# A SYNOPTIC-AEROLOGIC STUDY OF THE ONSET OF THE SUMMER MONSOON OVER INDIA AND BURMA

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ABSTRACT

A comparison of the mean winter and summer flow patterns at 8 km in the vicinity of India shows that a trough located to the east of India in winter has shifted westward by summer. A study of the onset of the summer monsoon during 1946 shows that this movement is comparatively rapid and coincides with the "burst of the monsoon" over India. The movement of the trough is explained as being due to changes in the long-wave pattern brought about by the presence of the Himalayan mountain complex combined with seasonal variations in the latitude of the circumpolar jet stream of the northern hemisphere.

## 1. Introduction

Many meteorologists (Blanford, 1889; Harwood, 1921; Ramanathan and Ramakrishnan, 1937; Wagner, 1931) have described the arrival of the summer monsoon over India and Burma. It intrudes gradually into Burma during late April and May, whereas over India it holds back for several weeks. During these weeks, most of the subcontinent experiences its most intense heat spell of the year. The monsoon then begins over India, often advancing over a broad latitudinal belt within a few days.

As early as 1686, Halley had stated in the Memoirs of the Philosophical Society of Great Britain that the cause of the monsoon is differential heating, a theory that has remained unchallenged to the present day. No satisfactory explanation, however, has yet been offered as to why the monsoon is retarded over India as compared with Burma and why it subsequently advances in the spectacular manner that has led people to speak of the "burst of the monsoon."

It is the purpose of this paper to examine that problem. The method used represents to some extent a departure from that of previous investigators who sought the principal clue in the circulation over the south Indian Ocean. Recent literature suggests that the upper-air flow of the northern hemisphere also may be a factor of principal importance. One of the earliest papers putting forth this view is that of Rodewald (1936) when he commented on Wien's (1936) description of meteorological conditions attending the disaster of a German expedition on Nanga Parbat (26,182 ft) in northwestern India. Rodewald showed a map of Siberia and India, together with available 6-km winds, and attempted to relate the fatal surge of the monsoon with conditions to the north. In recent years Riehl (1945; 1947) and Cressman (1948a) have noted that there are large-scale interrelations between the flow aloft of high and low latitudes of the northern hemisphere and that these relations profoundly affect tropical weather. Although no claim is made that southern-hemisphere influences should be discounted, it appears reasonable to raise the question whether such interrelations should not also play a major role in determining Indian weather.

Examination of mean seasonal flow patterns at 8 km, a level sufficiently high to permit a broad exchange of air across the Himalayan Mountains, indicates a close connection between air flow in high and low latitudes. In December (Ramanathan and Ramakrishnan, 1937) a considerable portion of the belt of the westerlies circles the southern rim of the Himalayas (fig. 1). In spite of the altitude of the level shown, the streamlines follow the contours of the mountains. As prescribed by these contours there is a trough line near longitude 85°E. The summertime picture (Wagner, 1931) is entirely different (fig. 2). Although the westerlies have retreated northward, there is a trough line extending continuously from middle to low latitudes just west of the mountains near 75°E. This represents a westward displacement of the low-latitude trough of 10 degrees of longitude from the wintertime position. The subtropical ridge line extends along 35°N and a col therefore appears over northwestern India. To the north of the subtropical ridge the westerlies move over the Himalayas with clockwise curvature in correspondence with the requirements of the vorticity theorem. Figs. 1 and 2 show that Burma is always situated to the east of the mean position of the principal upper-air trough, whereas India lies to its west in winter and to its east in summer. Superposition of the high tropospheric flow pattern and its attendant pressure field on the low-level circulations therefore must have the effect of accelerating the monsoon over Burma and of retarding it over India as long as the mean trough persists near 85°E. After its shift to 75°E, southerly wind components at high levels prevail over the entire Burma–India region and must reinforce the

[1] The investigation reported in this paper was carried out by the author at the University of Chicago.

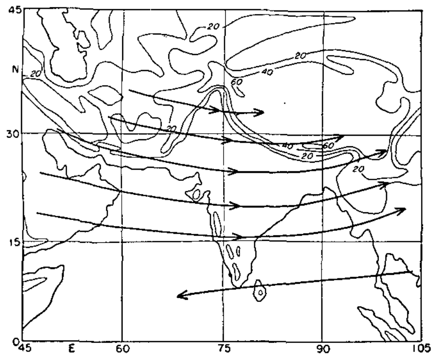

FIG. 1. Mean winter circulation at 8 km over India and its neighborhood (after Ramanathan and Ramakrishnan).

