The Southern Oscillation and Long-Range Forecasting of the Summer Monsoon Rainfall over India

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ABSTRACT

The Indian summer monsoon rainfall and the Darwin pressure anomalies are examined for the 81-year period 1901–81. It is found that the tendency of the Darwin pressure anomaly before the monsoon season is a good indicator of the monsoon rainfall anomaly. During the 81-year period, there were only two instances (1901, 1941) when a negative tendency of winter (December, January, February) to spring (March, April, May) Darwin pressure anomaly was followed by a monsoon rainfall anomaly of less than minus one standard deviation; and only three instances (1916, 1933, 1961) when a positive tendency was followed by a rainfall anomaly of more than one standard deviation. Therefore, if the Darwin pressure anomaly during March, April and May is below normal, and if the Darwin seasonal pressure anomaly has been falling, a non-occurrence of drought over India can be predicted with a very high degree of confidence. Similarly, above normal Darwin pressure during March, April and May, and increasing seasonal pressure anomaly is a good indicator of the non-occurrence of very heavy rain over India.

1. Introduction

At the beginning of the present century, Sir Gilbert Walker, then the head of the India Meteorological Department, was searching for the potential predictors of the Indian monsoon rainfall. Walker's search for global predictors at large distances from India was motivated by the earlier work of his predecessor Sir John Eliot who had noted an association between high pressure over Mauritius and Australia, and droughts over India. Walker was also motivated by the already published papers of Hildebrandsson (1897) who had noted an opposite polarity of pressure at Sydney and Buenos Aires, and Lockyer and Lockyer (1902) who had further confirmed the pressure seesaw between the Indian Ocean and Argentina (Normand, 1953).

Walker made a comprehensive study of the distant correlations and coined the expression, "the Southern Oscillation". He also denoted two Northern Oscillations (in the North Atlantic and North Pacific) to describe the global see-saws of surface pressure. Walker (1923, 1924) developed regression equations which used South American pressure (Santiago) and equatorial pressure (Djakarta) in antecedent seasons as predictors to estimate the monsoon rainfall over different parts of India. The other predictors were South Rhodesia rainfall, Java rainfall, Zanzibar rainfall, Dutch Harbor temperature and Capetown pressure. Although it is beyond the scope of this paper to examine the relative independence of various predictor parameters, it is reasonable to state, based on the present-day knowledge of the time evolution of the Southern Oscillation phenomenon, that most of the Walker's predictors (with the possible exception of the Himalayan snow accumulation) were manifestations of different facets of the Southern Oscillation.

Pressures in South America and in the equatorial Pacific have been used by the India Meteorological Department as predictors of the monsoon rainfall and are considered to be two of the more reliable predictors (Rao, 1965). However, Jagannathan (1960) has pointed out that not only do different periods have large fluctuations in the value of the correlation coefficient between the April and May South American pressure and the seasonal mean (June, July, August, September) rainfall over the Indian Peninsula region, but that the overall correlation coefficient for the period 1875–1960 was only 0.34. Similarly, for the period 1901–60, the correlation coefficient between mean January–May pressure over Djakarta and subsequent monsoon rainfall over northwest India was only −0.12. Pant and Parthasarathy (1981) have reported that the correlation coefficient between the spring Southern Oscillation index [as defined by Wright (1975)] and Indian monsoon rainfall is 0.34.

The purpose of this study is to re-examine the relationship between the Southern Oscillation and the Indian monsoon rainfall using Darwin pressures for the period 1901–81. We chose to examine the Darwin pressure because its long-term record is considered to be more reliable and homogeneous than that for other equatorial stations (Trenberth, 1976). Although the Tahiti minus Darwin pressure is considered to be a better index of the Southern Oscillation (Chen, 1982; and E. M. Rasmusson, personal communication, 1983), a long time record of Tahiti pressure is not available, and moreover, for the available data (1935–81) the correlation coefficient between the spring Tahiti pressure and Indian monsoon rainfall is only 0.01. The summer monsoon rainfall data over 31 subdivisions of India was provided by the India Meteorological Department. We carried out a detailed space and time consistency check on this data set and, with the help of the scientific staff of the India Meteorological Department, corrected several errors which were either due to keyboard errors or copying mistakes. This data set uses all the raingage stations available at the time of compilation of these data and, in our opinion, is one of the more reliable data sets for Indian monsoon rainfall. A detailed discussion of the rainfall data including its space–time variability will be published elsewhere (Shukla, 1983). The seasonal (June, July, August, September) percentage departure from normal (P) for a subdivision is calculated by

$$P = [(\bar{R} - \bar{\bar{R}})/\bar{\bar{R}}] \times 100,$$

where $\bar{R}$ is the average of rainfall for all the stations in the subdivision for which data are available during that season, and $\bar{\bar{R}}$ the average of normal rainfall for the same stations for the same season. Normal is defined as the average for 50 years (1901–50). Since the number and locations of the stations for which rainfall data are available is not the same for each year, the percentage departure as defined above is probably the most appropriate parameter with which to study the interannual variability of monsoon rainfall. An area-weighted average of the percentage departures for each of the 31 subdivisions of India is taken as a measure of the Indian summer monsoon rainfall anomaly.

