Breaks in the Indian summer monsoon as a phenomenon of interaction between the easterly and the sub-tropical westerly jet streams[1]

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ABSTRACT

The present paper contains the results of the study of a synoptic situation over India during a period of 8 days in which normal monsoon conditions were followed by a break and were further followed by a return to normal monsoon. This study has shown that during breaks in the monsoon, a trough in the middle latitude westerlies with a jet embedded in it increases considerably in its amplitude and gets retarded as it moves into the Tibetan Plateau on account of its entering a region of weaker basic current. The large-amplitude trough weakens or destroys completely the Tibetan high at the 500 mb level and appreciably weakens the easterlies at the higher levels to the south of the Himalayas. Protruding into India and Pakistan, the large amplitude trough contributes to the development of heavy rainfall along and near the foot of the Himalayas which is characteristic of the break conditions. The southward protrusion of the trough and its subsequent movement eastward, is also indirectly responsible for a corresponding shift of the high over Iran and Arabia, which, in its turn, seems to lead to the formation of a secondary jet core in the easterlies west of 80° E between 20° N and 25° N. Consequent on the above developments, the westerly jet which had retreated to the north of the Himalayas at the time of the onset of the monsoon re-enters the Indo-Pakistan sub-continent during the breaks. Thus we see during break conditions, the remarkable spectacle of two jets of entirely different types—the easterly and the sub-tropical westerly—within a short latitudinal distance of each other and dynamically interacting with each other.

The above detailed study, supplemented by a general examination of the monthly mean 700 mb charts for the northern hemisphere for a period of 10 years, suggests that active monsoon over India is closely associated with high index circulation in middle latitudes over Asia and neighbourhood, while weak monsoon is closely associated with low index circulation over the same region.

1. Introduction

The Indian Summer monsoon, better known in India as the southwest monsoon, is perhaps the most important and well-developed secondary circulation in the atmosphere, exercising a very significant influence on the general circulation. The monsoonal circulation over India generally lasts from June to September, July and August being considered as the typical monsoon months, when the circulation is more or less a steady feature over the major part of the country. During these two months, the equatorial trough better known among Indian Meteorologists as the "monsoon trough" lies steadily over the Gangetic plain stretching roughly from 30° N 75° E to 23° N 88° E. The monsoon period, including July and August, is however not a period of steady rains all over India. Nor is the activity of the monsoon uniform from year to year even in July and August. While in some years the monsoon activity is well-maintained over a whole month, in some other years there are well-defined large-scale interruptions in the rains, generally lasting from 3 to 10 days at a time. These interruptions in the monsoon rains are known as "breaks" in the monsoon.

[1] The material contained in this paper was presented by the author in a Seminar in the International Meteorological Institute in Stockholm on April 28, 1961.

One of the most well-known facts connected with the break-conditions is the shift of the monsoon trough from the normal position indicated above to the foot of the Himalayas, the axis of the trough very roughly extending from 32° N 75° E to 26° N 90° E (RAMASWAMY, 1958). The other equally well-known fact connected with the breaks is the occurrence of heavy rainfall along and near the foot of the Himalayas.

A survey of all the available literature prior to 1956 shows that there has been considerable emphasis on the changes which take place in the lower troposphere and at sea level in association with the break. Koteswaram had, however, discussed in a short note about upper level (700 mb) lows in *low latitudes* in the Indian area during southwest monsoon season and breaks in the monsoon (KOTESWARAM, 1950).

Since 1956, there has been a distinct shift in the emphasis from the small changes at the surface and lower troposphere to the large changes in the middle and upper troposphere during break-conditions (KOTESWARAM, 1956; RAMASWAMY, 1958; KOTESWARAM, 1958, 1960; and PISHAROTY & ASNANI, 1960).

In addition to the above, a few authors (PISHAROTY & B. N. DESAI, 1956; FLOHN, 1957) have made, on the basis of their general synoptic experience, certain very brief and general statements about middle or upper tropospheric conditions associated with breaks. As far as the present writer is aware, these authors have not published any synoptic charts in support of their statements.

In 1958, the author (RAMASWAMY, 1958) published a number of synoptic charts and vertical time-sections to show that the variations in the mid-tropospheric flow patterns over and to the north of India during active and weak summer monsoon spells are far greater than the variations in the moisture content of the air or the positions of the monsoon trough at sea level or the streamline convergence in the lower tropospheric wind field. The author has also produced adequate synoptic evidence to show that breaks in the monsoon were associated at the 500 mb level with an extension of a large amplitude trough from the higher middle latitudes into sub-tropical Indo-Pakistan. On the other hand, active monsoon conditions were found to be associated at the 500 mb level with easterlies sweeping over northern India with an extensive high over Tibet and a concentration of zonal westerlies further to the north.

These conclusions were based on a study of the daily sea level and upper air charts for the Asiatic continent for July 1953, a month of unusually active monsoon, and August 1954, a month of prolonged breaks in the monsoon. Unfortunately, in these charts, no data were available over Sinkiang, Mongolia and China. The conclusions drawn on the basis of these analyses were, therefore, necessarily, of a broad nature.

2. Data utilised and methods of analysis in the present study

The author has since had access to the 500 mb charts for 00 GMT published by the Meteorological Service of the Chinese Republic. These contained a good coverage of data over Sinkiang, Mongolia and China and over the Tibetan Plateau, besides the data over U.S.S.R. and Eastern Europe. Consequently, the analysis over these regions was much more definite than in the earlier paper.

The data contained in these Chinese charts along with the data for Pakistan and other Southern Asian countries as published in the Indian and Pakistan Daily Weather Reports and Overseas Supplement to the Daily Weather Reports of the United Kingdom were utilised in the preparation of the charts for the present study.[1] The data for India were taken from original scrutinised registers available in the India Meteorological Department. In drawing contours over the Indian Region, much greater weight was given to the winds than to the radio-sonde values on account of the errors in the radiosonde data (RAMASWAMY, 1956). For a few Indian stations for which 00 GMT actual wind data were not available, the winds for that hour were computed by working out the mean of the winds for 12 GMT of that day and 12 GMT of the previous day.

Vertical time-sections for a large number of stations in India and Pakistan and daily cross-sections of the zonal winds along the meridian

[1] A brief abstract of some of the results contained in the present paper has appeared in the proceedings of the *Symposium on Monsoons of the World*, India Meteorological Department (1960).

