic studies of historical datasets have been traditionally very useful in suggesting empirical approaches to long-range forecasting. Sometimes, the necessity of producing long-range forecasts has compelled investigators to develop empirical relationships between different facets of the coupled atmosphere–ocean–land system, even if a plausible physical basis for such a relationship is not understood. However, such empirical attempts have sometimes led to the discovery of important processes in the atmosphere. A good example in this category is the work of Walker (1924), who was charged with the responsibility of producing long-range forecasts for monsoon rainfall over India. Based on some of the work of other investigators of that time and on his own intuition that the fluctuations of the Indian monsoon should be related to the world-wide circulation features, he initiated a massive project of calculating correlation coefficients between monsoon rainfall and several other atmospheric circulation parameters at different locations over the world. A by-product of this effort was a recognition of the extensive nature of the Southern Oscillation.

It therefore seems appropriate, and perhaps even desirable, that the existence of significant empirical relationships among different components of the atmosphere–ocean–land system be documented and discussed because it might provide some insight into the underlying physical and dynamical processes. It is in this spirit that this paper presents some empirical evidence of relationships between monsoon rainfall and other features of the planetary-scale circulation. We were motivated by the possible usefulness of these re-

---

* Former affiliation: Indian Institute of Tropical Meteorology, Pune 5, India.

lationships for operational long-range forecasting, and therefore we have discussed only the circulation features preceding the summer monsoon season. We recognize, however, that such relationships, or even more significant ones, could exist between the monsoon rainfall and the subsequent atmospheric circulation. We have made an attempt to interpret the available empirical evidence in light of the recent advances in our understanding of the mechanisms for interannual variability of large-scale, low-frequency atmospheric circulation anomalies, and we hope that these empirical results will provide some stimulation for theoretical and modeling studies.

Attempts have been made for more than 100 yr to forecast the summer monsoon rainfall over India. The general procedure for making these forecasts has consisted of finding suitable predictor parameters and developing regression equations based on the past data. These regression equations are then utilized to forecast the summer monsoon rainfall over India. For a comprehensive review of the earlier works on long-range forecasting of summer monsoon rainfall over India, the reader is referred to the papers by Blanford, 1884; Walker, 1933; Jagannathan, 1960; Bannerjee et al., 1978; Thapliyal, 1982; Shukla and Paolino, 1983; Shukla, 1986a; Mooley et al., 1986.

A crucial step in developing empirical formulae for long-range forecasting requires the selection of appropriate predictor parameters. In the past this has been guided sometimes by the intuition of individual investigators and sometimes by an objective search among a large number of parameters. It should be noted, however, that even the objective statistical search is generally carried out for the datasets readily available to the investigator. In fact, the datasets used by Walker were mostly for the stations from the then British colonies.

The two circulation features which we have examined here in relation to the Indian summer monsoon rainfall are

a) life cycle of the Southern Oscillation
b) seasonal transition of the midtropospheric circulation over India

Based on a review of the existing literature and analysis of available data, we have concluded that the characteristics of these two circulation features preceding the summer monsoon season show the most significant relationship with the monsoon rainfall and they also lend themselves to a reasonable interpretation as slowly varying features of the planetary-scale circulation.

We first describe the rainfall data used in this study (section 2) and present a brief description of the space-time variability of these two parameters separately, along with the data utilized (sections 3 and 4). In section 5, we develop a linear regression equation to predict summer monsoon rainfall over India using some measure of these two circulation features as predictor parameters. Section 6 gives a summary and discussion of the results and concluding remarks.

2. Rainfall data

The rainfall data are taken from Mooley and Parthasarathy (1984) for the period 1939–78, and from Mooley et al. (1986) for the period 1979–84. Average rainfall over the plains of India for each monsoon season (June, July, August, September) is obtained by weighting each station rainfall by the area of the district in which the station is located. Data for 306 stations (see Fig. 1) evenly distributed over the plains of India were used for the period prior to 1981, and for about 250 stations for the years 1981–84. It should be noted that the hilly regions of India with high spatial variability of rainfall and a sparse rain gage network are not included in the averaging. Previous works have shown that it is not inappropriate to average rainfall anomalies for the whole monsoon season, and over a large area, because the major droughts and floods are persistent during the rainy season and occupy most of the country (Mooley and Parthasarathy, 1984; Shukla, 1986b).