2. Results

Fig. 1 shows the data used for the present study: the thin line denotes the 12-month running mean of

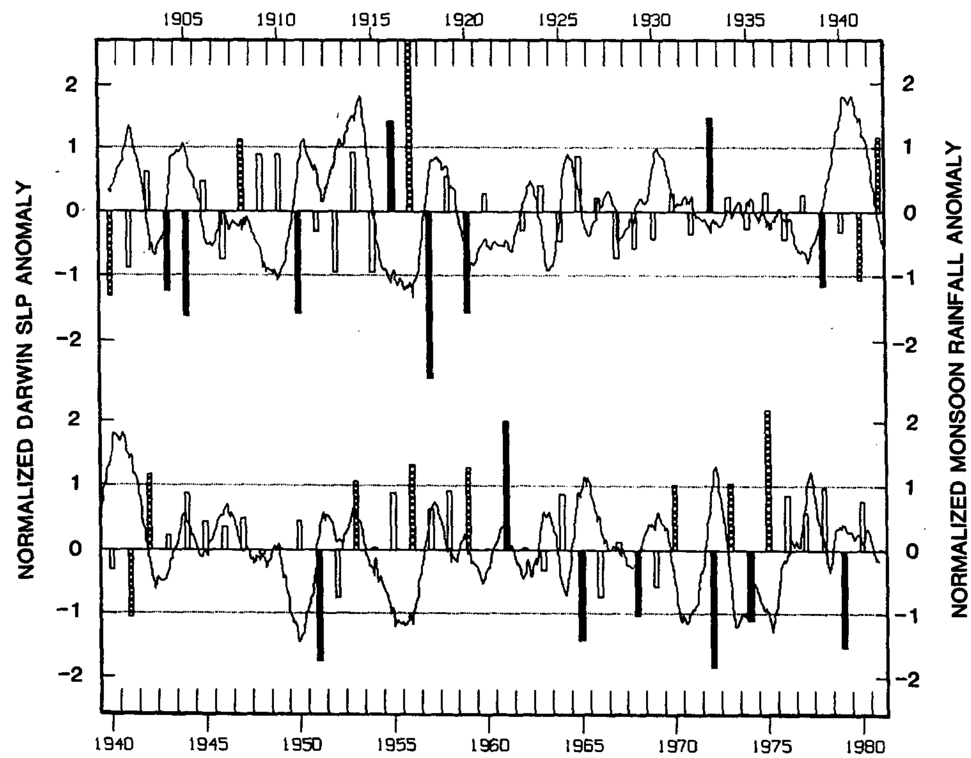

FIG. 1. Twelve-month running mean of normalized monthly Darwin pressure anomaly (thin line) and normalized Indian monsoon rainfall anomaly (bars). Years with normalized rainfall anomaly of more than one or less than minus one standard deviation are shown by solid black bars for positive, and hatched bars for negative trend of the Darwin pressure anomaly.

the normalized Darwin pressure anomaly and the bars denote the normalized Indian monsoon rainfall anomaly. For normalization, the anomaly is divided by its standard deviation. The normalized rainfall departure is larger than one standard deviation for the years 1908, 1916, 1917, 1933, 1942, 1953, 1956, 1959, 1961, 1970, 1973 and 1975; and is less than minus one standard deviation for the years 1901, 1904, 1905, 1911, 1918, 1920, 1939, 1941, 1951, 1965, 1968, 1972, 1974 and 1979. The former group of years will be referred to as the heavy monsoon rainfall years and the latter as the deficient monsoon rainfall years. In Fig. 1, all the heavy and deficient rainfall years are shown either by solid black or hatched bars, depending upon whether the trend of the seasonal Darwin pressure anomaly (March, April, May, minus December, January, February) was positive or negative.

The composite normalized seasonal mean Darwin pressure anomalies averaged for all the heavy monsoon rainfall years, and the deficient rainfall years, are shown in Fig. 2. The central block of the graph denotes the summer months for which the monsoon rainfall was considered, and the following and the preceding months are represented along the abscissa to the right and to the left of the central block. Along the ordinate are the values of the composite three-month running mean pressure anomaly. In the remainder of this paper, the northern winter season, consisting of the months December, January and February, are denoted as DJF, and the spring season, consisting of the months March, April and May, as MAM.