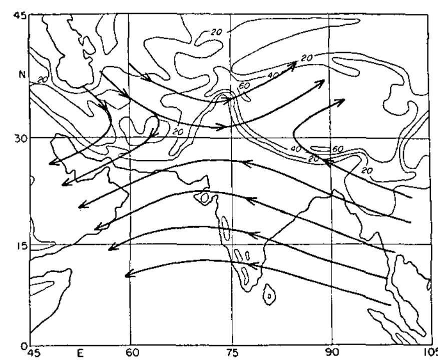

FIG. 2. Mean summer circulation at 8 km over India and its neighborhood (after A. Wagner).

monsoon everywhere. It follows that the change of the upper circulation can explain the pattern of advance of the monsoon initially noted. However, it is necessary to show that the shift of the mean trough position occurs very rapidly and coincides with the burst of the monsoon. It is further necessary to find an explanation for any sudden displacement of the mean trough, an explanation which can be applicable in every year.

These questions will now be studied during the period of the advance of the monsoon in 1946. For that year 500-mb charts of the northern hemisphere, prepared by the United States Air Force, are available, offering an excellent opportunity for relating meteorological developments over India–Burma with the upper-air circulation over Siberia and the hemisphere as a whole.

## 2. The advance of the monsoon in 1946

In order to establish at first the sequence of events that took place over India in the spring of 1946, upper wind charts for the 5000-, 10,000-, and 20,000-ft levels were drawn for every day during May and June. The forward edge of the monsoon, generally identified as the "Equatorial Convergence Zone" (ECZ) of the Indian Ocean, is said to be a warm low-pressure area with circulation decreasing with altitude. Nevertheless it was quite difficult to detect the ECZ on the surface and 5000-ft charts, whereas at 10,000 ft it could usually be located with ease. Winds were sparse at 20,000 ft. At that level the circulation, as far as it could be determined, had even greater streamline amplitude than at 10,000 ft, but the axes of disturbances were oriented more north–south and the flow resembled wave motion to a greater extent.

Fig. 3 shows the 10,000-ft flow for the afternoons of alternate days during the critical weeks of the advance of the monsoon and the heavy line of fig. 5 summarizes the movement of the ECZ during that period.

At the beginning of the series, on May 21 and 23, an anticyclonic cell overlies the southern part of the peninsula (fig. 3). To its north the flow over India is mainly westerly but with northerly components, whereas the few available winds over southern Burma and the Andaman Islands indicate southwesterly flow. We thus encounter the trough aloft still near its average location of winter. As the flow pattern of these days is typical of that prevailing during most of the three preceding weeks, it is evident from continuity requirements that a portion of the air yielding the copious early monsoon rains over Burma must be the same air that previously has moved over India without producing heavy rainfall.

During the subsequent days, the high-pressure cell over southern India shifts northward and the ECZ advances into southern India coupled with the development of a westward-moving Bengal Sea depression. After an interruption of the advance from May 26 to May 31, the "burst of the monsoon" follows and terminates only six days later after moving 12–14 degrees of latitude northward. A second retreat occurs between June 6 and June 8, and then the position of the ECZ becomes more steady near 23°N.

If we compare the streamline charts of the initial and final days of the series, we at once gain the impression that the streamlines over central India have rotated cyclonically, with the result that the northerly component of the flow over India has disappeared.[2] In order to test this impression quantitatively, profiles of the average height of the 500-mb surface (approximately 2 km below the mean charts in figs. 1 and 2) between latitudes 20°N and 30°N, as given by the Air Force northern-hemisphere charts, were computed for 5-day intervals between 40°E and 130°E (fig. 4). During the first three weeks of May, the upper trough remains steadily at 90°E and the ridge to its west near 60–65°E. Definite evidence of a breakdown of the steady pattern is obtained May 21–25, when the trough splits and one branch moves westward as the ECZ first moves northward. Evidently this branch cannot maintain itself as yet, since the mean trough again lies over the Bay of Bengal on May 26–30 coincident with the interruption of the monsoon. After the end of May, the trough definitely moves to 80°E

[2] This shift also has the result of bringing air with a longer sea trajectory into India, as pointed out by Dr. S. Petterssen in a discussion of this paper with the writer.