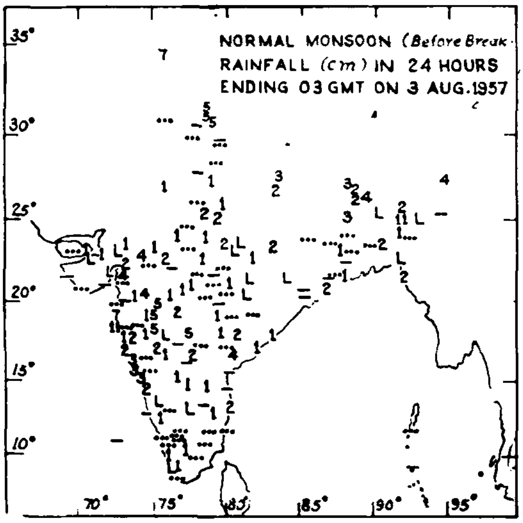

FIG. 1. Normal monsoon conditions over India before the onset of break conditions. Rainfall in 24 hours ending at 03 GMT on August 3, 1957. The symbol ... denotes rainfall between 0.01 and 0.24 cm. The symbol —— denotes rainfall between 0.25 and 0.49 cm. The symbol L denotes rainfall between 0.50 and 0.75 cm. The figures indicate rainfall correct to whole centimetres.

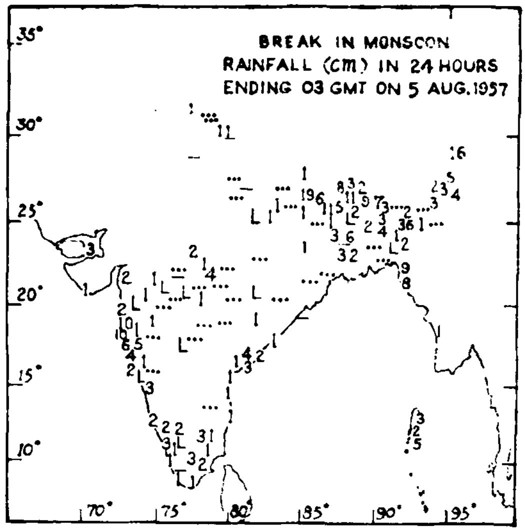

FIG. 2. General break in monsoon rains over India. Rainfall in 24 hours ending at 03 GMT on August 5, 1957. Symbols and figures have the same meaning as in Fig. 1. Note the heavy rainfall along and near the foot of the Himalayas which is characteristic of the break conditions and the rainfall along the west coast of peninsular India which is largely determined by orography. Note also that there is less rainfall over the rest of India, spatially as well as in amount, during the break. Compare Fig. 2 with Figs. 1 and 3.

75° E were also prepared and analysed. For the latter, the wind data of all stations lying within 5° longitudes of the 75° E meridian were utilised. The data required for these cross-sections outside India were extracted from I.G.Y cards available in the India Meteorological Department.

3. Case selected for the present study

During the first half of August 1957, there was a short break followed by a revival of the monsoon over India. The monsoon conditions were about normal[1] over the greater part of the country on August 3 (Fig. 1). On the morning of August 4, the axis of the monsoon trough at sea level which was previously rather to the south of its usual position over the Gangetic plain began to shift towards the foot of the Himalayas and a general break in the monsoon

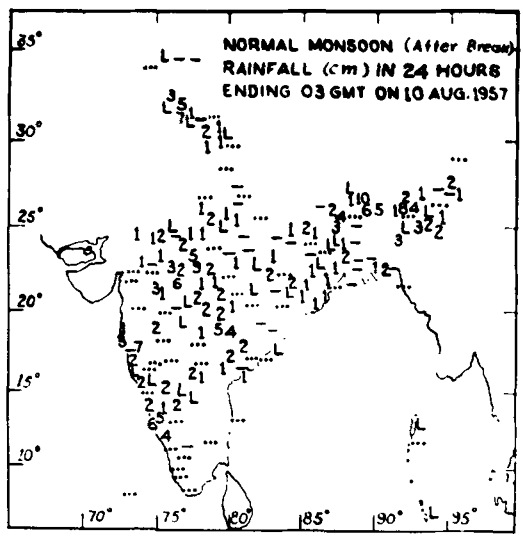

Fig. 3. Normal monsoon conditions over India after the break. Rainfall in 24 hours ending at 03 GMT on August 10, 1957. Symbols and figures have the same meaning as in Figs. 1 and 2. Note the well-distributed rainfall.

[1] The terms "normal monsoon" and "active monsoon" as used in this paper are more or less synonymous. These terms are used to describe the activity of the monsoon over India as a whole. They do not refer to the activity in any particular State or region within the country.