One of the remarkable features of this figure is the simultaneous occurrence of high (low) Darwin pressure anomaly with low (high) monsoon rainfall and the persistence of this pressure anomaly for approximately six months after the monsoon. This association of pressure anomaly and monsoon rainfall, however, is not useful for the long-range forecasting of monsoon rainfall. For the purpose of predicting monsoon rainfall, the most useful antecedent parameter appears to be the trend of the Darwin pressure anomaly before the summer monsoon season. The Darwin pressure anomaly decreases from DJF to MAM before the occurrence of heavy monsoon rainfall, and increases before the occurrence of deficient monsoon rainfall. The value of the Darwin pressure anomaly itself during the preceding DJF and MAM does not appear to be a useful parameter because its values fluctuate around zero. Because of this striking relationship between the composite Darwin pressure anomaly in the pre-monsoon months and the composite monsoon rainfall, we have examined the association between pre-monsoon Darwin pressure trend and summer monsoon rainfall over India. The Darwin pressure trend is defined as the MAM minus DJF pressure anomaly.

The correlation coefficient between the normalized monsoon rainfall anomaly and difference of normalized MAM and DJF Darwin pressure anomaly is −0.46, which, in absolute value, is higher than that

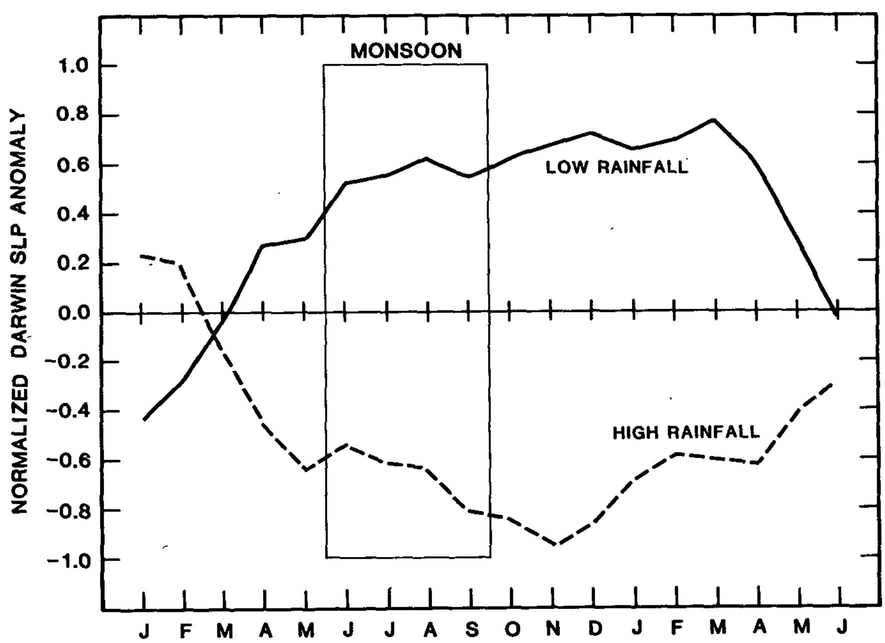

FIG. 2. Composite of normalized Darwin pressure anomaly (three-month running mean) for heavy monsoon rainfall years and deficient monsoon rainfall years.

for the normalized MAM Darwin pressure anomaly (0.32). The correlation coefficient between normalized Darwin pressure trend and rainfall anomaly is −0.42. We are not aware of any other antecedent parameter whose correlation coefficient with the monsoon rainfall is as high as −0.42 for a time series as long as 81 years.

Fig. 3a shows a scatter diagram between the normalized Darwin pressure trend and the normalized Indian monsoon rainfall anomaly. Most of the severe drought years are in the lower right quadrant, and most of the very heavy rainfall years are in the upper left quadrant of the scatter diagram. It is seen that during the 81-year period examined here, there were only two occasions when a negative Darwin pressure trend was followed by a normalized rainfall anomaly of less than −1.0. The near absence of points in the lower left corner of this scatter diagram suggests that a negative Darwin pressure trend should be a very useful predictor for the non-occurrence of drought over India. Similarly, a positive Darwin pressure trend should be a good predictor for the non-occurrence of excessive rain. This can also be seen in Fig. 1, where the solid black bars and the hatched bars represent those years for which the trend of the Darwin pressure anomaly was positive and negative, respectively, and the absolute value of the rainfall anomaly was greater than one standard deviation. It is seen that there are only two years of deficient rainfall with negative trend, and only three years of heavy rainfall with positive trend of Darwin pressure anomaly.