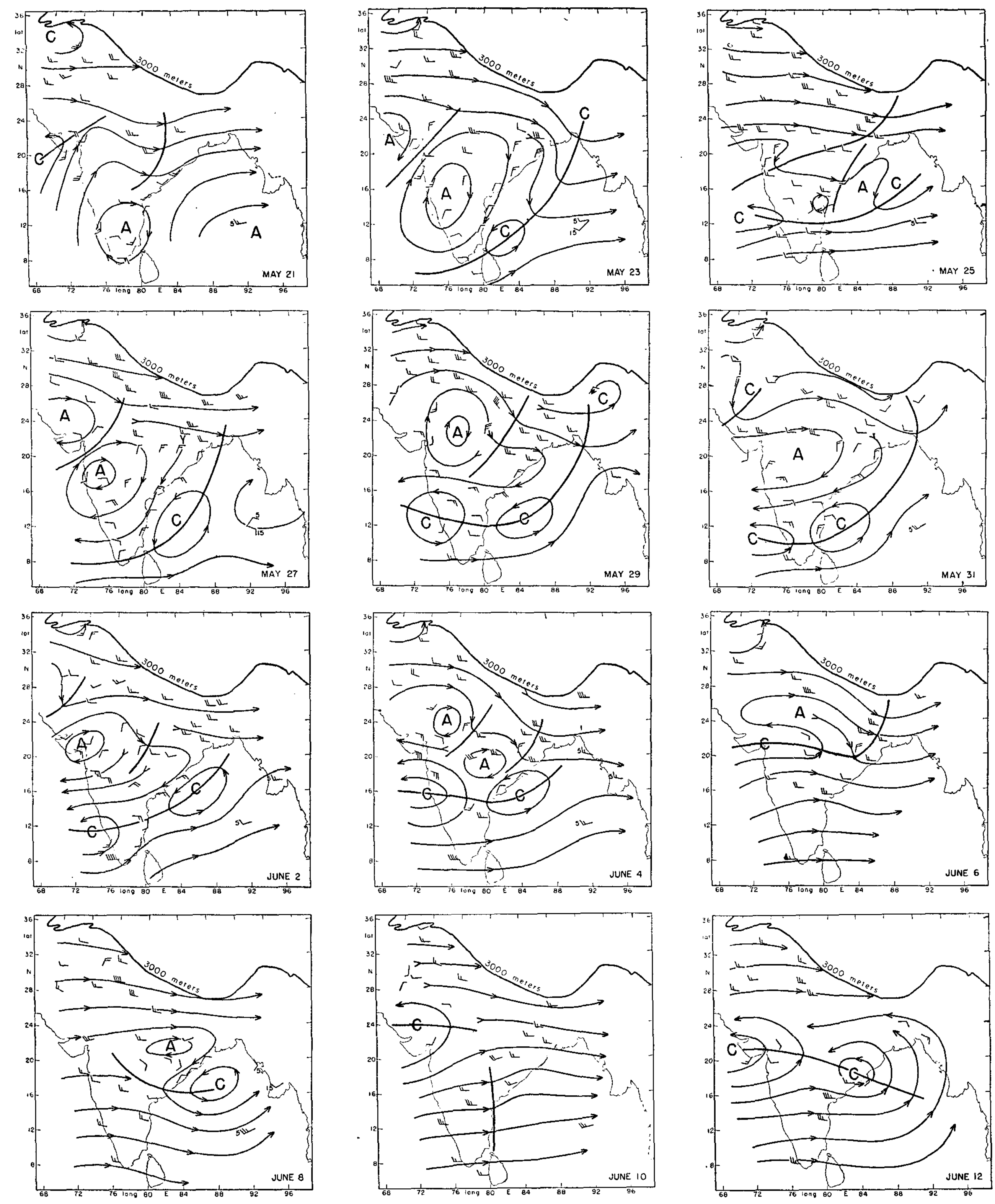


FIG. 3. Streamline charts at 10,000 ft, 21 May–12 June 1946. Thick lines indicate the Equatorial Convergence Zone (ECZ). Wind data are taken from the afternoon observations.

as the ECZ becomes established near the northern end of the peninsula.