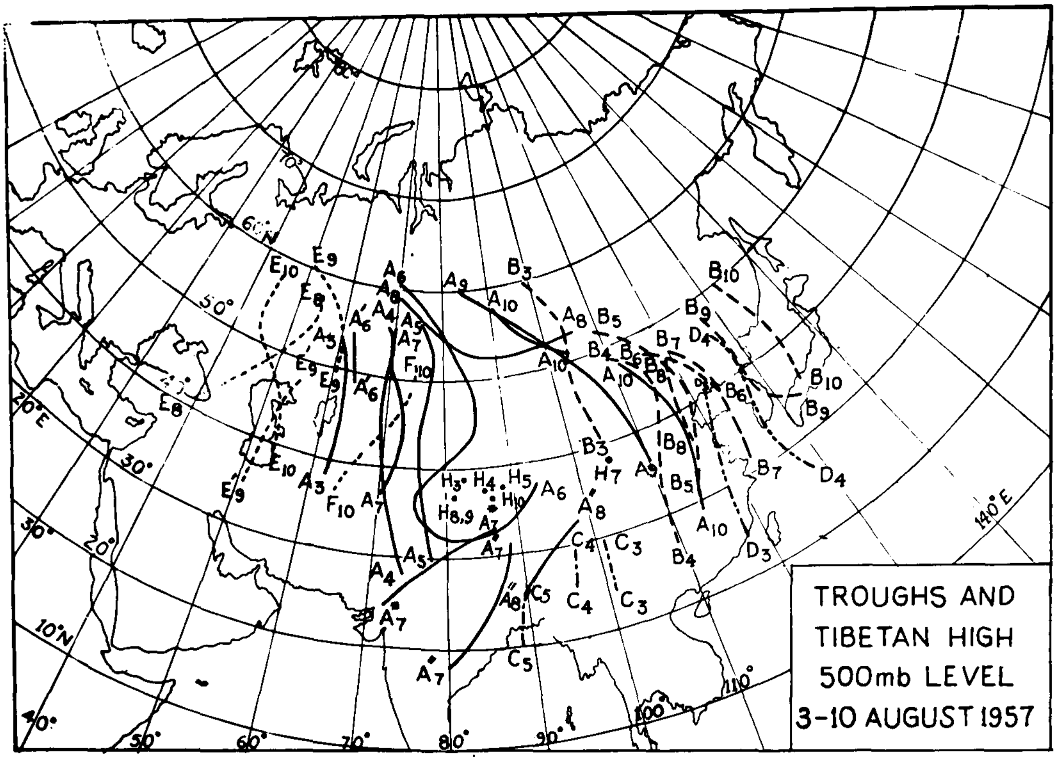

FIG. 4. Successive positions of the troughs and the centres of the closed Tibetan high at the 500 mb level during the period August 3 to 10, 1957. A_3A_3, A_4A_4, A_5A_5 ... $A_{10}A_{10}$ *indicate the successive* positions of the same trough on 3, 4, 5 ... 10 August 1957 respectively. Likewise, B_3B_3, B_4B_4 ... $B_{10}B_{10}$ represent the successive positions of another trough on the different dates. H_3, H_4, H_5 ... H_{10} indicate the positions of the central region of the *closed* high over Tibet on 3, 4, 5 ... 10 August. Note how the trough A_3A_3 near Aral Sea on August 3 increases in amplitude and gets retarded as it moves into Tibet on August 6 (A_6A_6). *Note also that there is no* H_6 *in the diagram indicating the collapse of the* Tibetan high on August 6.

rains began to set in over the country. As is usual under such conditions, there was very heavy rain along and near the foot of the Himalayas. Talpaigwri (26°32′ N, 88°43′ E) in Sub-Himalayan West Bengal reported 11 cm of rain, Cherrapunji (25°15′ N, 91°44′ E) 36 cm and Motihari (26°40′ N, 84°55′ E) 19 cm on the 5th (Fig. 2). By August 7, the monsoon began to revive over the country and a shallow depression formed in the Bay of Bengal off the Orissa coast on the evening of August 8. By August 10, the shallow depression had moved into the central parts of the country as a low pressure area and active[1] monsoon conditions with well-distributed rainfall began to prevail over the greater part of the country (Fig. 3).

[1] See note p. 339.

The situation just described brings out in a very rough way within a short period of eight days the more important features of the rainfall distribution observed in the earlier study (RAMASWAMY, 1958) in persistent and strikingly different spells in two different years, namely during the prolonged weak monsoon spell of August 1954 and the prolonged active monsoon spell of July 1953. While the study of a short spell as in the present paper may have the disadvantage that it does not enable us to see the characteristics of typical persistent weak monsoon or typical persistent active monsoon, it has the advantage that it enables us to see in a short spell, the entire sequence of variations from active monsoon to weak monsoon and from weak monsoon back to active monsoon. Hence the choice of the present case for study.

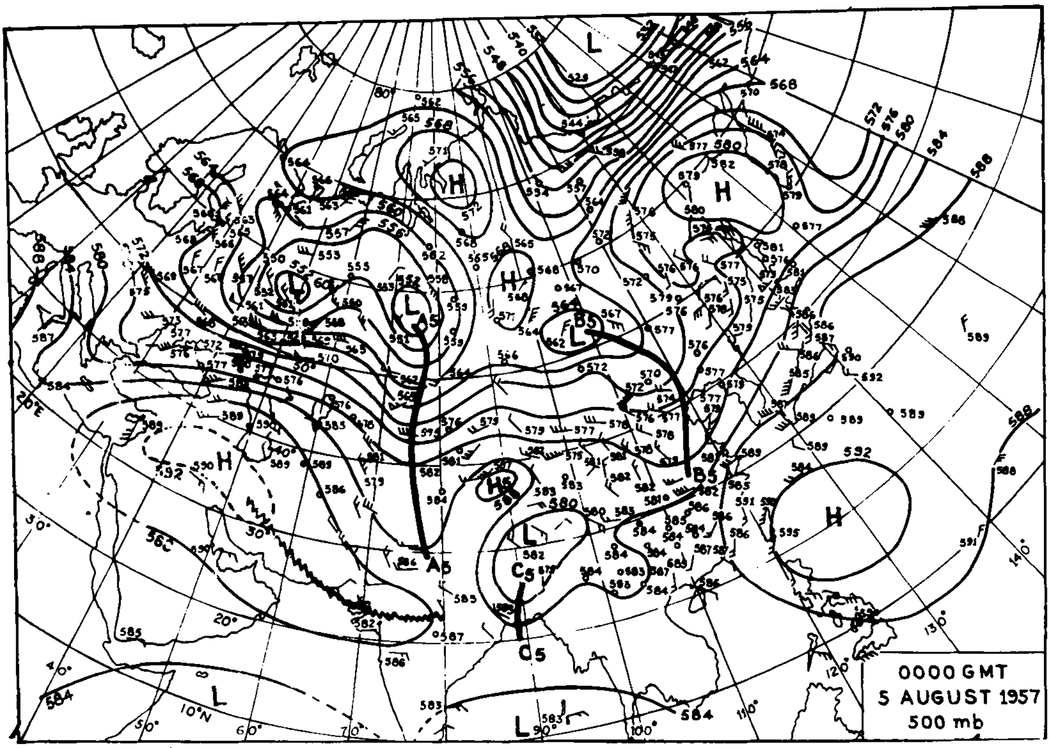

FIG. 5. 500 mb pattern during the break conditions: August 5, 1957. The chart shows the 500 mb pattern during the earlier stages of the break. The contour heights have been plotted correct to tens of metres and the contours have been drawn at intervals of 40 metres. The continuous thick lines are trough lines and the zig-zag line is a ridge-line. Dotted contour lines have been drawn in regions where the analysis is rather uncertain. The other symbols have the same meaning as in Fig. 4. Note the large amplitude trough A_5A_5, the shrinking Tibetan high H_5, and the anticyclonic cell over Iran and Arabia extending into the central parts of India in the rear of the large-amplitude trough.

4. Analysis of the Asian charts

Fig. 4 shows the successive positions at the 500 mb level of the trough lines which affected Asia south of latitude 60° N and between 40° E and 140° E during the period August 3, to August 10, 1957. The figure also shows the successive positions at the 500 mb level of the centre of the closed high over Tibet during this period.