Rasmusson and Carpenter (1983) have identified 18 El Niño years during the 81-year period examined here, and these years have been denoted by incomplete circles in Fig. 3a. For 8 of the 18 El Niño events, the normalized rainfall anomaly is less than −1.0, and for 14 of the 18 events the rainfall anomaly has a negative sign. However, the predictive value of this relationship is limited only to the El Niño years. During the 81-year period examined here, there were 14 instances of normalized rainfall anomaly being less than −1.0, and 6 of these 14 cases were not associated with El Niño. If an El Niño event has already been observed in the preceding winter and spring, a prediction of deficient monsoon rainfall over India can be made with some degree of confidence. But the relationship between the El Niño and the monsoon rainfall applies to a limited number of years, the ones when El Niño occurs, whereas the relationship between the Southern Oscillation and monsoon rainfall is applicable for all years. Monitoring of both the parameters can provide very useful guidance for the long-range forecasting of monsoon rainfall.

It is likely that a negative trend in the DJF to MAM pressure is an indicator of below normal pressure during the monsoon season. If so, a combination of the Darwin pressure anomaly and its trend during the pre-monsoon season should provide better guidance for the anomaly of monsoon rainfall. Fig. 3b shows

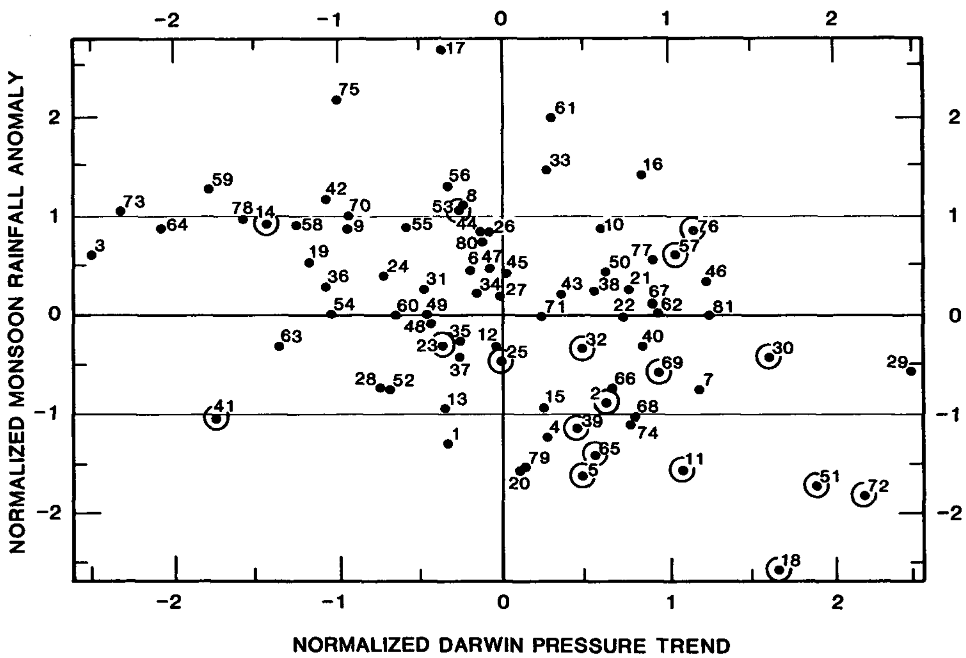

FIG. 3a. Scatter diagram between the normalized Darwin pressure trends (MAM − DJF) along the abscissa, and normalized Indian monsoon rainfall anomaly along the ordinate. The numbers denote the year (minus 1900). The El Niño years are enclosed within incomplete circles.