Up to this point, the analysis has given support to the hypothesis initially presented. The advance of the monsoon is closely linked with the westward progression of the trough at 500 mb, whose motion is in accord with that demanded by seasonal mean conditions. Moreover, its westward displacement is relatively abrupt. It is necessary now to determine the reason for this displacement. The monsoon itself conceivably could be the cause, although that solution would preclude an explanation of the almost discontinuous behavior of monsoon and upper flow pattern over India when contrasted with Burma. It is more plausible to say that the events over India are linked with broadscale changes in the upper flow over at least a large portion of the northern hemisphere, as suggested by Rodewald (1936). The following sections will investigate the feasibility of this solution.

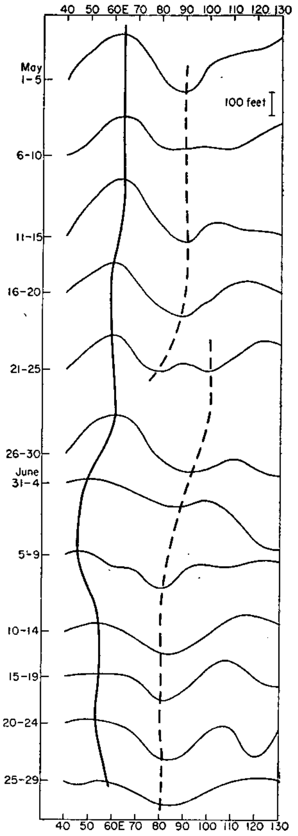


FIG. 4. The average height of the 500-mb surface between 20°N and 30°N as a function of longitude and time, computed for 5-day periods. Vertical dashed lines indicate the position of 5-day mean troughs and vertical solid lines the position of 5-day mean ridges.

### 3. The zonal westerlies at 500 mb over the Eurasian continent

As a first step we shall extend our study over the Eurasian continent as a whole. Fig. 5 shows the geostrophic west wind averaged between 0°E and 130°E for 5-day intervals during May and June. At the beginning of May, the region of strongest westerlies, hereafter called the jet stream, is situated near 30°N. This jet moves northward to about 40°N in the last week of May and then disintegrates abruptly in the first week of June. Meanwhile a new jet has steadily worked southward from the Arctic until there are two west wind maxima in the second half of May. The northern jet (whose motion is characteristic of that suggested by Rossby (1947)) becomes dominant at the beginning of June. The Bay of Bengal trough begins to move westward as the low-latitude jet is displaced

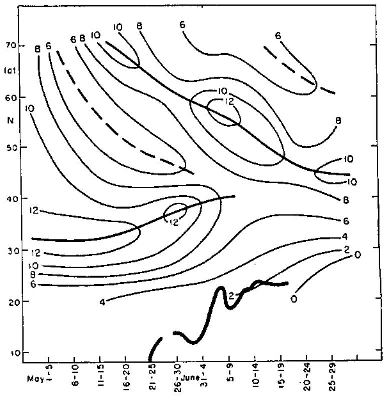

FIG. 5. Mean geostrophic west wind at 500 mb between longitudes 0 and 130°E as a function of time and longitude, computed for 5-day periods. Isolines are labelled in m sec$^{-1}$ with the position of the maxima (the jet) and minimum being indicated by heavier solid and dashed lines. The heaviest line at the bottom gives the latitude of the ECZ over India (from daily charts).

northward and *the burst of the monsoon coincides with the period of collapse of the southern jet.*

These time correlations are significant. Although fig. 5 is only representative of the Eurasian continent as a whole, inspection of the daily 500-mb charts indicates, in spite of frequent uncertainty of analysis north of India due to lack of data, that locally in this area the portion of the westerly stream that during the premonsoon season had circled the Himalayas along their southern border is displaced to the north of the mountains. Because of the deformation of the flow imposed by this huge mountain range a basic readjustment of the wave pattern aloft must occur. The orographically determined phase shift, schematically indicated in fig. 6, agrees closely with the observed, except that the observed trough at 80°E is somewhat farther east than the trough in the dashed streamline at 70°E. Perhaps this may be ascribed to the fact that the high-level flow in which the trough and ridge position are determined, extends above the mountains, though it is affected by them.