The actual 500 mb patterns during the maximum phase of the break-monsoon conditions, namely on August 5 and 6, are of great interest to us and have, therefore, been reproduced in Figs. 5 and 6. As a contrast, the 500 mb pattern after the break had ended and normal monsoon conditions got restored, is shown in Fig. 7.

An examination of these four diagrams leads to the following conclusions:

(*a*) During the period 3rd to 6th a middle latitude trough in the westerlies approached Tibet from the west. After the 3rd, the amplitude of the trough increased and as the trough approached Tibet, the high over that region began to shift eastwards. On the 6th when the large amplitude trough lay over Tibet, the high over that region had collapsed. The high over Arabia and Iran (see sub-para (*k*) in Section 7) also simultaneously extended into central and peninsular India and the adjoining Indian seas. These developments at the 500 mb level synchronised with the maximum phase of the break in the monsoon over India. On August 7, the large amplitude trough broke up into a complex system. Two troughs, A_7^* A_7^* and A_7'' A_7'' (Fig. 4), remained over northern India. The middle latitude portion of the trough over Sinkiang had a slight retrograde motion, presumably due to the accentuation and southward

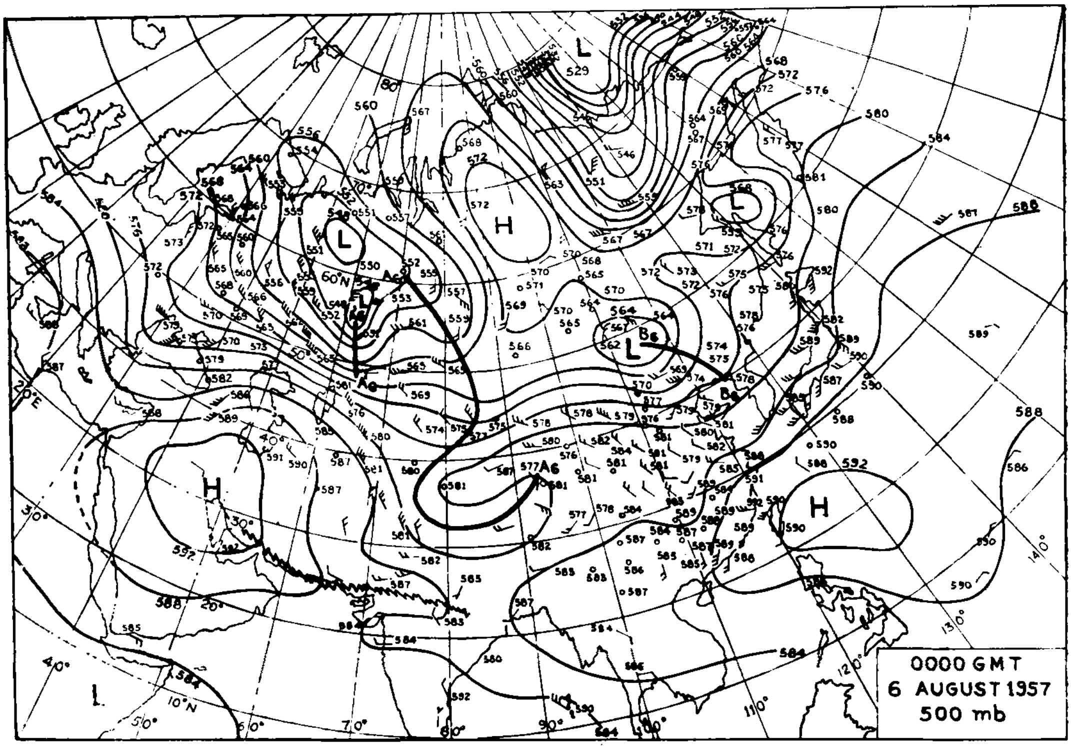

FIG. 6. 500 mb pattern during the break conditions: August 6, 1957. The chart shows the 500 mb pattern at the peak of the break-conditions. Symbols, etc. have the same meaning as in Figs. 4 and 5. The large amplitude trough has protruded further southwards and moved eastwards and wiped out the Tibetan high. In association with this development, the high to the west of the trough has extended over the peninsular India and the adjoining Indian seas also.

extension of the high further to the northeast over U.S.S.R. (not shown in the diagram). The middle-latitude trough A_7 A_7, however, moved eastwards after the 7th. By the 10th, it had passed away east of 115° E. The ridge associated with the high over Arabia and Iran also retreated northwestwards to its normal position. The developments between the 8th and 10th synchronised with the reappearance of the high over the Tibetan plateau, its accentuation and the onset of active monsoon conditions over India.

(*b*) During the weak monsoon phase, the large amplitude trough had brought in strong westerlies into West Pakistan and northern India. These westerlies had reached jet intensities at the 300 mb level and aloft over northwest Pakistan.

(*c*) On the other hand, during the normal monsoon phase there was a good concentration of westerlies between 40° N and 50° N north of the Tibetan high (Fig. 7). Data for the 300 mb level were unfortunately not available for the Chinese Sinkiang–Mongolian Region. But, from the general speed of the westerlies at the 500 mb level over these areas, one can infer that the winds must have attained well above jet intensity at the 300 mb level. There was also a well-marked *low* over southern peninsular India: a complete change from the patterns during the weak monsoon phase (e.g. cf. Figs. 6 and 7).

5. Analysis of vertical time sections

Figs. 8 and 9 show the vertical time sections over Calcutta (22°39′ N, 88°27′ E) and New Delhi (28°35′ N, 77°12′ E) during the period August 3 to 10, 1957 and their association with the general behaviour of the monsoon over