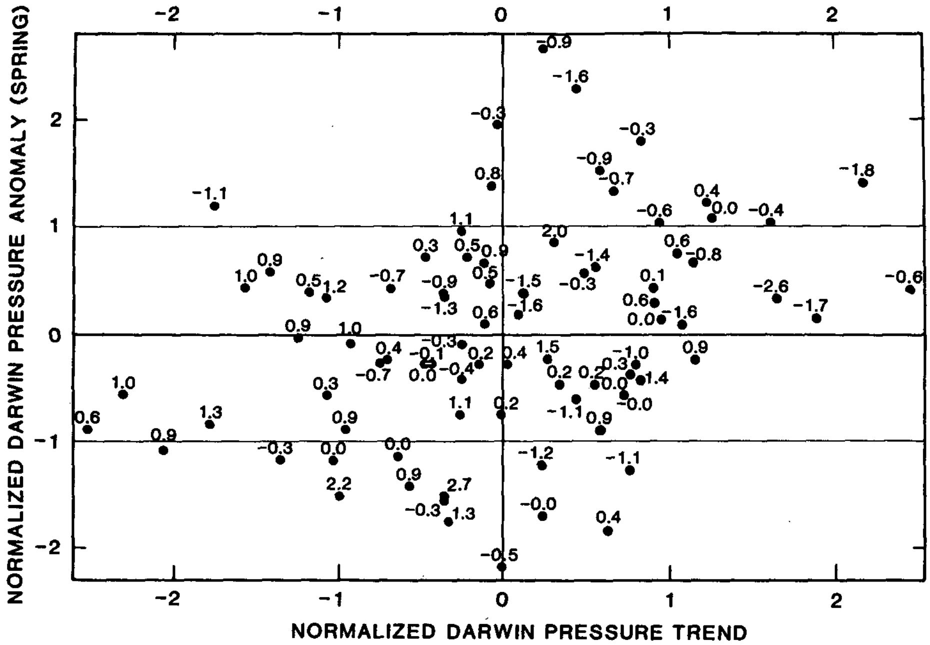

FIG. 3b. Scatter diagram between the normalized Darwin pressure trend (MAM − DJF) along the abscissa, and normalized MAM (northern spring) Darwin pressure anomaly along the ordinate. The numbers denote the normalized Indian monsoon rainfall anomaly.

a scatter diagram between Darwin pressure trend along the abscissa and normalized MAM pressure anomaly at Darwin along the ordinate. The numbers represent the normalized monsoon rainfall anomaly for each of the 81 years. Nine of the twelve years with normalized rainfall anomaly equal to or greater than 1.0 occur on the left half of the diagram for negative Darwin pressure trend, and twelve of the fourteen years with normalized rainfall anomaly less than or equal to −1.0 occur on the right side for positive

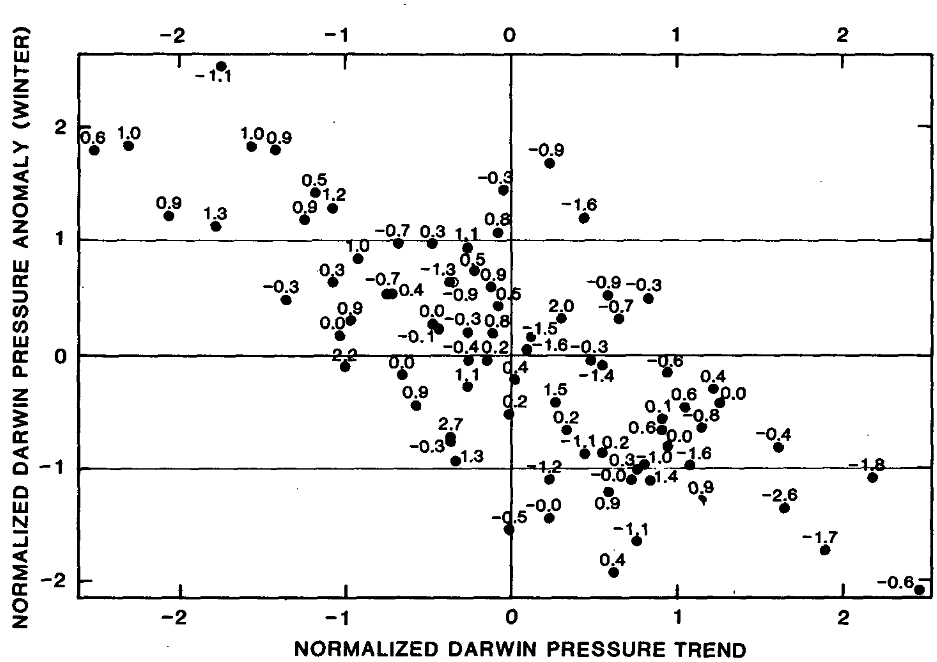

FIG. 3c. As in Fig. 3b except for the normalized DJF (northern winter) Darwin pressure anomaly along the ordinate.

values of the trend. It is remarkable that none of the 17 years with normalized rainfall anomaly close to or less than −1.0 occur in the lower left quadrant of the diagram. In fact, of the 26 years in the lower left quadrant, there was only one year (1928) when the normalized rainfall anomaly was as small as −0.7, and the remaining four negative values were not any smaller than −0.4. Similarly, most of the large negative values fall in the upper right quadrant. Of the 13 years with standardized rainfall anomaly larger than 1.0, there was only one year (1961, with a value of 2.0) in the upper right quadrant; and of the 24 years in the upper right quadrant, the rainfall anomaly was more than 0.9 only in two years (2.0 in 1961, and 0.9 in 1915). This scatter diagram suggests that if MAM Darwin pressure is lower than its normal value, and if DJF to MAM trend shows that the Darwin pressure is falling, a prediction of non-occurrence of drought over India in the subsequent monsoon season would be generally accurate; similarly, a positive anomaly in MAM Darwin pressure together with a positive trend from DJF to MAM would provide a highly reliable forecast of non-occurrence of heavy monsoon rainfall.