3. The Southern Oscillation

A large body of literature exists on the space-time variability of the Southern Oscillation. The pioneering study by Bjerknes (1969) and recent observational analyses by Rasmusson and Carpenter (1982), and numerical simulations by Lau (1985) have shown that the planetary-scale tropical sea level pressure anomalies, manifested as a seesaw between the Indian Ocean and the Pacific Ocean, occur in conjunction with the episodes of large-scale SST anomalies in the tropical Pacific. The life cycle of these SST anomalies is about one year, and the interval between the two adjacent warm events can range from 2–7 years.

Walker (1924) was the first one to demonstrate a possible relationship between the Southern Oscillation and monsoon rainfall over India. Several of the predictor parameters used by Walker were some measures of the Southern Oscillation. Several recent observational and modeling studies have established that there is a remarkable association between warm SST anomalies in the eastern and central Pacific Ocean, above normal pressure in the eastern Indian Ocean, and an eastward shift of the main convection zone near the western Pacific and Australia. The results of numerical experiments by Shukla and Wallace (1983) suggest that an eastward shift of the main convection zone in the western Pacific and associated changes in the location of the Walker cells produce descending motion over the Indian subcontinent. Since the rainy season over India is mainly confined to the summer months (June, July, August, September), a low frequency circulation system like the Southern Oscillation can be an important and useful predictor for the monsoon rainfall be-

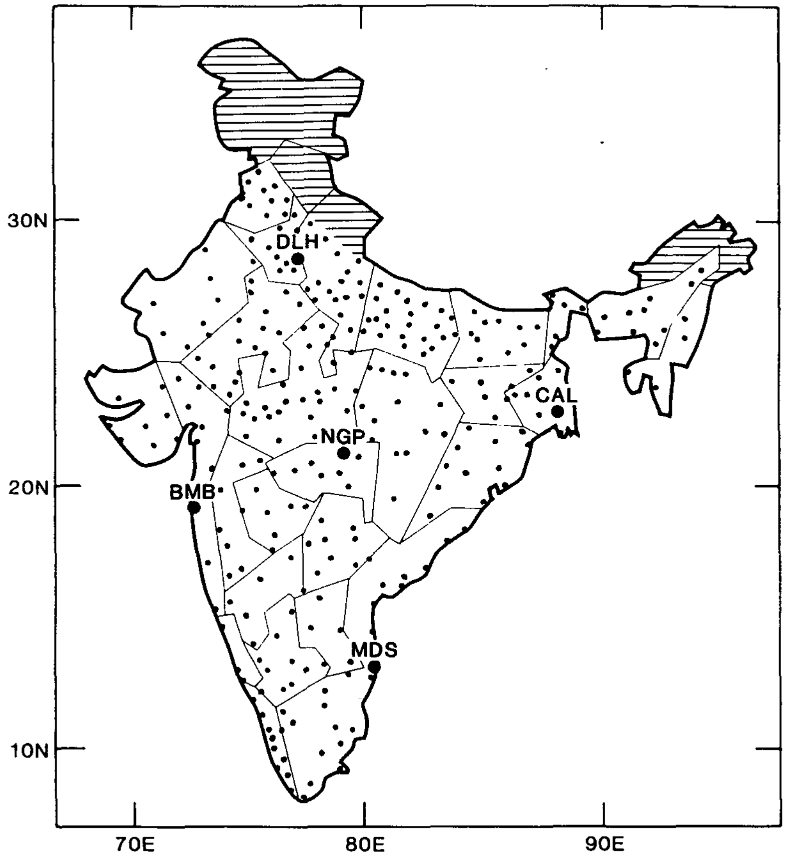

FIG. 1. Locations of the stations and the subdivisions for which rainfall is averaged. Hatching indicates the hilly regions not included in the averaging.

cause of a possible phase locking between the seasonal cycle and the low-frequency circulation anomaly. Based on these considerations, we believe that there is a reasonable basis for choosing the Southern Oscillation as a possible predictor for the summer monsoon rainfall over India.