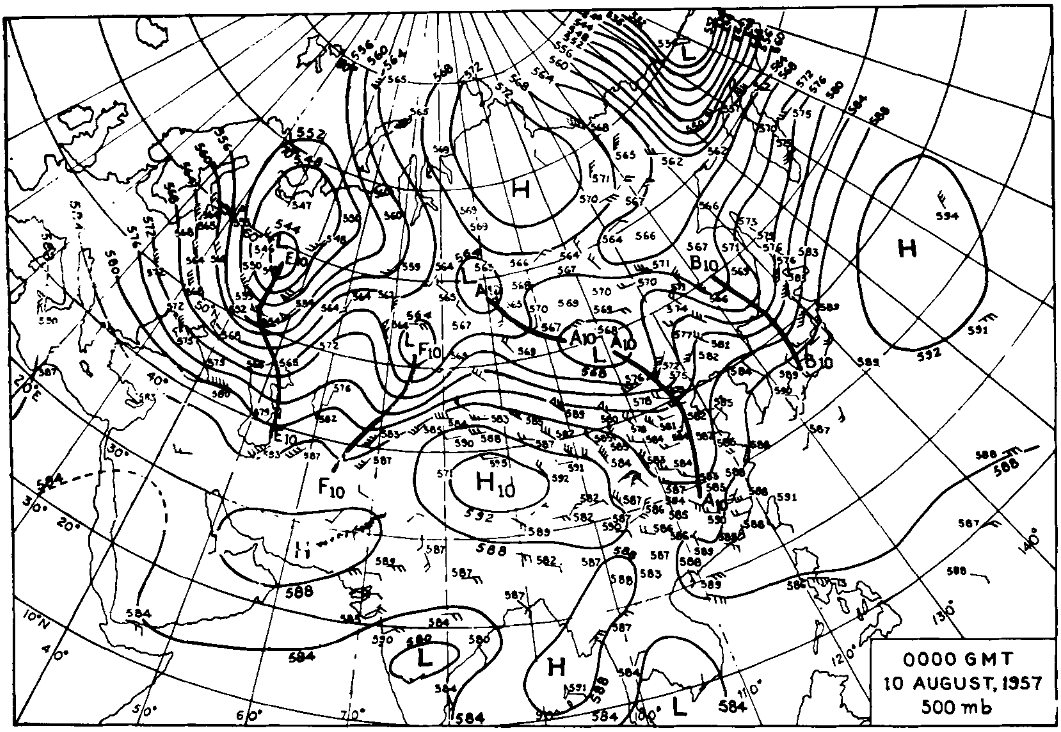

FIG. 7. 500 mb pattern during the normal monsoon conditions after the break: August 10, 1957. The chart shows the 500 mb pattern during normal monsoon conditions after the break. Symbols have the same meaning as Figs. 4, 5 & 6. The large amplitude trough over northern India seen in Figs. 5 and 6 has disappeared. With the disappearance of this trough the anticyclonic cell over Iran and Arabia has gone back to its normal position and the Tibetan high has developed to its full extent. Note the closed low over peninsular India. Compare the systems in this figure with those in Fig. 6 at the maximum phase of the break in the monsoon.

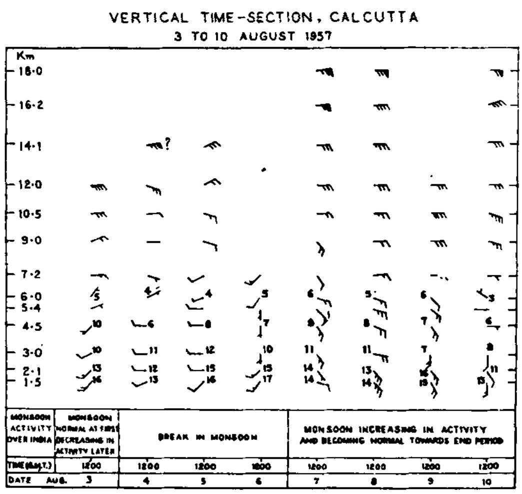

FIG. 8. Vertical time-section for Calcutta August 3 to 10, 1957. The heights shown along the Y-axis correspond to the standard isobaric levels. The figures plotted near the winds are the humidity mixing ratios. Compare the winds during the break with those before and after the break. Note that the westerly component in the winds is much stronger in the middle troposphere and the easterly component is weaker in the upper troposphere during the break.

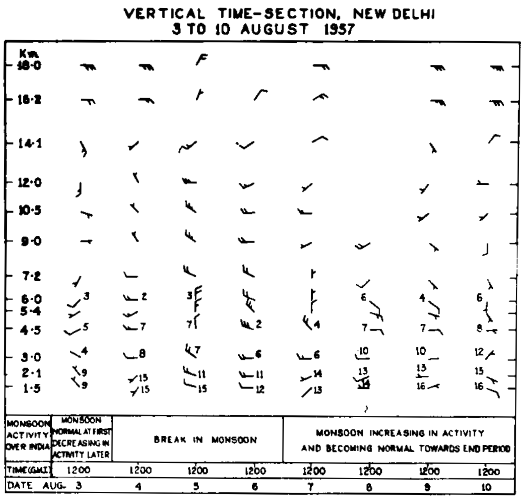

FIG. 9. Vertical time-section for New Delhi August 3 to 10, 1957. Same convention in plotting as in Fig. 8. Compare the winds during the break with those before and after the break. Note the very pronounced westerly component in the winds up to 14 km and the weaker easterly component at higher levels during the breaks.

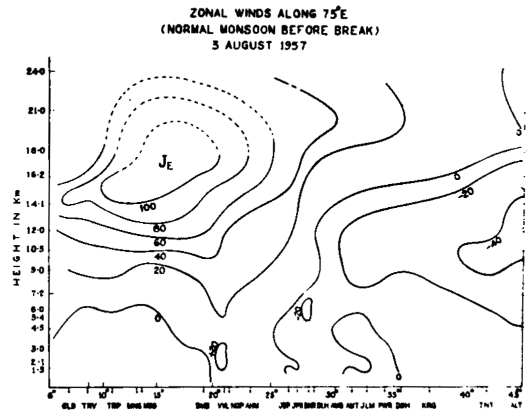

FIG. 10. Zonal winds along meridian 75° E during normal monsoon before break (August 3, 1957). The heights shown along the Y-axis correspond to standard isobaric levels. The isopleths of wind speed are in knots. Positive values indicate easterly winds and negative values indicate westerly winds. Dotted lines have been drawn where the analysis is rather uncertain due to paucity of observations. J_E is the position of the easterly jet core near 15° N. Note the secondary maximum in easterlies near lat. 20° N. The westerlies are increasing in speed to the north of 28° N. The westerly jet core is beyond the northern limit of this cross-section and is near 50° N.

the country. The following conclusions may be drawn from these time sections:

CALCUTTA

During weak monsoon, the westerlies are conspicuous in the mid-troposphere. Easterlies prevail at 9.0 km and aloft and increase with height. It is, however, important to note that *the easterlies are significantly weaker during break-monsoon.* During normal monsoon, on the other hand, *the easterlies are stronger.*

NEW DELHI

During break-monsoon, the westerlies dominate the whole of the mid-troposphere and the upper troposphere upto 12.0 km. *Easterlies prevail at higher levels but they are significantly weaker during the break than during normal monsoon up to all heights for which observations are available (viz. up to about 18.0 km).*

6. Analysis of the cross-sections of zonal winds

The cross-sections of the zonal winds along 75° E during the period under study (i.e. August 3 to 10, 1957) were drawn with considerable emphasis on their continuity in space as well as time. This was necessary for getting a consistent picture of the day-to-day variations and also of the spell as a whole.