Fig. 3c shows a similar scatter diagram between the normalized Darwin pressure trend along the abscissa and normalized DJF Darwin pressure anomaly along the ordinate. The most prominent feature of Fig. 3c is the strong inverse relationship (correlation coefficient = −0.74) between DJF pressure anomaly and DJF to MAM trend; if DJF pressure anomaly is above normal, the DJF to MAM tendency is negative and vice versa. This suggests that the Darwin pressure anomaly is not stable during northern winter and undergoes a marked transition from DJF to MAM. However, the DJF Darwin pressure anomaly by itself has little value for the prediction of the subsequent Indian summer monsoon rainfall.

3. Influence of monsoon rainfall on the Southern Oscillation

The need for the prediction of monsoon rain makes it necessary to examine the Southern Oscillation features before the monsoon season; however, it should be recalled that one of the important findings of Walker was to show that the Indian monsoon rainfall has significant correlations with the subsequent global circulation. Normand (1953) aptly wrote,

> To my mind the most remarkable of Walker's results was his discovery of the control that the Southern Oscillation seemingly exerted upon subsequent events and in particular of the fact that the index for the Southern Oscillation as a whole for the summer quarter June–August, had a correlation coefficient of 0.8 with the same index for the following winter quarter, though only of −0.2 with the previous winter quarter. It is quite in keeping with this that the Indian monsoon rainfall has its connections with later rather than with earlier events. The Indian monsoon therefore stands out as an active, not a passive feature in world weather, more efficient as a broadcasting tool than as an event to be forecast.

Fig. 4 shows the correlation coefficient between the normalized monsoon rainfall anomaly and the Darwin pressure anomaly for six months before and six months after the monsoon season. The absolute values of the correlations are found to be the largest

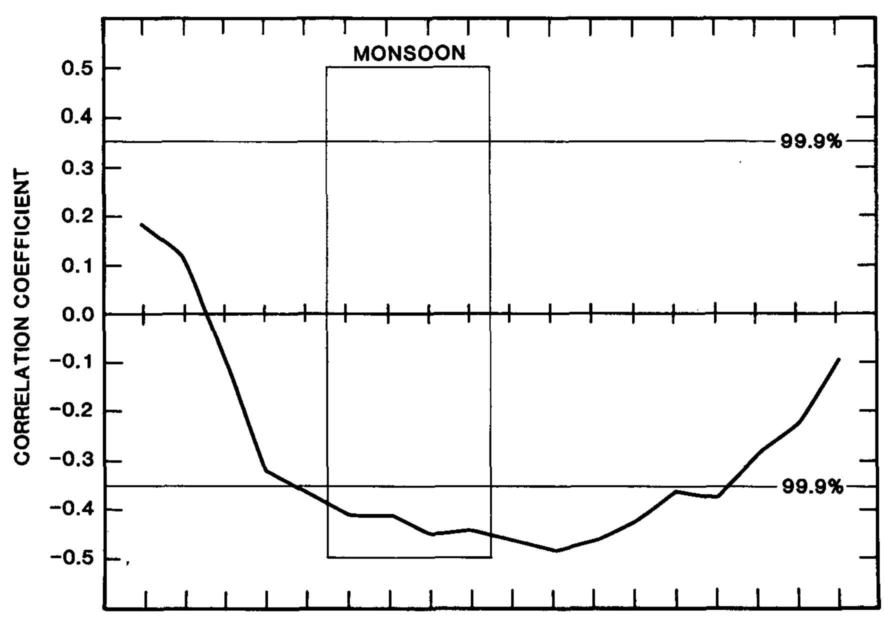

FIG. 4. Correlation coefficient between the Indian monsoon rainfall anomaly and three-month mean Darwin pressure anomaly at various lags.