Walker knew that the association between the monsoon rainfall and the Southern Oscillation was especially significant for the circulation parameters during and after the monsoon season. However, since Walker's main motivation was operational long-range forecasting, he chose the circulation parameters during the preceding spring and winter seasons as predictors. For example, Walker (1924, 1933) used the sea level pressure anomalies for tropical stations in Indonesia and South America—they represent the intensity of the Southern Oscillation—during the preceding season as predictors for summer rainfall. We now know (see for example, Shukla and Paolino, 1983) that the temporal persistence of the Southern Oscillation is highly variable during different seasons, and the seasonal auto-correlation of the Southern Oscillation is the lowest from winter to spring, followed by spring to summer. The value of the Southern Oscillation (as measured by the anomaly of Darwin sea level pressure) during the spring season for years of severe monsoon droughts is not significantly different from the values for years of heavy monsoon rains (see Fig. 2 of Shukla and Paolino, 1983). It is therefore not surprising that the correlation coefficient between the Southern Oscillation and the monsoon rainfall is not high. Recognizing this property of the Southern Oscillation, Shukla and Paolino (1983) suggested that, rather than using the amplitude, the tendency (phase) of the Southern Oscillation should be a better predictor. It was found (Shukla and Paolino, 1983) that correlation between a Southern Oscillation index (Darwin pressure) during spring and monsoon rainfall over India for an 81 year period is only −0.32, whereas the correlation coefficient between the tendency of the Southern Oscillation {spring [March, April and May] (MAM) minus winter [December, January and February] (DJF) sea level pressure for Darwin} and monsoon rainfall over India for an 81-yr period is −0.46. We have therefore chosen to include the Southern Oscillation tendency as one of the predictor parameters for developing a linear regression equation to predict the Indian summer monsoon rainfall. The difference between the April and January sea level pressure at Darwin will be used as a measure of the tendency of the Southern Oscillation.

The Darwin monthly mean sea level pressure data are taken from Shukla and Paolino (1983). This dataset was obtained from the National Center for Atmospheric Research. Darwin is located near one of the nodes of the Southern Oscillation. Hence, the time series of Darwin pressure which is available for a long period has been used to describe the life cycle of the Southern Oscillation. Based on the earlier results of Shukla and Paolino (1983), we have used the tendency of the Darwin pressure rather than the Darwin pressure itself.

4. Seasonal transition of midtropospheric circulation over India

A midtropospheric anticyclone over southern India and its seasonal migration towards the north are a well-known feature of the climatology of the seasonal cycle of the atmospheric circulation. Figure 2 shows the location of the 500-mb ridge during the months of January, April, July and October. The axis of the ridge is located from the streamline analysis of the wind data. These figures are based on the average wind data for the period 1951–65, collected and analyzed by the India Meteorological Department (1972). The 500-mb ridge along 75°E is seen at about 11.5°N during January, 15°N during April and 28.5°N during July, which is its northernmost location during the peak of the monsoon season. By October, the ridge position shifts southward to 20°N. It is reasonable to conjecture that the northward and the southward displacements of this midtropospheric anticyclonic circulation are related to the seasonal march of the solar radiation and the associated diabatic heat sources.

Although the general character of this seasonal transition remains the same during each year, there are some differences in the latitudinal position of the ridge from one year to the other. Figure 3 shows the 500-mb flow for April, 1951 and April, 1956. During April, 1951 the location of the ridge along 75°E was at about 12°N whereas in 1956, the ridge was at about 17.5°N. Monsoon rainfall was below normal during 1951 and above normal during 1956. Earlier studies have shown that if the latitudinal position of the 500-mb ridge during April is much south (north) of its normal position, rainfall over India for the subsequent summer monsoon season is mostly much below (above) normal. For the first time, Banerjee et al., (1978) developed a regression equation between the latitudinal position of the 500-mb ridge along 75°E during April and the cube root of the number of Indian subdivisions with normal or above normal summer monsoon rainfall for prediction of percentage of such divisions. Thapliyal (1982) developed empirical formulae to predict monsoon rainfall over peninsular India by utilizing ridge position. Recently, Mooley et al., (1986) have shown that the relationship between the April ridge position and monsoon rainfall over India is highly significant and stable.