Figs. 10 and 12 show the cross-sections on August 3 and 10, 1957, i.e. before and after the break. Fig. 11 shows the cross-section on August 5, 1957, i.e. during the break itself. An analysis of these cross-sections brings out interesting features such as comparatively little variation in the depth of the monsoon westerlies along the west coast of India during normal monsoon and break conditions and the replacement of the easterlies by westerlies along the foot of the Himalayas (i.e. northward shift of the monsoon trough) in the lower troposphere during the break. We do not, however, propose to go into these aspects. We shall confine our attention mainly to the upper tropospheric wind field.

The most salient features of these three cross-sections are summarised below.

Normal monsoon conditions before and after the break (Figs. 10 and 12)

(i) The easterly jet stream extends between 5° N and 25° N with its core probably near about latitude 15° N. There is, however, a secondary maximum between 19° N and 22° N.

(ii) Before the break, no westerly jet core is observed within the limit of the cross-section. Examination of the constant pressure charts shows that the jet core is near latitude 50° N.

(iii) After the break, a well-defined jet core is found near latitude 42° N. The westerly jet core is near about 12 km level while the easterly jet core is, as is to be expected, near about the 17 km level.

(iv) From (i), (ii) and (iii) above, we can conclude that the westerly jet core during normal monsoon is, in the mean, near 46° N and that the distance between the easterly and westerly jet cores in this situation is, in the mean, about 31 degrees of latitude.

Break-monsoon conditions (Fig. 11)

(i) During the break conditions, the easterly jet stream holds sway between 5° and 22° N. There is a jet core near latitude 12° N, somewhat south of its position during normal monsoon. The secondary maximum between 19° and 22° N has become more pronounced and has a jet core near 20° N.

(ii) There is a remarkable extension of middle and upper tropospheric westerlies equatorward up to latitude 26° N. Associated with this extension, there is pronounced horizontal wind-shear between 26° and 33° N above 10 km. There is also a westerly jet stream between 30° N and 42° N. An analysis of the day-to-day developments during the period under study (i.e. August 3 to 10, 1957) suggests that the westerly jet stream during the break-period had probably two cores, one near 32° N and another near 40° N (they have been indicated by J_W with interrogation marks in Fig. 11).

(iii) From the above, we are led to infer that the distance between the easterly and westerly jet cores during the break period is only about 12 degrees latitude as against 31 degrees latitude during normal monsoon conditions. Even if we rule out the postulate of twin westerly jets and assume that there is only one westerly jet core and we fix it at 36° N (marked J_W in Fig. 11), the lateral distance between the easterly and westerly jet cores during the break-period is only about 16 degrees latitude as against 31 degrees latitude during normal monsoon conditions. While it is not claimed that these figures, by themselves, have any special significance, it

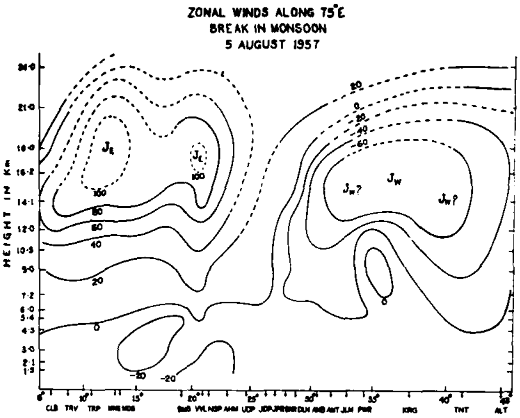

FIG. 11. Zonal winds along meridian 75° E during break (August 5, 1957). Same convention in plotting and analysis as in Fig. 10. Note that the main easterly jet core has shifted slightly southward and that the secondary maximum near 20° N has developed into jet intensity. Twin westerly jet cores in the positions indicated with interrogation marks appear probable. The latitudinal distance between the easterly and the westerly jet cores is only about 12 degrees of latitude as against 31 degrees, in the mean, before and after the break (Figs. 10 and 12).

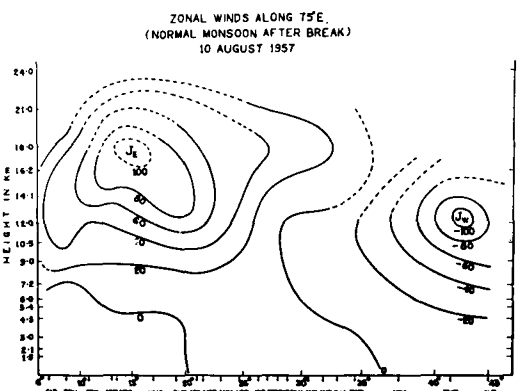

FIG. 12. Zonal winds along meridian 75° E during normal monsoon after break (August 10, 1957). Same convention in plotting and analysis as in Figs. 10 and 11. The main easterly jet core is near 15° N. The secondary maximum in the easterlies is near about 20° N and the westerly jet core is near 42° N.

cannot be denied that they present irrefutable evidence to show that the westerly jet stream is far away from India during normal monsoon and that it makes a very definite approach towards the easterly jet stream over peninsular and central India during breaks in the monsoon.

7. Breaks in the southwest monsoon as a phenomenon of interaction between the easterly and the sub-tropical westerly jet streams

Based on these detailed synoptic studies and our past experience with southwest monsoon situations, we would make the following general observations.

(*a*) The Tibetan Plateau exercises a pronounced sheltering effect on the air-streams flowing over and near the plateau (ACADEMIA SINICA, 1958; FLOHN, 1958). Consequently, the westerlies above the plateau are much weaker than those at the same level to the east or west of the plateau. This pronounced weakening of the basic current has a very important dynamic effect on the upper troughs moving eastwards: the troughs get retarded and at the same time their amplitude grows larger for the reasons explained by BERGGREN, BOLIN & ROSSBY (1949) and by ROSSBY (1959).

(*b*) During normal monsoon conditions, there is an extensive and well-marked high over the Tibetan Plateau at the 500 mb level and aloft with a more or less zonal westerly flow to the north of the high. Wind speeds in these zonal westerlies attain jet intensity at the 300 mb level and aloft. Under such conditions minor wave-troughs usually move eastwards from Sinkiang to the north of the Tibetan high (ACADEMIA SINICA, 1958).