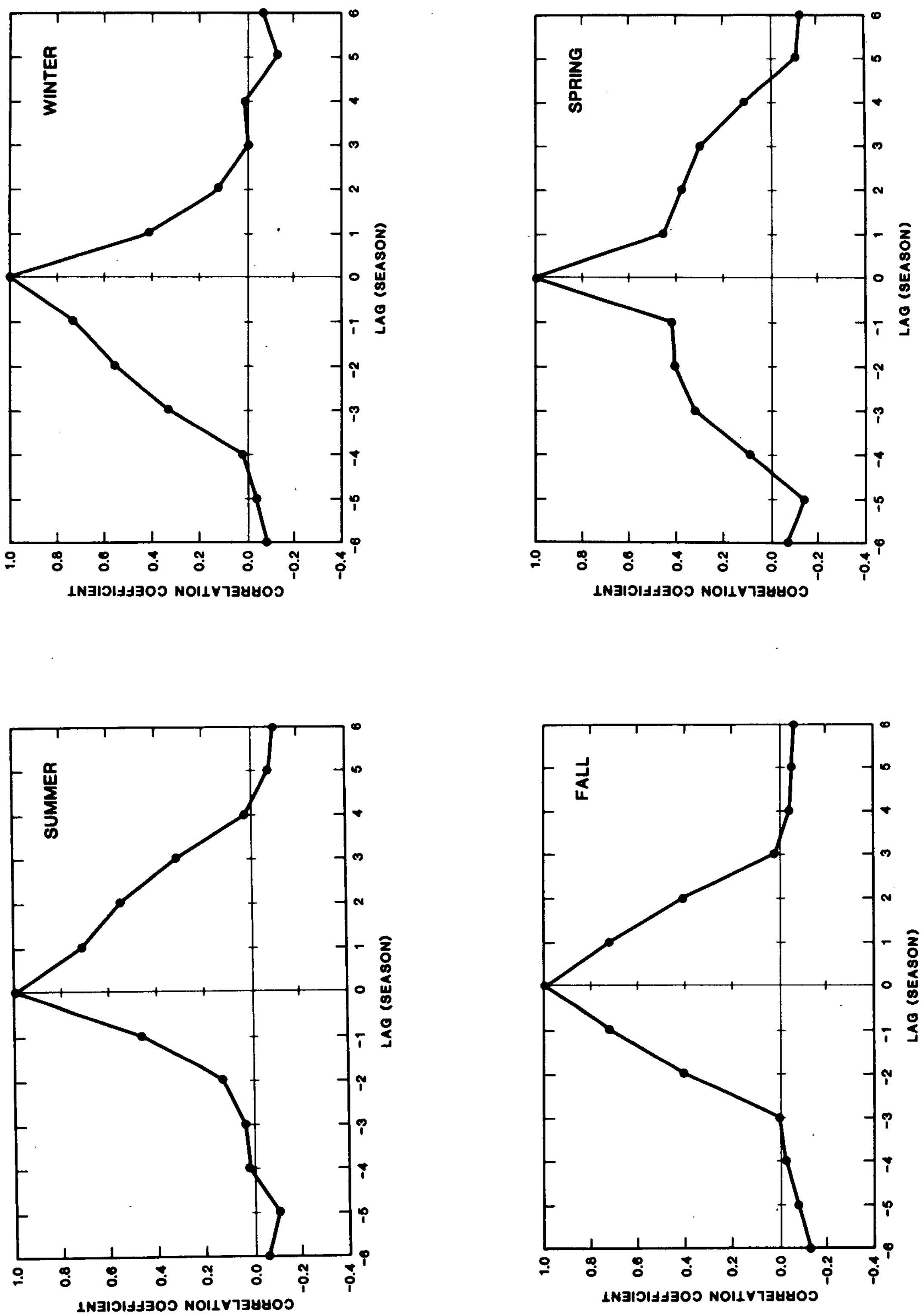

FIG. 5. Autocorrelation of northern summer (June, July, August), fall (September, October, November), winter (December, January, February) and spring (March, April, May) seasonal mean Darwin pressure anomaly at various lags.

during and following the monsoon season, suggesting the possible role of the monsoon rainfall fluctuations (and the associated changes in the location and intensity of diabatic heating fields) in affecting the subsequent global circulation. The correlation coefficient between the monsoon rainfall and the Tahiti minus Darwin pressure was very similar to the one shown in Fig. 4 with opposite sign.

Fig. 5 shows the autocorrelation of seasonal mean Darwin pressure anomaly at different seasonal lags. In agreement with the earlier results of Walker, the largest correlation between adjacent seasons is found between the northern summer and fall, and the fall and winter pressure anomalies. The smallest correlations between adjacent seasons are found between northern winter and spring, and spring and summer. We do not know why the autocorrelations have such a strong seasonal dependence. Nicholls (1979) has suggested that the air-sea interaction over the Indonesian region can explain the seasonal variation of autocorrelation of Darwin pressure. It is also possible that the slow decay of autocorrelations from summer to fall and from fall to winter is related, at least in part, to the impact of the summer monsoon rainfall on the planetary-scale circulation.