The foregoing suggests that the sequence of events culminating in the burst of the monsoon begins with a northward shift of the general circumpolar westerly current aloft over Eurasia. As the southern portion of

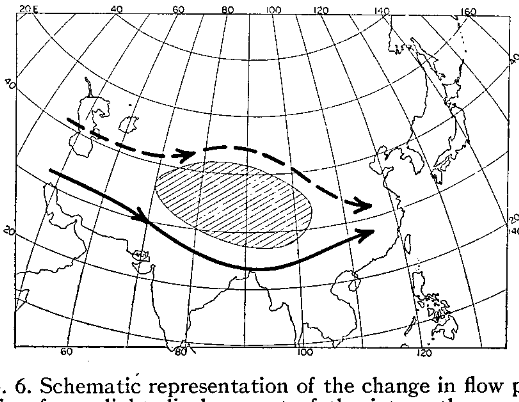

FIG. 6. Schematic representation of the change in flow pattern resulting from slight displacement of the jet north or south of the Himalayan mountain complex.

this current ceases to flow around the southern periphery of the Himalayas in order to circle their northern border, a rapid westward displacement of the low-latitude mean trough is enforced. As a result, the northerly component of the flow aloft over India is suddenly replaced by a southerly component at the same time as the subcontinent comes under the influence of the convergence east of the trough line that must be present in order to effect the westward progression of the trough. *The combination of these two factors, when superimposed on the pressure gradient resulting from the large-scale differential heating, results in the observed violent advance northward of the ECZ.* Thus a temporary northward displacement of the westerlies would produce only a temporary advance of the monsoon followed by a retreat if the westerlies return to their original latitude.

## 4. The middle-latitude wave pattern over Eurasia

Although the preceding section establishes a definite relation between the *westerly flow* of the upper troposphere and the advance of the monsoon, the University of Chicago studies (Cressman, 1948a; Riehl, 1945) on the interrelation between the *disturbances* of high and low latitudes suggest that this feature should also be investigated.

Rossby (1939) has formulated an expression relating motion and wave length of long nondivergent waves in a barotropic atmosphere to the speed of the zonal current and the variation of the Coriolis parameter with latitude. Subsequent synoptic study, notably by Cressman (1948b) has demonstrated that application of Rossby's formula to daily weather maps is practicable and realistic, in spite of the great complexity of the observed atmosphere. As indicated in fig. 5, the structure of the Eurasian westerlies undergoes a drastic change at the end of May. It is therefore reasonable *a priori* to expect that a transformation of the structure of the middle-latitude long-wave pattern should accompany the redistribution of the zonal current.

In order to determine the long-wave pattern, the average height of the 500-mb surface between 40°N and 60°N has been calculated for 5-day intervals over Eurasia during May and June (fig. 7). For the remainder of the hemisphere, this somewhat lengthy routine was carried out for the period May 10 to June 10 only, and 700-mb profiles (obtained from the Extended Forecast Section of the United States Weather Bureau) have been added for the remainder of the period. The averaging process between 40°N and 60°N was carried out for every 10 degrees of longitude, but in a manner somewhat different from that employed by other investigators (Cressman, 1948b). Investigation of upper-air charts reveals that, in general, troughs and ridges in middle latitudes are not oriented from north to south but rather from northeast to southwest, and therefore averaging along meridians frequently tends to obscure the long-wave pattern. For this reason the computations were carried out along axes slanting from northeast to southwest. For example, the height at 60°N, 100°E, was averaged with those at 50°N, 90°E and 40°N, 80°E.

The long-wave pattern over Eurasia as determined in this manner is featured during the larger part of May by a prominent ridge over central Asia (about 50°E) flanked by troughs at both borders of the continent. Thus the upper flow has a northerly component

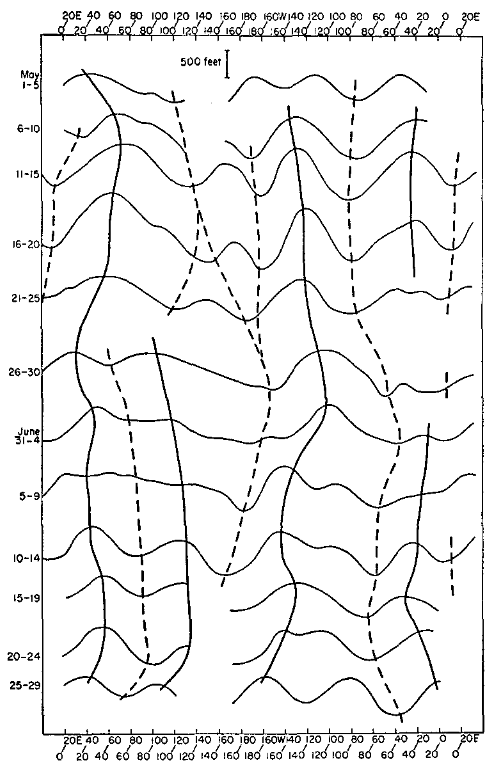


FIG. 7. The average height of the 500-mb surface between 40°N and 60°N as a function of longitude and time, computed for 5-day periods. Vertical dashed lines give the position of the 5-day mean troughs and the vertical solid lines the position of the 5-day mean ridges.