(*c*) Occasionally, troughs of relatively larger amplitude extend to latitudes south of 40° N over Russian Turkestan. Such situations would normally occur during periods of *low* index circulation when there is pronounced meridional flow with jets embedded in the meridional patterns (ROSSBY, 1959).

(*d*) In such situations, the relatively large amplitude troughs move eastwards over the Tibetan plateau. The troughs get retarded and at the same time their horizontal amplitude grows larger for the reasons stated in sub-para (*a*) above. The troughs thus extend into West Pakistan and northern India.

(*e*) If the eastward moving large amplitude trough is initially a deep one, it will shift the Tibetan high eastward and weaken it. It may even destroy it completely at the 500 mb level as in the case we have illustrated in the present paper (Fig. 6). In this process, the easterlies over northern India (associated with the Tibetan high) also get weakened considerably and may even be completely replaced by westerlies at the 500 mb level. *It is in such situations, that there are breaks in the monsoon rains over India.*

(*f*) The middle-latitude trough which has penetrated into West Pakistan and northern India moves relatively slowly and is characterised by a jet in the rear of the trough-line at the 300 mb level and aloft. Ahead of the trough, however, the westerlies are much weaker. Consequently the trough is of the diffluent (fanning contours) type and is characterised by pronounced upper level divergence ahead of the trough line (PETTERSEN *et al.*, 1955; RAMASWAMY, 1956). As the region ahead of the trough line is situated along and near the foot of the Himalayas and as the moist southwest monsoon current pervades these regions in the lower troposphere, the upper level divergence should contribute to the up-draught of the monsoon air and consequent heavy rainfall over these regions. The fact that there is actually very heavy rainfall in these regions during break-monsoon conditions does therefore lead us to think that our general line of reasoning should be acceptable.

(*g*) An important effect of the southward protrusion of the large amplitude trough into northern India and its subsequent slow eastward movement is the associated southeastward shift of the high over Arabia and Iran at 500 mb level and aloft. This high protrudes into India *south of 30° N* and contributes to the dry weather conditions over that part of the country. That such a high exists and that it is significant in connection with the dry weather conditions has also been recently pointed out by PISHAROTY & ASNANI, (1960). It should however be emphasised that *it is the powerful system of the trough in the westerlies with the jet embedded in it that controls the movement of the Iranian high and as such it is the westerly system which should be considered as the primary cause for the inducement of dry weather over the country.*

(*h*) The qualitative statements made in the above paragraphs are in no way inconsistent with the conclusions of YIN (1949) about the onset of the southwest monsoon over India and with the observations recently made by YEH DAO & LI (1959) about upper air circulations over the northern hemisphere.

(*i*) In the situation studied in this paper, the break in the monsoon lasted two to three days. The mechanism for the break is the same even when it lasts for a week or more. In such situations, the large amplitude trough remains more or less quasi-stationary over north India with the Iranian high extending into India south of 30° N. An instance of this type is the break in the monsoon between August 19 and 25, 1954 (RAMASWAMY, 1958).

(*j*) In sub-para (*e*) above, we have stated that the Tibetan high at the 500 mb level is sometimes destroyed completely by the invading large amplitude trough. Observations, however, leave no doubt, that the Tibetan high persists at the higher levels although in a weaker state. In the southern periphery of this high are the easterlies increasing with height and concentrating into a jet stream with its core over peninsular India near about 15° N.

(*k*) In the normal wind-flow pattern sat 300 mb level and aloft in August (normal chart not reproduced in this paper), there is a high over Iran and North Arabia with a ridge-line roughly along Lat. 27° N. There is also at these levels a broad region of confluence between the easterlies on the southern periphery of the Iranian high and the easterlies over the Peninsula. During break-conditions, this Iranian high extends southeastwards as already pointed out in sub-paragraph (*g*) above. Such an extension of the high towards the strong current of easterlies over peninsular India would result in increased confluence and seems to be associated with the accentuation of the secondary maximum to jet intensity in the region referred to above.

(*l*) Whatever may be the mechanism of the easterly jets we note the remarkable *observational fact that, during breaks, in the Indian Southwest monsoon, the westerly jet intrudes into Indo-Pakistan, the easterly jet develops a secondary core to the north of the main jet core, thus resulting in two jets of entirely different types coming very near to each other*. On the other hand during normal monsoon conditions, the westerly jet moves far to the north of the Himalayas, and the easterly jet stream holds sway over India in the manner discussed by KOTESWARAM (1958, 1960).

(*m*) In sub-paragraph (*b*) above, we have stated that normal monsoon conditions are associated with an extensive and well-marked Tibetan high, a more or less zonal flow to the north of the high, a westerly jet far to the north of India and absence of pronounced wave-patterns in the westerlies south of 40° N. Such a situation should normally be associated with a *high* index circulation in the middle latitudes. On the other hand, we have seen in sub-paragraphs (*c*) to (*f*) above that break-conditions in the monsoon are associated with large amplitude troughs protruding into India and with a westerly jet embedded in the rear of these troughs. Such a situation should normally be expected in *low* index circulation in middle latitudes. In order to examine this aspect a little further, a general examination was made of the mean monthly northern hemisphere circulation patterns at 700 mb level and aloft as published in the *United States Weather Bureau Monthly Weather Review* in the typical monsoon months July and August in the years 1950–59. During this ten-year period, the months July 1950, July 1953, July 1956, August 1953, August 1955 and August 1958 were characterised by active monsoon with well-distributed rainfall over India, the rainfall recorded in these months in the country as a whole being 14 % to 36 % above normal and the excesses being as high as 25 % in July 1956 and 36 % in August 1955. It was interesting to find (KLEIN, 1950; HAWKINS, 1953; KLEIN 1953; NAMIAS & DUNN, 1955; KREUGER, 1956; WOFFINDEN, 1958) that one or more of the several well-known characteristics of a high zonal index circulation were found in the mean monthly circulation in the middle latitudes over Asia and the neighbourhood during these months. The mean westerly jet during these months was also north of 45° N over Asia. In addition, in three out of the six cases (July 1953, 14 % excess; August 1955, 36 % excess; July 1956, 25 % excess in the monsoon rainfall) there was an abnormally intense and contracted polar vortex. In contrast to the above, July 1951, August 1951, August 1954 and July 1955 were characterised by weak monsoon over India with deficiency in the rainfall over the country as a whole ranging from 10 % to 20 %. In the above cases except in July 1951, the middle latitude conditions over Asia and neighbourhood corresponded to low index circulation with large amplitude troughs protruding into the sub-tropics (OLIVER, 1951; OLIVER, 1951; WINSTON, 1954; and ANDREWS, 1955). It is pertinent to note in this connection that on account of the high variability of middle latitude patterns, anomalies in these patterns are likely to be smoothened out considerably in a *monthly mean* picture. As such, it should be very difficult to find in these *monthly mean pictures* significant associations between middle latitude patterns and low latitude weather of the type we have actually observed in *individual daily situations*. The fact that, in spite of this, certain associations have been found between montly mean middle latitude patterns and the activity of the monsoon over India as a whole, does give support to our view that the middle latitude westerly circulation in general and the westerly jet in particular play a very important role in determining the activity of the monsoon over India. For more details about the middle latitude patterns in July 1953 and August 1954, the reader is referred to the earlier publication by the author (RAMASWAMY, 1958).