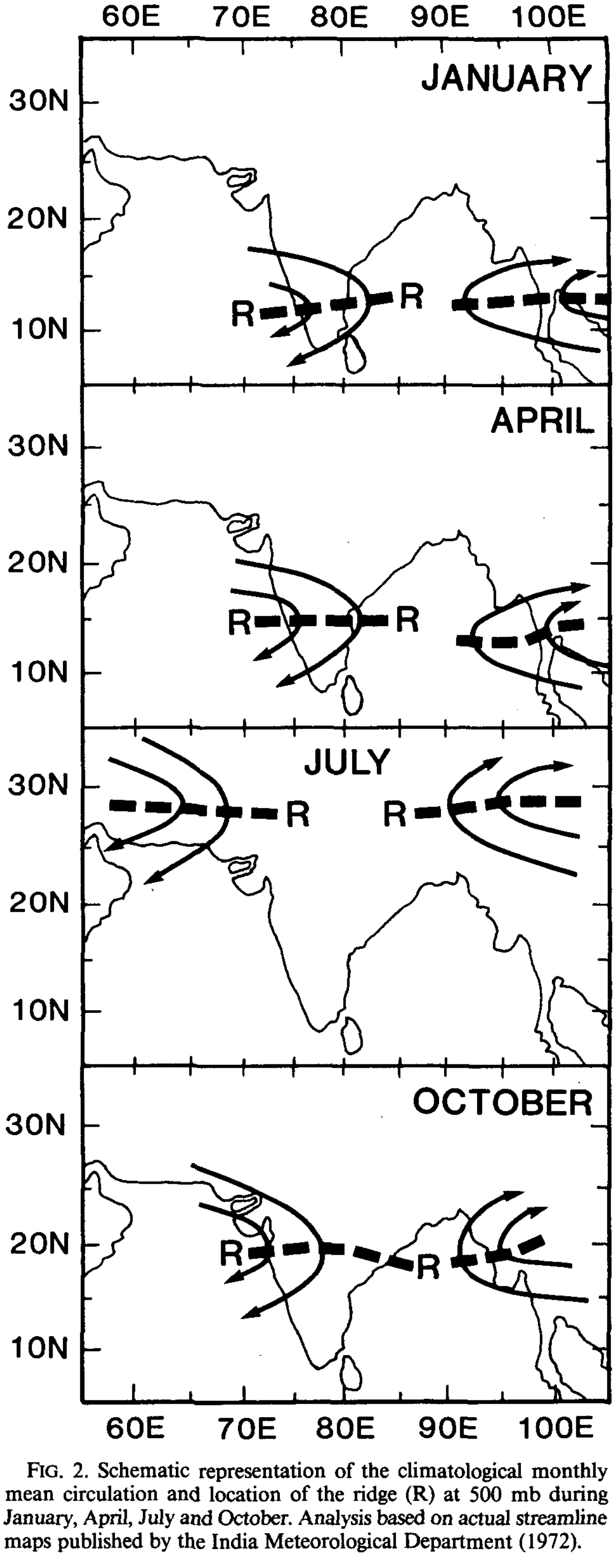

FIG. 2. Schematic representation of the climatological monthly mean circulation and location of the ridge (R) at 500 mb during January, April, July and October. Analysis based on actual streamline maps published by the India Meteorological Department (1972).

The difference between the southernmost (11°N) and the northernmost (18°N) positions of the 500-mb ridge during April is only 7° latitude in a dataset of 46

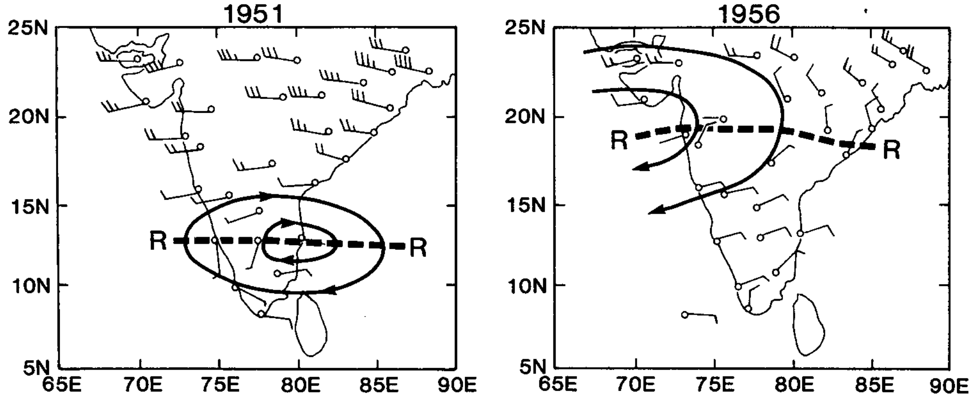

FIG. 3. Monthly mean (April) winds at the Indian upper air stations at 500 mb for the years 1951 and 1956.

