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On foreshadowing southwest monsoon rainfall over India with mid-tropospheric circulation anomaly of April

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ABSTRACT. In recent years there have been attempts to relate the distribution of rainfall of Indian southwest monsoon with antecedent upper air factors near the scene of activity for the purpose of long range forecasting. Several upper air factors are critically examined in this context to make a judicious selection. It is found that the total monsoon rainfall over the country is significantly correlated with the latitudinal position of the sub-tropical ridge on the mean circulation chart of April at 500 mb level. A regression equation is developed with a sample data for a period of 21 years (1950-1970). On testing the regression equation for an earlier eleven-year period (1939-1949) and a later five-year period (1971-1975), it is observed that the average deviation between computed and actual southwest monsoon seasonal rainfall distribution turns out to be 6 per cent, which is quite encouraging.

Years, when the sub-tropical ridge at 500 mb in April is poleward of the normal position are followed by good monsoon rainfall distribution while years when the ridge is equatorward of the normal position are followed by poor southwest monsoon rainfall. The study specially brings out that it may be possible with this technique to obtain an indication, in early May, about the probability of occurrence of a highly deficient southwest monsoon season. Such an advance indication of a probable extreme sub-normal rainfall year would be of vital economic significance in the execution of such weather dependent projects as water resources planning, power distribution adjustment, alternative food production programmes etc.

1. Introduction

The Indian economy is so intimately linked with the rainfall during the southwest monsoon months, June to September (this accounts for over 75 per cent of the annual rainfall over large parts of the country) that foreshadowing the large scale features of this rainfall in space and in time is perhaps, the most fundamental problem of Indian meteorology. Because of its great practical importance this problem has engaged the attention of meteorologists in India ever since the India Meteorological Department came into existence a century ago. In recent years, the needs of agricultural planning for feeding a rapidly growing population have brought this problem very much to the forefront.

Early attempts in seasonal forecasting — The monsoonal circulation is the largest perturbation of the general circulation of the atmosphere affecting the entire eastern half of the northern hemisphere. The problem of prediction of the vagaries of the monsoon is quite complex, by no means a simple and straight forward one. Before upper air data became available and the three dimensional nature of the atmospheric circulation began to be comprehended, efforts to foreshadow monsoon rainfall over the country necessarily had to be based on surface meteorological parameters, antecedent to the onset on the monsoon rains in May-June. The classic work in this direction was that of Sir Gilbert Walker during the period 1904-1924, when he was the Director General of the India Meteorological Department. His approach to the problem was a skilful combination of physical insight and mathematical ability (Walker 1925). Presuming that the monsoon rainfall, which is the outcome of a large scale seasonal atmospheric circulation, should have associations with antecedent surface features not only over India but also over other parts of the globe, Walker embarked on a comprehensive correlation study for selection of predictors and evolved a statistical regression technique for foreshadowing the monsoon rains over large parts of the country in terms of their departures from normal.

Revision of formulation—The Walker formula for foreshadowing monsoon rainfall has undergone some revision in subsequent years. In particular, certain upper air parameters have been incorporated as predictors in the regression equations (Jagannathan 1960).

While the modified Walker formula is the current technique in the Department for foreshadowing the monsoon rainfall, there has been increasing realisation in recent years that a critical and systematic examination of the large volume of upper air data that are now at our disposal should be undertaken for a fresh approach to the problem. The results of one such study are reported in the present paper.

2. The tropospheric ridge and its seasonal migration

An important feature of the tropospheric circulation over India is the sub-tropical ridge and its seasonal north-south migration. In Fig. 1 are shown the latitude-height profiles of the ridge axis along the meridian of 75°E across India for the months January to June. The ridge can be located at all tropospheric levels from 850 to 100 mb levels during the months January to April. It will be seen that in these months the mean position is around 17° to 18° N upto 700 mb, above which the axis of the ridge slopes equatorwards upto about 200-150 mb; aloft, the slope reverses (Ramage and Raman 1972).