4. Discussion and summary

The observational evidence presented here, taken with a large body of earlier results, show a close relationship between the El Niño, the Southern Oscillation and the Asiatic summer monsoon. We have neither proposed nor explained any mechanisms, but simply presented some observational facts which appear to be useful for operational forecasting. It is difficult, at this stage, to clearly identify the forcing and the response, but it is reasonably clear that these three phenomena influence or are influenced by each other at different stages of their life cycle. Angell (1981) found a strong relationship between the monsoon rainfall and the equatorial sea surface temperature (SST) anomalies in the following winter, but Rasmusson and Carpenter (1983) showed that the equatorial Pacific SST anomalies have a long life cycle and, therefore, since the SST anomalies are observed even before the monsoon season, they can be a potential predictor for the monsoon rainfall. Since the El Niño and Southern Oscillation are intimately linked (Rasmusson and Carpenter, 1983), the antecedent Southern Oscillation can also be a useful predictor of monsoon rainfall. The present study has demonstrated that the phase of the Southern Oscillation is a better predictor of monsoon rainfall than its spring or winter value. Although the mechanisms of interactions between El Niño, Southern Oscillation and monsoons are not well understood, the predictability of monsoon rainfall is especially enhanced due to its precise seasonality and the long-period changes associated with the Southern Oscillation. Large changes in the monsoon rainfall naturally influence the subsequent atmospheric circulation which may influence the rainfall of other regions. Since it is appealing to think in terms of forcings due to diabatic heat sources and sinks, the changes in heating associated with the warm SST anomalies in equatorial Pacific, and those due to the fluctuations of monsoon rainfall, seem to be the two most important forcing functions for atmospheric circulation anomalies. A global distribution of observed precipitation would be needed to test these concepts further.

In the present paper we have shown that the Darwin pressure and its trend can be utilized to make highly reliable forecasts of the non-occurrence of droughts or heavy rains over India. This was, however, only a preliminary study, and further analysis might provide more quantitative relationships.

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REFERENCES

Angell, J. K., 1981: Comparison of variations in atmospheric quantities with sea surface temperature variations in the equatorial eastern Pacific. *Mon. Wea. Rev.*, **109**, 230–243.

Chen, W. Y., 1982: Assessment of Southern Oscillation sea-level pressure indices. *Mon. Wea. Rev.*, **110**, 800–807.

Hildebrandsson, H. H., 1897: Quelques recherches sur les entres d'action de l'atmosphere. *Kon. Svenska Vetens.-Akad. Handl.*, **29**, 33 pp.

Jagannathan, P., 1960: Seasonal forecasting in India. A review. India Meteor. Dept., Special Publ. DG0.82/650 [Available from Director General, Lodi Road, New Delhi-3, India].

Lockyer, N., and W. J. S. Lockyer, 1902: On the similarity of the short-period pressure variation over large ares. *Proc. Roy. Soc. London*, **73**, 457–470.

Nicholls, N., 1979: A simple air-sea interaction model. *Quart. J. Roy. Meteor. Soc.*, **105**, 93–105.

Normand, C., 1953: Monsoon seasonal forecasting. *Quart. J. Roy. Meteor. Soc.*, **79**, 463–473.

Pant, G. B., and B. Parthasarathy, 1981: Some aspects of an association between the Southern Oscillation and Indian summer monsoon. *Arch. Meteor. Geophys. Bioklim.*, **B29**, 245–252.

Rao, K. N., 1965: Seasonal forecasting—India. WMO Tech. Note No. 66, 17–130 [WMO No. 162.TP.79.].

Rasmusson, E. M., and T. H. Carpenter, 1983: The relationship between eastern equatorial Pacific sea surface temperatures and rainfall over India and Sri Lanka. *Mon. Wea. Rev.*, **110**, 517–528.

Shukla, J., 1983: Interannual variability of monsoons. Chap. 5.3 *Monsoons*, J. S. Fein and P. L. Stephens, Eds., Wiley (in press).

Trenberth, K. E., 1976: Spatial and temporal variations of the Southern Oscillation. *Quart. J. Roy. Meteor. Soc.*, **102**, 639–653.

Walker, G. T., 1923: Correlations in seasonal variations of weather, VIII. *Mem. India Meteor. Dept.*, **24**, 75–131.

——, 1924: Correlations in seasonal variations of weather, IX. *Mem. India Meteor. Dept.*, **24**, 333–345.

Wright, P. B., 1975: An index of the Southern Oscillation. Climate Research Unit, Rep. CRU RP4, Norwich, U.K., 22 pp.