yr (1939–84), and therefore it is important to establish that these changes are not due to errors in determining the location of the ridge or due to high-frequency transients of the tropospheric circulation. We have examined the location of the 500-mb ridge for the months of April, May, June and July for the period 1948–67 for which individual monthly mean upper air charts were available to us. We found that for most of the drought years the position of the 500-mb ridge was consistently south of its normal position for the months of April, May and July. Similarly, for years with above normal rainfall over India, the location of the ridge was generally to the north of its normal position for each of these months. For years with deficient rainfall, the average location of ridge for April, May and July was 13.9°, 16.7° and 25.3°N, respectively, and for years with excess rainfall the corresponding locations were 18.5°, 21.7° and 30.5°N, respectively. Due to the absence of a well-organized circulation during June, when the monsoon sets in over India, it was not possible to determine the location of the ridge for 8 out of 20 yr. It was also found that correlation coefficients between the ridge location during April and May was 0.63, and between April and July was 0.55. These values are significant at the 95% level and therefore it is reasonable to conclude that a delayed northward movement of the ridge is a temporally coherent phenomenon.

Although it is difficult to advance a physically consistent hypothesis to explain this relationship, it appears that a delayed northward displacement of the 500-mb ridge is a good indicator of the subsequent planetary-scale circulation which produces large-scale anomalous descending motion over the Indian region. We believe that the abnormality of the seasonal evolution of the midtropospheric circulation, as measured by the April ridge location, is not due to some random process; rather, it is a feature of the slowly varying planetary-scale circulation whose causes are not well understood. We do not even know whether the factors responsible for the delayed northward advancement of the anticyclonic circulation are related to the anomalous heat sources near the equator, or midlatitude circulation including anomalous snow cover anomalies over Eurasia. However, since northward advancement of the 500-mb ridge is an important feature of the seasonal cycle of the tropospheric circulation, we believe there is some justification for considering it as a possible predictor parameter to develop empirical relationships to predict summer monsoon rainfall over India.

Locations of the 500-mb ridge during April along 75°E are taken from Banerjee et al. (1978) and Mooley et al. (1986). Fixation of the intersection of the 500-mb ridge and the 75°E longitude involves a subjective determination of the location of the ridge after manual analysis of the available wind data. We could not obtain the maps analyzed by Banerjee et al. for our own examination of the uncertainty in fixing the ridge position. We have manually analyzed 500-mb wind data for April for the years 1948–67 for which individual monthly mean charts were available to us from the *Indian Weather Review,* published by the India Meteorological Department. We found that the locations of the ridge along 75°E as determined by us were the same or differed by less than 1° from those by Banerjee et al. In order to facilitate comparison of our results with those from other published works, we have taken the data for ridge position from Banerjee et al. and Mooley et al. The ridge locations, the Darwin pressure change and the Indian monsoon rain for the period 1939–84 are given in Table 1.

5. A linear regression equation to predict monsoon rainfall

We have utilized past data to develop a regression equation,

$$Y = aX_1 + bX_2,$$

where

Y normalized rainfall anomaly (i.e., anomaly divided by standard deviation) for India for the summer monsoon

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
				Std dev	82.2	2.0	1.3

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

The past values for Indian monsoon rainfall, ridge location and Darwin pressure trend, as given in Table 1, are available to us for 46 yr (1939–84). The mean value of summer rainfall is 857 mm, the mean location of the 500-mb ridge during April is 15.3°N, and the mean value of the change in Darwin pressure (April–January) is 3.0 mb. In an earlier paper by Shukla and Paolino (1983), the tendency of Darwin pressure was defined as the change from winter (DJF) to spring (MAM) pressure at Darwin. Considering the operational utility of these results, we have chosen the central months (January and April) of the two seasons to calculate the tendency which does not change the results. We have used successive 30 yr periods to calculate the values of the coefficients a and b. Table 2 gives the values of the coefficients a and b and multiple correlation coefficients (mcc) for successive 30-yr periods. Correlation coefficients (cc) between rainfall and the ridge position and rainfall and the Darwin pressure change are also given in Table 2.