In May, the ridge cannot be located at 850 mb but can be traced at 700 mb and aloft. The ridge slopes equatorwards from 20° N at 700 mb to 15°N at 300 mb above which it is more or less vertical with little tilt. In June, the ridge can be traced above 500 mb sloping polewards from 23°N at the mid-troposphere to about 27°N at 150 mb. The large northward shift of the ridge axis from May to June is noteworthy.

A point of interest is that at 500 mb level the seasonal movement of the ridge axis from January to May towards the north is regular and organised

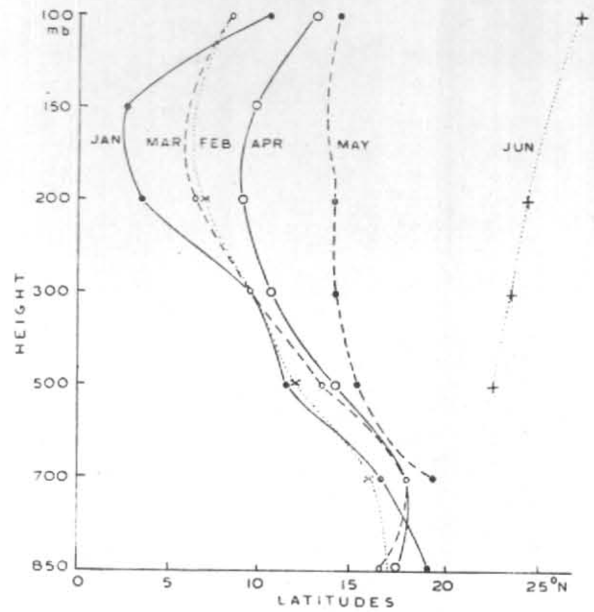

Fig. 1. Location of sub-tropical ridge at 75°E longitude

when we are considering the normal based on a large number of years, which is the data on which Fig. 1 is constructed. This is not the case at levels at or below 700 mb. Also, at 300 mb the mean ridge position shows little change from January to March while the shift is rapid from April-May.

Significance of 500 mb level—It is known that the winter circulation prevails in the upper troposphere over north India upto the beginning of May while summer conditions begin to get established in the lower troposphere over Peninsular India by March. The winter circulation over north India is essentially extra-tropical, characterised by the periodical passage of deep troughs in the westerlies of the upper troposphere while the tropical easterly disturbances are most pronounced in the lower troposphere over the southern parts of the Peninsula. The mid-tropospheric 500 mb ridge in April is the transition zone between the westerly sub-tropical regime of the upper troposphere to its north and the easterly tropical regime of the lower troposphere to its south.

Association between 500 mb ridge axis and monsoon rainfall—The present study is based on the location of the 500 mb ridge axis in the mean monthly upper wind chart for April and its association with the behaviour of the subsequent southwest monsoon rainfall for that year. Data for the period 1939-1975 have been examined.

Pilot analysis —To focus atention on the nature of the association that the study has brought about,