both over and north of India. During the period May 21 to May 25, the imminence of a breakdown becomes apparent as the central Asia ridge weakens and begins to move westward. At this time the monsoon first becomes established over southern India. Subsequently, a mean trough establishes itself in central Asia as the high-latitude jet (fig. 5) progresses southward. After June 9, a long-wave pattern prevails which is almost the inverse of that dominating the continent during May. We see, therefore, that a profound rearrangement of the long-wave pattern has taken place in association with the changes in the distribution of the westerly current. The central Asia trough, apparent during June, must be the northward extension of the trough shown on Wagner's summer map (fig. 2). Thus, after the beginning of June, a mean trough that is continuous from high to low latitudes overlies central Asia. The existence of such polar or extended troughs was discussed by Riehl (1945) and Cressman (1948a).

It is certainly of more than casual interest that the rapid phase shift of the northern long-wave pattern coincides with the equally rapid phase shift of the low-latitude wave pattern, with the northward shift of the southern jet, and with the transition from premonsoon to monsoon regime over India. The monsoon advances after the long-wave pattern of May had broken down, but before the clear establishment of the new regime in the period June 10–14. In the intermediate period of transition, the height profiles over central and eastern Asia are rather flat and we must pass into a more detailed consideration of daily profiles in order to ascertain more closely the linkage between events north and south of the Himalayas. Such profiles were constructed for the interval May 31 to June 12, the period of prime interest (fig. 8).

On May 31, the day on which the retreating monsoon attains its lowest latitude (fig. 5), a ridge overlies the region north of India. On the following days this ridge is supplanted by a trough which stagnates over central Siberia from June 3 to 6 and then rapidly disappears eastward. The burst of the monsoon coincides with the arrival and stagnation of this trough. Another ridge follows. (Its displacement between June 1 and June 4 seems rather discontinuous and this ridge line has been entered on fig. 8 as a smooth line in spite of the profiles on June 2 and 3. This, however, is not an essential feature of the discussion.) Between June 4 and June 7 the ridge advances eastward with weakening. Nevertheless, as it passes across 70–90°E (June 6–8) the monsoon suffers its second setback (fig. 5). The following trough again stagnates in this area and deepens, and the daily profiles assume the same shape as the mean profile June 10–14, while the ECZ again recovers its latitude of June 6.

The foregoing description shows the gradual settling of a mean trough in central Asia. It is characteristic of a region occupied by a mean trough that secondary troughs moving into it deepen (Fultz, 1945), and that the corresponding minor ridges weaken. Such changes of intensity are clearly shown in fig. 8, which therefore suggests that the mean trough begins to form about June 1. In view of the westward motion of a portion of an east Asia trough (fig. 7), the daily events portrayed by fig. 8 can also be interpreted in terms of the mechanism of discontinuous retrogression of troughs of a long-wave band as described by Cressman (1948b).

Opposite changes of intensity of secondary troughs must have taken place over central Siberia during the first part of May when a mean ridge occupied that area. As the deepening and filling of secondary systems relative to mean troughs and ridges has been exhaustively described in the literature, no computation was carried out for that period. Using the description of Fultz (1945) and others, we may infer that in the first weeks of May troughs weaken as they move from Europe to central Asia, and then strengthen until they reach the Pacific coast. Therefore, any effects of superposition of such trough on low-latitude disturbances over India must have been negligible. In contrast, the troughs are no longer damped out over central Siberia after the end of May, and we now observe an interplay between the secondary disturbances of middle latitudes and the monsoon, which is entirely analogous to changes of the intensity of waves in the trade-wind stream under superposition of extratropical troughs (Cressman, 1948a). With the *mean trough* located between 75°E and 80°E, the monsoon surges forth as minor middle-latitude troughs enter the mean trough, and falls back as minor ridges enter the mean trough. Thus the events of June 1946 bear out Rodewald's hypothesis of 1936. As it is well known that oscillations of the monsoon occur throughout the summer, it follows that *analysis of the upper-air conditions over Siberia offers a potent method for forecasting latitudinal displacements and changes of intensity of the monsoon on a short-term basis.*