The regression equations are utilized for predicting rainfall for 1 yr just preceding the 30-yr period and 1 yr just after the 30-yr period, except for the first 30-yr period (1939–68), which is utilized only for 1969, and the last 30-yr period (1955–84), which is utilized only for 1954. This procedure was used earlier by Kung and Sharif (1980) and appears to be more desirable for operational forecasting because with this procedure the regression equations can, at least partially, take into account the systematic changes in the relationship between the predictors and the predictand. The procedure described above provides 32 yr of data for independent

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

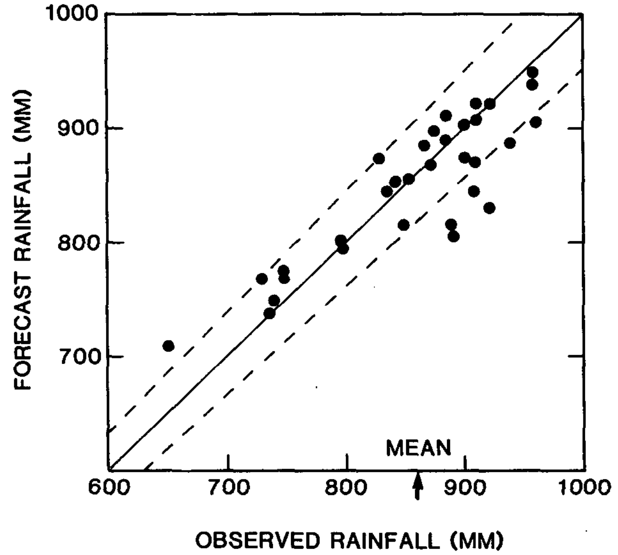

FIG. 4. Observed and forecast rainfall (millimeters) for 32 yr of verification. The arrow indicates the long-term mean rainfall (853 mm) and the dashed lines represent ±5% of the solid line.

verification. The overall measure adopted for assessment of the accuracy of the forecasts is the root-mean-square error (rmse). If F_i and O_i are forecast and observed Indian monsoon rainfall for the ith year, then $\text{rmse} = [\sum_{i=1}^{n} (F_i - O_i)^2/n]^{1/2}$, n being the number of years for which forecasts are made. The rmse for predicted rainfall for these 32 yr was found to be 35.8 mm, which is 4.2% of the mean rainfall, and is considerably smaller than the standard deviation of summer monsoon rainfall, which is 82 mm. In most cases the error in the predicted rainfall is smaller than half the standard deviation of rainfall. It should be noted that if a regression equation was developed using only the first (last) 30 yr and used for prediction for the remaining 16 yr, the rmse would have been 41.3 (29.9) mm. This is consistent with higher variability of Indian monsoon rainfall during the last 20 years.

Figure 4 shows the results for 32 yr of verification. Actual rainfall (millimeters) is given along the abscissa and the predicted rainfall is given along the ordinate. The arrow along the abscissa denotes the long-term mean rainfall. The two dotted lines represent ±5% of the actual rainfall. It should be noted that out of 32 yr, forecast error is more than 5% only in seven cases and more than 10% only in one case. Prediction for years of below normal rainfall is especially better because out of the 13 such years, there is only 1 yr for which the error is more than 5% and the rmse for these 13 yr is only 27.8 mm. Table 3 gives the forecast and the observed Indian monsoon rainfall for the 32 years, 1939–54 and 1969–84.

The variance explained by the regression equation with both predictors is 65% (multiple correlation coefficient = 0.82). We are not aware of any other two predictors which explain such a large percentage of variance of monsoon rainfall using more than 30 yr of data.

The correlation coefficient between the ridge position alone and rainfall for the entire 46-yr period is 0.71, and between Darwin pressure change and rainfall is −0.58, but the correlation coefficient between the ridge position and the Darwin pressure tendency is only −0.25, which is not significant at the 95% level. This suggests that these two predictor parameters are not likely to be related to each other. In order to test the independence of the two predictor parameters, chi-square statistic was also calculated for three class intervals of these predictor parameters. The chi-square value was found to be far less (1.3 for 4 degrees of freedom) than that required to be significant even at the 90% significant level (7.78), and the two parameters can be taken to be quasi-independent.

6. Summary and concluding remarks

Previous works by a large number of investigators suggest that the characteristics of the Southern Oscillation and the seasonal evolution of the midtropospheric circulation are strongly associated with the monsoon rainfall over India. We have used some

TABLE 3. Forecast vs observed Indian monsoon rainfall (millimeters) for 32 yr (1939–54 and 1969–84).