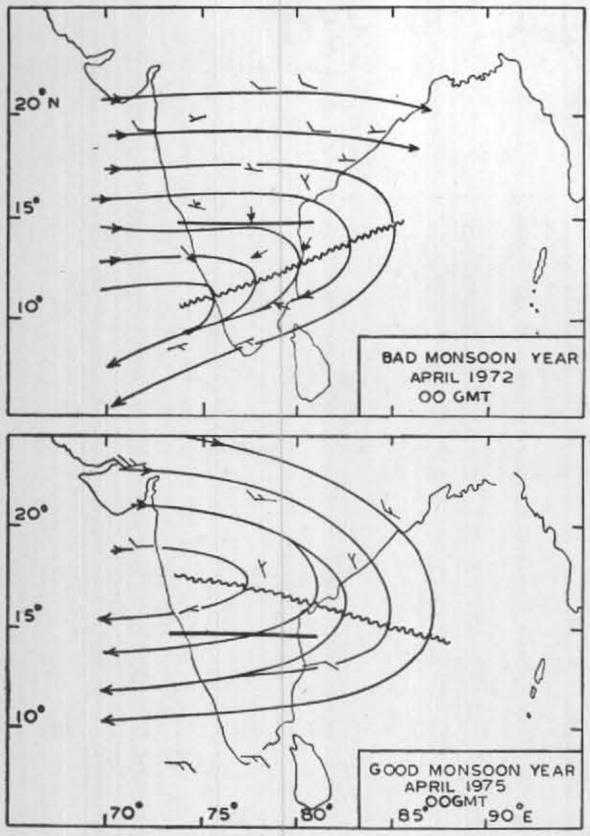

Fig. 2. Mean flow at 500 mb level

the location of the 500 mb ridge in April for two recent years of contrasting monsoon rainfall activity are shown in Fig. 2. It will be seen that in 1972, which was a year of highly deficient rainfall (one of the worst on record) the ridge axis was located markedly southward, nearly 3·5 degrees of latitude equatorward of the average position along 75°E. The wind flow on either side of the ridge axis was weak and disorganised. On the other hand, in 1975, which was a year of excellent monsoon rains the ridge was located, along the meridian 75°E as much as 3·5 degree of latitude north of the mean position.

The normal position of the ridge axis is shown by the thick line along 14·25°N on both the charts. In the chart for 1975, the wind flow on either side of the ridge axis is well defined and even moderately strong.

Application to other years — Having noticed such large differences in the location of the 500 mb ridge in selected years of contrasting monsoon rainfall activity it was decided to undertake a systematic study for the entire period for which upper wind data are available and to derive a regression relationship between the latitudinal location of the 500 mb ridge in April and the performance of the ensuing southwest monsoon rainfall for the years.

3. Method of analysis and results

Utilising all available upper wind summaries (rawin and pilot balloon) of 00 GMT of April, mean upper air charts were prepared, year by year, for the twenty one year period 1950 to 1970. April mornings being relatively cloud free, 500 mb was reached by many pilot balloon ascents and the wind summaries were thus unbiassed. It was noticed that, over Peninsular India, the western end of the sub-tropical ridge was more marked than its eastern end. The position of the western end of the ridge along the meridian 75°E at 500 mb in April, could, therefore be scaled year by year with an accuracy of half degree of latitude.

Seasonal rainfall distribution during monsoon— Distribution of seasonal rainfall is generally described sub-divisionwise and for this purpose, the country has been divided into 31 sub-divisions (as on 1971). Sub-divisional normals worked out on the basis of long-term records are used for describing seasonal rainfall. In describing weekly rainfall distribution, the departmental convention categorises rainfall, in each sub-division as normal (departure between +19% to —19%) deficient (departure from normal between —20% to —59%), scanty (departure of —60% or less) and excess (departure of +20% and above). While delineating seasonal distribution, the departmental convention classifies precipitation normal (—10% to +10%), slight deficit/excess (±11% to ±25%), moderate deficit/excess (±26% to ±50%) and large deficit/excess (≷±50%). These categorisations do not help to reflect realistically total monsoon rainfall over the country as a whole on account of large disparity in the spatial areas of the sub-divisions. The ideal approach would be to obtain a ratio of the year's rainfall over the plains of the country in relation to the long term average. This is a time consuming process. To start with, a rainfall parameter was evolved for the purpose of this study, to represent seasonal rainfall distribution, over the plains of the country in relation to the long term average.