Thus we have seen that broadscale phase shifts of the long-wave pattern coupled with variations of the latitude of the high-level jet streams governed the

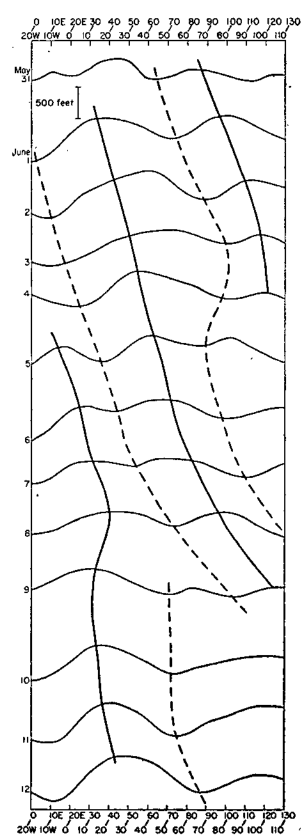

FIG. 8. Average daily heights of the 500-mb surface between 40°N and 60°N as a function of longitude and time. Vertical dashed lines show the position of the daily troughs and vertical solid lines the position of the daily ridges.

seasonal advance of the monsoon in 1946. Studies of conditions in other years are necessary to determine to what extent the events of 1946 have general validity. It appears plausible, however, that the foregoing considerations, which are based not on statistical relations but on physical principles developed primarily in other areas of the globe, have a good chance of general verification.

### 5. Hemispheric wave pattern and zonal current

The correlations of monsoon and low-latitude wave pattern with the westerly jet streams and high-latitude wave pattern offer a method of experimentation for preparing monsoon forecasts over several days. Our study has succeeded mainly in coordinating the monsoon of 1946 with the general circulation changes over Eurasia as a whole, but leaves unanswered such questions as to why the low-latitude jet moved northward and broke down as it did, and why the long-wave pattern in the north changed just at the end of May. Such questions lead us at once to some of the most difficult problems of meteorology for which no one has as yet found complete solutions. Within the framework of this report it appears fitting to describe, in conclusion, a few of the outstanding features of the hemispheric circulation at 500 mb, as presumably any answer to the question just raised must come from at least hemispheric considerations.

It is well known that the latitude at which the strongest westerlies are found is farther north in summer than in winter (Willett, 1944) and that the subtropical ridge line also shifts northward. Thus the progressive weakening of the westerlies in low latitudes, as shown quite generally by fig. 5, is a commonplace occurrence. The interesting feature is the discontinuity in jet streams at the end of May which is reminiscent also of what is observed frequently over North America during spring.[3] There the jet stream of winter tends to remain in low latitudes until late in the season while a second maximum develops over northern Canada. The "Hudson Bay High," a generally recognized feature of North American weather during spring (Bowie and Weightmann, 1917), separates these two westerly streams. Thus there is a rather interesting analogy between conditions over Asia and America.

If we construct a time section of zonal winds similar to fig. 5 for the western northern hemisphere (fig. 9) we see that a separation of jet streams is not in evidence over that portion of the world, although a study of North America alone may well bring out the climatic feature just mentioned. As a whole, the western hemisphere exhibits only one jet which is centered 15 degrees north of the Asiatic jet during the early part

[3] This was brought to the attention of the writer by Professor Riehl.

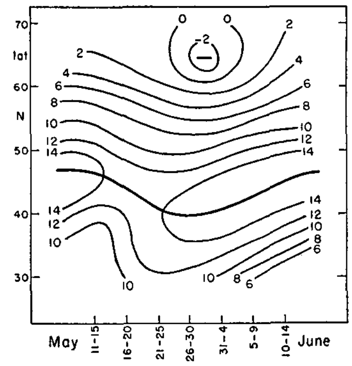


FIG. 9. Meridional distribution of geostrophic west wind as a function of time averaged from 0° westward to 130°E for 5-day periods. Isolines are labelled in m sec$^{-1}$, with the west-wind maximum indicated by the solid line.

of May. There is in existence, therefore, a considerable asymmetry of the circumpolar current relative to an axis coincident with the earth's own axis of rotation.