	Year										
Rainfall	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949
Forecast	796	814	767	938	884	828	870	874	942	868	900
Observed	789	850	729	958	866	921	907	901	942	872	902
	1950	1951	1952	1953	1954	1969	1970	1971	1972	1973	1974
Forecast	898	748	797	925	891	872	891	911	717	921	767
Observed	875	737	792	920	885	829	939	886	653	912	747
	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	
Forecast	948	853	805	845	769	825	853	738	904	845	
Observed	960	855	880	908	746	881	842	736	959	835	

quantitative measures of these two circulation features and developed a linear regression equation to predict the Indian summer monsoon rainfall. We have used the January to April change of the Darwin sea level pressure as a measure of the evolution of the Southern Oscillation, and the latitudinal position of the 500-mb ridge along 75°E during April as a measure of the progression of the seasonal cycle of the midtropospheric circulation over India. We have found (but not yet understood) that these two features of the atmospheric circulation are quasi-independent and therefore a multiple regression formula using these two parameters as predictors gives quite useful forecasts for monsoon rainfall. Since the predictors used in the regression equation require a knowledge of the monthly mean atmospheric circulation during April, these results can be used for operational long-range forecasting of seasonal mean summer monsoon rainfall over India.

We hope these results might provide some motivation for future modeling and observational studies using simple and complex models of the atmosphere. An examination of the performance of atmospheric general circulation models (GCMs) for simulating the mean annual cycle and its interannual variability as well as observational studies should help in understanding the mechanisms responsible for the observed relationships between the Southern Oscillation, the midtropospheric circulation and the summer monsoon rainfall over India. The GCM simulations with seasonally varying solar and lower boundary forcing should be first examined to see if the models are capable of simulating the annual cycle of the northward and southward displacements of the midtropospheric anticyclonic circulation over India. If GCMs were able to simulate these features of the annual cycle realistically, they could be used to carry out some controlled numerical experiments to study the possible influence of tropical and/or extratropical lower boundary anomalies in accelerating or delaying the normal evolution of the seasonal cycle of the midtropospheric circulation. For example, Is it likely that the normal seasonal march of the midtropospheric circulation is interrupted by anomalous tropical heat sources which might be related to, among other things, SST anomalies over the tropical oceans? Likewise, Is is possible that anomalous snow cover during the previous winter and spring seasons could influence the seasonal transitions of atmospheric circulation from spring to summer?

We have examined the relationship between the April ridge location and December through March Eurasian snow cover. Snow cover data from 1967–82 (adjusted for the bias during the period 1967–74) were obtained from Dickson (1984), and for 1983 and 1984 from the Climate Analysis Center. The correlation coefficient between the two parameters is −0.49, which is marginally significant at 95%, suggesting a possible relationship between the winter snow cover and the spring circulation. The larger Eurasian snow cover could be associated with the colder atmospheric conditions during winter and spring, which could delay the seasonal transition from spring to summer. A more comprehensive analysis of a possible relationship between Eurasian snow cover and monsoon rainfall can be carried out only after a longer time series of reliable snow cover data will be available.

One of the obvious limitations of this study is the subjectivity involved in determining the location of the 500-mb ridge along 75°E. However, we found that the manual analysis by two different meteorologists did not produce any significant change in the positioning of the ridge. We initiated this study with considerable skepticism on our part about the strong relationship between the ridge location and the monsoon rainfall. We were particularly concerned with the narrow latitudinal range (11°–18°N) within which the 500-mb ridge during April fluctuates. However, after our own analysis of the 20-yr data (1948–67), we were sufficiently impressed by the temporal consistency of the seasonal evolution of the midtropospheric circulation and undertook to develop a regression equation using this as a predictor. A more comprehensive analysis of the space–time variability of the midtropospheric circulation over India is a subject for a separate study.

Finally, we would like to present some conjectures and speculations. Recently several investigators have presented some evidence of tropical, quasi-periodic, eastward propagating fluctuations with periods of 30–60 days and 2–4 years. If the phase of a 2–4 year fluctuation with respect to the seasonal cycle is such that the large-scale descending motions occur over the Indian region during the months of the summer monsoon season, this could produce large-scale monsoon droughts. It is also likely that a suitable phase matching between the multiyear oscillations and the 30–60 day oscillations could contribute towards explaining the occurrence of floods and droughts over India. A comprehensive analysis of global datasets will be required to establish the validity of these conjectures.