Regression equation—An attempt was then made to link the year to year positions of the sub-tropical

TABLE 1

Year	Value of L	Value of R		Deviation	Average deviation (%)
		Actual (%)	Computed (%)		
1975	17°30′	97	100	3	
1974	13°30′	63	71	8	
1973	16°45′	97	94	3	
1972	11°00′	32	57	25	
1971	16°45′	77	94	17	
1949	17°00′	90	96	6	6 (excluding the value obtained in 1972) and 7.2 taking 1972 into account.
1948	14°30′	87	78	9	
1947	18°00′	100	100	0	
1946	17°15′	97	98	1	
1945	16°45′	97	94	3	
1944	14°30′	87	78	9	
1943	16°00′	94	89	5	
1942	17°30′	94	100	6	
1941	11°15′	62	58	4	
1940	15°30′	94	85	9	
1939	14°00′	68	75	7	

ridge at 500 mb, along 75° in April (L) with the rainfall parameter R in the succeeding monsoon season. The evolved rainfall parameter, R, was defined as the ratio of the number of sub-divisions having normal or above normal rainfall distribution in June-September (—19% to +19% or greater) to the total number of sub-divisions (31) in the country, expressed as a percentage. That is, if the monsoon rainfall is normal or above normal in 28 out of 31 sub-divisions, R will be assigned a value of about 90% and so on. Using actual values of L and R for the period 1950-1970, a regression equation, giving the best fit, was obtained as under—

$$R^{1/3} = 0{\cdot}1237\ L + 2{\cdot}4772$$

(The above relationship is valid upto L=17°30′ N where R=100. If L is more than 17°30′ N, then R should be taken as 100).

The above relationship was subjected to the Chi-square and Student's 't' tests and no significant difference between the actual and theoretically calculated values of R was obtained.

4. Application to individual years

The equation was tested for a few years outside the selected sampling period (*i.e.*, 1950-1970) and the results are given in Table 1.

5. Discussion

One serious shortcoming of the conventional regression technique in use in the Department for making long range rainfall forecast is that it fails to identify the extreme years especially the highly deficient rainfall years. The new regression tool now under test (Table 1), however, seems to help identify highly sub-normal years (say 1951, 1972 and 1974) reasonably well.

Out of the 21 years (1950 to 1970) used for developing the regression equation, only in 1963, the existence of the ridge at 500 mb over the Peninsula could not be clearly delineated. The ridge was, however, seen over the Bay of Bengal but was not well marked. There was marked activity of both westerly troughs of middle latitudes and of easterly troughs of low latitudes over the Indian sub-continent upto the beginning of third week of April 1963. This might have been responsible for obliteration of the ridge at 500 mb in April of that year. In all other years the position of the ridge was delineated as accurately as possible on the mean charts specially constructed year by year for the purpose. The kinematic technique of analysis adopted might account for an error in the position of the ridge of less than half a degree of latitude.

The results of the test of validity of the regression equation developed as applied to the years 1939 to 1949 and to the subsequent years 1971 to 1975 appear encouraging. The average deviation between the actual and computed values of R obtained from the application of the regression equation works out to be 6% excluding the highly sub-normal year 1972. In the extreme year of drought, *viz.*, 1972, the equation yields 57% at the computed value of R which means 14 sub-divisions. In another deficient year 1941, the expected and actual number of deficient sub-divisions were respectively 14 and 13; the corresponding figures for yet another deficient year 1974, were 12 and 10. Thus, the technique now evolved has helped to identify, with sufficient degree of confidence, extreme years of monsoon rainfall activity, especially highly deficient rainfall years like 1941, 1972 and 1974. However, it may not be possible to anticipate in which sub-divisions deficiency might actually occur.

A composite chart was prepared for 500 mb April for four good monsoon years (1956, 60, 70 and 75) and compared with that for four bad years

(1951, 65, 66 and 72). The ridge locations displayed characteristics similar to good and bad monsoon years. One feature, however, stood out in the good years compositie, *viz.*, that of well pronounced westerly and easterly winds on either side of the ridge. In the bad years composite, the wind field was weak and disorganised.