(*n*) *As the changes discussed in the above sub-paragraphs are on a much larger scale and much more pronounced than those observed in the lower troposphere* (RAMASWAMY, *1958*), *we arrive at the conclusion that the dynamical processes associated with the movement of the sub-tropical westerly jet into Indo-Pakistan and its dynamical interaction with the tropical easterly jet play a fundamental role in the development of breaks in the Indian southwest monsoon.*

(*o*) The westerly jet stream is circumpolar in character and, therefore, perturbations in it in any part of the northern hemisphere are bound to influence the high level circulation patterns over Asia in general and India in particular. On the other hand, the easterly jets over south Asia and Africa are relatively local in character. Further, the wave-patterns in the upper troposhperic middle latitude westerlies are much more pronounced than those in the upper tropospheric low latitude easterlies. Consequently, the study of the circulation patterns in the upper tropospheric westerlies, although they may be more distant than those in the upper tropospheric easterlies is likely to lead to fruitful results in forecasting the still obscure large-scale vagaries of the Indian southwest monsoon.

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REFERENCES

ANDREWS, F. J., 1955, The weather and circulation of July 1955. *Mo. Weather Rev.*, **83**, pp. 149–152.

BERGGREN, R., BOLIN, B., and ROSSBY, C. G., 1949, An aerological study of zonal motion, its perturbations and break-down. *Tellus*, **1**, pp. 32 and 33.

FLOHN, H., 1957, *Large-Scale Aspects of the "Summer Monsoon" in South and East Asia.* 75th Anniversary Volume of the Journal of the Meteorological Society of Japan, p. 183.

FLOHN, H., 1958, Beiträge zur Klimakunde von Hochasien. *Archiv für wissenchaftliche Geographie*, Band *XII*, 4, p. 304.

HAWKINS, H. F., JR., 1953, The weather and circulation of July 1953. *Mo. Weather Rev.*, **81**, pp. 206 and 207.

KLEIN, H. W., 1950, The weather and circulation of July 1950. *Mo. Weather Rev.*, **78**, pp. 125 and 126.

KLEIN, H. W., 1953, The weather and circulation of August 1953. *Mo. Weather Rev.*, **81**, p. 252.

KOTESWARAM, P., 1950, Upper level "lows" in low latitudes in the Indian area during southwest monsoon season and "breaks" in the monsoon. *Ind. J. Met. Geophys.*, **1**, pp. 162–64.

KOTESWARAM, P., 1956, *Sci. Rep. Dep. Met., Univ., Chicago.* Project NR 082–120, p. 23.

KOTESWARAM, P., 1958, The easterly jet stream in the tropics. *Tellus*, **10**, p. 56.

KOTESWARAM, P., 1960, *Monsoons of the World—Report of the Symposium on.* Ind. Met. Dept. New Delhi, pp. 105–110.

KREUGER, F. A., 1956, The weather and circulation of July 1956. *Mo. Weather Rev.*, **84**, pp. 272–273.

NAMIAS, J., and CLAPP, P. F., 1949, Confluence theory of the high tropospheric jet stream. *J. Met.*, **6**, 5, p. 332.

NAMIAS, J., and DUNN, C. R., 1955, The weather and circulation of August 1955. *Mo. Weather Rev.*, **83**, pp. 166, 168.

OLIVER, J. V., 1951, The weather and circulation of July 1951. *Mo. Weather Rev.*, **79**, p. 143.

OLIVER, V. J., 1951, The weather and circulation of August 1951. *Mo. Weather Rev.*, **79**, pp. 160.

PETTERSSEN, S., DUNN, E. G., and MEANS, L. L., 1955, Report of an experiment in forecasting of cyclone development. *J. Meteor.*, **12**, pp. 58–67.

PISHAROTY, P. R., and DESAI, B. N., 1956, Western disturbances and Indian weather. *Ind. J. Met. Geophys.*, **7**, 4, p. 336.

PISHAROTY, P. R., and ASNANI, G. C., 1960, *Monsoons of the World—Report of the Symposium on.* Ind. Met. Dept., New Delhi, p. 115.

RAMASWAMY, C., 1956, On the sub-tropical jet stream and its role in the development of large-scale convection. *Tellus*, **8**, p. 52.

RAMASWAMY, C., 1958, A preliminary study of the behaviour of the Indian southwest monsoon in relation to the westerly jet-stream. *Special Palmen No. Geophysica*, **6**, pp. 455–476.

RAMASWAMY, C., 1960, *Monsoons of the World—Report of the Symposium on.* Ind. Met. Dept. New Delhi, p. 223.

ROSSBY, C. G., 1959, *The Atmosphere and the Sea in Motion.* (Rossby Memorial Volume.) Oxford University Press, New York, pp. 19, 27.

STAFF MEMBERS, ACADEMIA SINICA, 1957, On the general circulation over Eastern Asia (I). *Tellus*, **9**, p. 434.

STAFF MEMBERS, ACADEMIA SINICA, 1957, On the general circulation over Eastern Asia (II). *Tellus* **10**, pp. 61, 62, 68.

WINSTON, S. J., 1954, The weather and circulation of August 1954. *Mo. Weather Rev.*, **82**, pp. 229, 230.

WOFFINDEN, M. C., 1958, The weather and circulation of August 1958. *Mo. Weather Rev.*, **86**, pp. 312–313.

YEH TU-CHENG, DAO, SHIH-YEN, and LI. MEI-TSUN, 1959, *The Atmosphere and the Sea in Motion.* (Rossby Memorial Volume.) Oxford University Press, New York, pp. 249–267.

YIN, M. T., 1949, A synoptic-aerologic study of the onset of the Summer Monsoon over India and Burma, *J. Met.*, **6**, p. 393.