Acknowledgments. We are grateful to Mr. Dan Paolino for the benefit of several useful discussions and for his help in the computations of the regression equations. We are also grateful to Professor James L. Kinter for his valuable comments on the original manuscript. We thank Ms. Sharon Busching for typing the paper and Ms. Laura Rumburg for drafting the figures.

This research was supported under the auspices of the Science and Technology Initiative (STI) to foster United States–India collaboration on monsoon research through NSF Grant ATM-8414660, and NASA's Global Weather Program (NASA-NAGW-558).

REFERENCES

Banerjee, A. K., P. N. Sen and C. R. V. Raman, 1978: On foreshadowing southwest monsoon rainfall over India with midtropospheric circulation anomaly of April. *Indian J. Met. Hydrol. Geophy.*, **29**, 425–431.

Bjerknes, J., 1969: Atmospheric teleconnections from the equatorial Pacific. *Mon. Wea. Rev.*, **97**, 163–172.

Blanford, H. F., 1884: On the connection of the Himalaya snowfall with dry winds and seasons of droughts in India. *Proc. Roy. Soc. London*, **37**, p. 3.

Charney, J. G. and J. Shukla, 1981: Predictability of monsoons. *Monsoon Dynamics*, Eds., Sir James Lighthill and R. P. Pearce, Cambridge University Press, pp. 99–110.

Dickson, R. R., 1984: Eurasian snow cover vs Indian monsoon rainfall—an extension of Hahn-Shukla results. *J. Climate Appl. Meteor.*, **23**, 171–173.

India Meteorology Department, 1972: *Upper Air Atlas of India and Neighborhood*. Published by India Meteor. Dept., New Delhi, 60 maps.

Jagannathan, P., 1960: Seasonal forecasting in India, a review. Indian Meteorological Department, Special Publication, DGO. 82/650. [Available from Director General, Lodi Road, New Delhi—3, India.]

Kung, E. C., and T. A. Sharif, 1980: Regression forecasting of the onset of the Indian summer monsoon with antecedent upper conditions. *J. Appl. Meteor.*, **19**, 370–379.

Lau, N. C., 1985: Modeling the seasonal dependence of the atmospheric response to observed El Niños in 1962–76. *Mon. Wea. Rev.*, **113**, 1970–1996.

Mooley, D. A., and B. Parthasarathy, 1984: Fluctuations in all-India summer monsoon rainfall during 1871–1978. *Climate Change*, **6**, 287–301.

——, —— and G. B. Pant, 1986: Relationship between all-India summer monsoon rainfall and location of ridge at 500-mb level along 75°E. *J. Climate Appl. Meteor.*, **25**, 633–640.

Nihoul, J. C. J., 1985: Coupled ocean–atmosphere models. *Elsevier Oceanography Series*, **40**, p. 767.

Rasmusson, E., and T. Carpenter, 1982: Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Nino. *Mon. Wea. Rev.*, **110**, 354–384.

Shukla, J., 1981: Predictability of the tropical atmosphere. *NASA Tech. Memo. 83829*, pp. 51.

——, 1986a: Long range forecasting of monsoons. *Monsoons*, Eds., Jay S. Fein and Pamela L. Stephens, Wiley and Sons, 523–547.

——, 1986b: Interannual variability of monsoons. *Monsoons*, Eds., Jay S. Fein and Pamela L. Stephens, Wiley and Sons, 399–463.

——, and D. A. Paolino, 1983: The Southern Oscillation and long-range forecasting of the summer monsoon rainfall over India. *Mon. Wea. Rev.*, **111**, 1830–1837.

——, and J. M. Wallace, 1983: Numerical simulation of the atmospheric response to equatorial Pacific sea surface temperature anomalies. *J. Atmos. Sci.*, **40**, 1613–1630.

Thapliyal, V., 1982: Stochastic dynamic model for long-range prediction of monsoon rainfall in peninsular India. *Mausam*, **33**, 399–404.

Walker, G. T., 1924: Correlations in seasonal variations of weather, X. *Mem. India. Meteor. Dept.*, **24**, 75–131.

——, 1933: Seasonal weather and its prediction. British Association for Advancement of Science, Rep. 103, 25–44. [Reprinted Annual Smithsonian Institute for 1935, 117–138.]

World Meteorological Organization, 1986: Program on long-range forecasting research, *LRF Research Rep. Series No. 6* (WMO/TD-No. 87), pp. 824.