The parameter used (500 mb ridge during April) describes an upper air atmospheric circulation feature of the Indian sub-continent. Unlike many other surface parameters used for nearly a century, this is close to the scene of monsoon activity. The application of the method is also simple. It has a potentiality for foreshadowing the probable distribution of seasonal rainfall about a month prior to the onset of the southwest monsoon. An idea about the efficacy of this technique can be had from Fig. 3, where the displacement of the sub-tropical ridge (on the April mean chart at 500 mb level) from its average position year by year for the period 1939 to 1975 has been indicated together with the number of sub-divisions where the total monsoon rainfall (Jun-Sep) was actually deficient and expected to be deficient as per the regression equation. The agreement between actual and computed number of deficient sub-divisions is quite encouraging. Then again in those years when the sub-tropical ridge was much south of its average position in April, the number of sub-divisions (both actual and computed) where subsequent monsoon rainfall was deficient, was also large.

In this context, it is worth recalling Ramage's remarks: 'The immense effect of direct solar heating of the deserts and of latent heat release from the great pre-monsoon thunderstorms of the Indian sub-continent on the atmosphere over India lead one to think that future monsoon rains may well be more closely related to previous local rather than far-off events. Certainly this new approach is worth a fair trail....'(Ramage 1971).

Herein, two very relevant questions come to mind: 'How far is it justified to forecast the probable distribution of monsoon rainfall on the basis of a synoptic parameter of April?' 'What is the physical linkage between the two?' A partial explanation is attempted.

The Indian summer monsoon is a part of the general atmospheric circulation. The zonal pattern of weather associated with the general circulation moves meridionally with the season. The southwest monsoon circulation system is

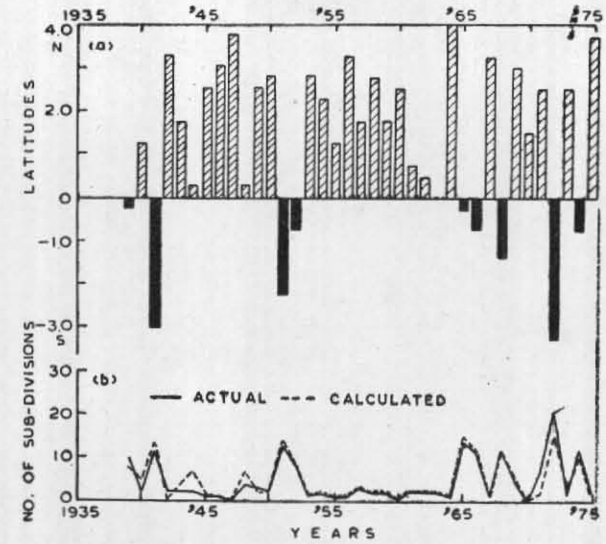

Fig. 3. April 500 mb ridge position and distribution of southwest monsoon rainfall (1939-1975)

(a) Deviation of ridge axis from long term average location (degrees latitude).

(b) No. of sub-divisions in which rainfall was actually deficient (——) compared to calculated deficiency (- - -).

semi-hemispherical in extent. A small 'circulation anomaly' in the degree of organisation of the southwest monsoon system may be brought about by perturbations due to regional imbalances in radiation input and resulting smaller scale weather systems. Such a 'circulation anomaly' though it may appear inconsequential, may manifest as a significant retarding factor on the progress of seasonal migration of zonal weather over the Indian sub-continent and result in an anomalous distribution of seasonal rainfall. The mechanism may be somewhat akin to the 'turbulence burst' visualised by Ramage (1976). The mechanism by which the major monsoonal framework gets influenced by this 'circulation anomaly' needs to be understood.

Now, the sub-tropical ridge in the tropospheric levels being a permanent feature of the general circulation, its progress of movement northwards is expected to throw some light as to how the monsoon circulation would organise itself in the season. As stated before, the maximum consistency in the northward movement of the ridge during the pre-monsoon months was noticed at 500 mb level. April being the peak summer month in Peninsula, it is expected that the position of the 500 mb ridge in this month in relation to its normal position would bring out the so-called 'circulation anomaly' on which the performance of the following monsoon depends to a large extent.