The second half of May witnesses an organized attempt to eliminate this asymmetry. As the jet works southward in the western hemisphere it moves in the opposite direction over Eurasia. However, when symmetry with respect to the earth's axis is accomplished at the end of May, the Asiatic portion of the jet breaks down, to be replaced by a new jet from higher latitudes. In the middle of June, zonal symmetry is once more in evidence. Although there are several publications of recent years (Rossby, 1947; University of Chicago, 1947; Rossby, 1949) that could be used for interpretation of these occurrences, it appears best to defer evaluation until a much larger sample of diagrams of the kind here assembled is available.

Regarding the long-wave pattern, we find that initially the hemispheric wave number is three (fig. 7). Troughs are situated at the Atlantic border of Europe, over the western Pacific Ocean and over North America. Ridges are encountered over central Siberia, the eastern Pacific Ocean and the eastern Atlantic Ocean. The wave lengths are not uniform but somewhat in proportion to the size of the continents and oceans. Apparently this longitudinal asymmetry represents an unsteady state, particularly over the Pacific where the profile is poorly defined during early May. Soon we note the presence of a separate trough in the east-central Pacific, which does not, however, obtain longitudinal symmetry. On the contrary, as the trough over the central Pacific deepens, and as the jet stream seeks to reduce its own asymmetry with respect to the polar axis, the west Pacific trough breaks down, one part merging with the central Pacific trough and the other retrograding toward Asia. At the beginning of June, the major disturbances undergo changes of position and intensity everywhere, and it is not until the period June 10–14 that one can again distinguish a definite wave pattern consisting of four waves. Thus the state of transformation that we have observed at the end of May in every item studied also applies to the hemisphere as a whole. Reversing the argument, we can state that the flow of the hemisphere in general is disturbed at the end of May and that the broadscale readjustment carries with it the burst of the monsoon as a feature of smaller scale.

## 6. Conclusions

This paper has attempted to correlate the burst of the Indian monsoon with the large-scale circulation changes over the northern hemisphere. Some definite links have become apparent in the course of the study. If these links are found also in other years, the forecasting of the advance of the monsoon, and presumably also its retreat, becomes in large measure a problem of forecasting the northern-hemisphere long-wave pattern and jet-stream positions.

The charts for May and June of 1946 yielded three outstanding pieces of information:

*a.* The burst of the monsoon occurs as a mean low-latitude upper-air trough is displaced rapidly from one steady position near 90°E to another relatively steady position near 80°E.

*b.* One factor that sets the low-latitude trough in motion is the northward displacement of a low-latitude westerly jet. As this jet begins to circle the Himalayas to their north rather than to their south, an orographically imposed phase shift of low-latitude mean trough and ridge positions necessarily follows.

*c.* The northward displacement of the low-latitude jet correlates in time with a general rearrangement of the northern hemisphere long-wave pattern that results in a replacement of a mean ridge by a mean trough over central Siberia. A polar trough then extends all the way from Siberia to the tropics.

The middle-latitude changes—displacement of the low-latitude jet and the formation of a mean trough over central Asia—act cooperatively and simultaneously as regards the monsoon. Whereas local differential heating—the ultimate cause of the monsoon—is unable to produce a northward motion of the Equatorial Convergence Zone while the large-scale dynamic features aloft are unfavorable for such displacement, the rapid reversal of high-level conditions at the end of May allows the Equatorial Convergence Zone to spurt northward subsequently in a spectacular manner.

The ultimate reasons for the developments at high levels in the northern hemisphere must be left open for explanation at a later time. Regarding central Asia, we find that several interesting speculations are possible. We may ascribe the northward motion of the low-latitude jet to the formation of a mean trough over central Asia. Conversely, we can say that the displacement of the jet enforces a rearrangement of the wave pattern. Of the two hypotheses, the latter is perhaps more attractive since it draws on a potent natural constant—the Himalayas. On the other hand, it is very difficult to estimate the order of magnitude of this particular mountain effect relative to the other factors that govern the hemisphere circulation. For this reason, it is best merely to present this last problem, looking for an answer to the future.

*Acknowledgments.*—The writer wishes to acknowledge the leadership and assistance of Prof. H. Riehl in the various aspects of this investigation. He also wishes to thank Dr. W. Bleeker, visiting Professor at the University of Chicago, under whom the analysis of the Equatorial Convergence Zone was completed.

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