In recent years, dynamicists (Lorenz 1969) aver that the atmosphere possesses an intrinsic range of predictability and that this might be around a month. Against this background, a simple initial test of physical reality was attempted between the 500 mb ridge location in April and the subsequent southwest monsoon activity. For this purpose, year-to-year 500 mb ridge location was correlated with the rainfall parameter R for the months June, July, August and September. It was found that the ridge position was insignificantly correlated with June rainfall while the correlations for July, and August were 0·51 and 0·60 respectively. In September, the correlation reduced to a lower value of 0·47. This ordering of correlations just about guarantees that no tangible physical explanation is immediately possible from the dynamic point of view. As a follow up of this investigation, it seems worthwhile examining whether the locations of the ridge positions of May/June have any correlation with rainfall distribution of August/September.

There may be a surface parameter linked with this 500 mb ridge position in April. Pre-summer distribution of solar radiation components between south Peninsular India and the sea-areas further south on the one hand and the large Indian subcontinent to the north may be a dominant factor. These aspects are separately under investigation.

6. Limitations of the technique

The new predictor used in this study pertains to year-to-year variation of the ridge at 500 mb level (6·0 km). 500 mb is in a transition zone between winter (upper) and summer (lower) circulations and presumably complexly reflects both. A regression combining the relation between the location of the axes of the ridge at 700 mb (3·0 km) and 200 mb (12.0 km) and monsoon rainfall distribution seems worth attempting.

In developing the regression, the parameter describing monsoon rainfall distribution R has been chosen to relate to a departure (—19% to +19% or greater) of seasonal sub-divisional precipitation, to describe normal or above normal rainfall. This limit is large compared to the departmental convention of —9% to +9% for normal distribution of seasonal rainfall. A limit of ±19% accounts for a large variability in sub-divisional precipitation than ±9% and has fortuitously yielded a higher correlation coefficient.

Again, the 500 mb ridge position yields a significant and high correlation coefficient (0·66) with total precipitation of the division 'Peninsula' employed in the departmental long range forecast memorandum. The correlation with northwest India precipitation is, however, small. On the other hand, R used as an index of total monsoon precipitation over the country as a whole, has yielded initially a high correlation (0·82) of some practical value. It seems desirable to give thought to the evolution of an index based more on actual rainfall distribution of a representative network than one of an arbitrarily chosen rainfall departure.

Finally, the authors are conscious of the impermanence of initially promising large correlations. This is borne by the experience of the behaviour of predictors in use in the long range forecast formulation of the Department as well as those of other investigators in the field. There is scope for further refinement of this work by computing mean resultant winds for 500 mb level of April for the entire period of data sample, namely, 1939-1975, comparison of ridge locations of individual years with the mean ridge positions obtained from such a long period homogenous sample, and choice of varying lengths of data sample for regression equation. Yet another aspect of improvement of the study could be through computation of mean vorticity fields.

7. Conclusion

Despite the above considerations, the attempt now made to associate an India based, easily compilable upper air parameter with subsequent total monsoon rainfall distribution seems to provide a reasonably acceptable tool to forewarn planners about a month ahead of the probability of occurrence of a highly deficient southwest monsoon seasonal rainfall year.

The position of the sub-tropical ridge on the April mean charts for 1976 along 75°E meridian is approximately 17°N. On the basis of the regression equation, our expectation in early May 1976 was that the monsoon rainfall for 1976 in the country might be normal except for a deficiency in 3 or 4 sub-divisions.

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REFERENCES

Jagannathan, P. 1960 *Seasonal Forecasting in India—A review.* India met. Dep.

Lorenz, E. N. 1969 *Tellus*, **21**, pp. 289-307.

Ramage, C. S. 1971 *Monsoon Meteorology*, p. 241, Academic Press, New York and London.

1976 *Bull. Amer. met. Soc.*, **57**, **1**.

Ramage, C. S. and Raman, C. R. V. 1972 *Meteorological Atlas of the International Indian Ocean Expedition*, **2** (upper air). National Science Foundation, Washington, D.C.

Walker, G. T. 1925 Weather and Long range forecasting, *Discovery, London*, **6**, p. 100.