VARIATIONS IN THE STRUCTURE OF THE UPPER WESTERLIES

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ABSTRACT

This study indicates that the jet streams which are observed on meridional cross sections appear first at high latitudes and usually shift slowly southward to low latitudes, where they eventually disappear. It is common to observe the presence of more than one upper west-wind maximum at the same time but at different latitudes. Average variations in the speeds of these maxima are studied. Splitting of a single west-wind maximum into two distinct maxima is occasionally observed on a hemispheric scale.

1. Introduction

In recent meteorological literature and practice there has been increasing use of the curve of the west-wind components averaged over a given band of longitudes on a constant-pressure surface. These are plotted as a function of the latitude for the representation of the intensity and position of the upper west-wind circulation. Examples of these curves can be found in [2] and [8]. Changes in the latitude and speed of the maximum west wind have been studied with respect to their relation to large-scale perturbations in the westerlies and with respect to other quantities related to the general circulation. However, no explanation exists at the present time for these changes, which occur during periods of from several days to several weeks. Although the existence of the atmospheric jet stream [6], [7], and [11] has been thoroughly demonstrated, no systematic study has been made of the jet stream on a hemispheric scale, or of its relation to the changes of the meridional profiles of the upper west wind.[3]

An investigation was made by Baum [1] to study the behavior of the jet at 700 mb from month to month over the North American continent. Baum computed the average geostrophic west wind for each month over each of the bands of five degrees of latitude for meridians ten degrees apart over North America. From these data, mean monthly positions of the jet stream for the months from July 1947 through June 1948 were determined. One interesting result of this work was that in most of the winter and spring months an essentially double structure of the jet was evident. The two jets observed on the mean charts were generally continuous across North America, about fifteen to twenty degrees of latitude apart. This result lends itself to two interpretations Separate daily cross sections for the same months would show either a single jet with two strongly preferred positions or two pronounced and persistent jets.

In view of the importance of the changes in the intensity and position of the maximum on the upper west-wind profiles, mentioned above, this study was begun in an attempt to obtain a description of the position and shifts of the jet stream (or streams) on a hemispheric scale, and the relation of these shifts to changes in the west-wind profile for upper level charts.

2. Analysis of mean cross sections

A first attack on this problem was made with the preparation of a series of ten mean cross sections. Each of these represents the geostrophic west wind and the potential temperature at a given time over the North American area, from 60°W to 130°W, and generally from about 25°N to about 65°N. Each of the ten mean cross sections represents the average of the eight individual north-south cross sections containing geostrophic west wind components and potential temperature. The latter were prepared at ten-degree longitude intervals from the constant pressure charts drawn for the 1000-, 850-, 700-, 500-, 300-, and 200-mb surfaces. The eight cross sections for each day were then averaged together, the center of averages being taken as the line following the strongest continuous wind maximum on the 300-mb chart for that day.

Fig. 1 contains the resulting ten mean cross sections. The center of averages for each mean section is indicated by a solid vertical line. The mean cross sections are located on the latitude scale of fig. 1 according to the mean latitudes of the centers of averages. The double arrows indicate the continuity of the individual jets from day to day. This continuity was established from the successive mean cross sections and 300-mb charts.

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[1] Submitted as a contribution to a research project on the general circulation sponsored by the Office of Naval Research.

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[3] Rossby [10] has suggested that the formation of jets may be considered a consequence of some kind of a turbulence wave which emanates from high latitudes and gradually advances southward during a certain time interval.

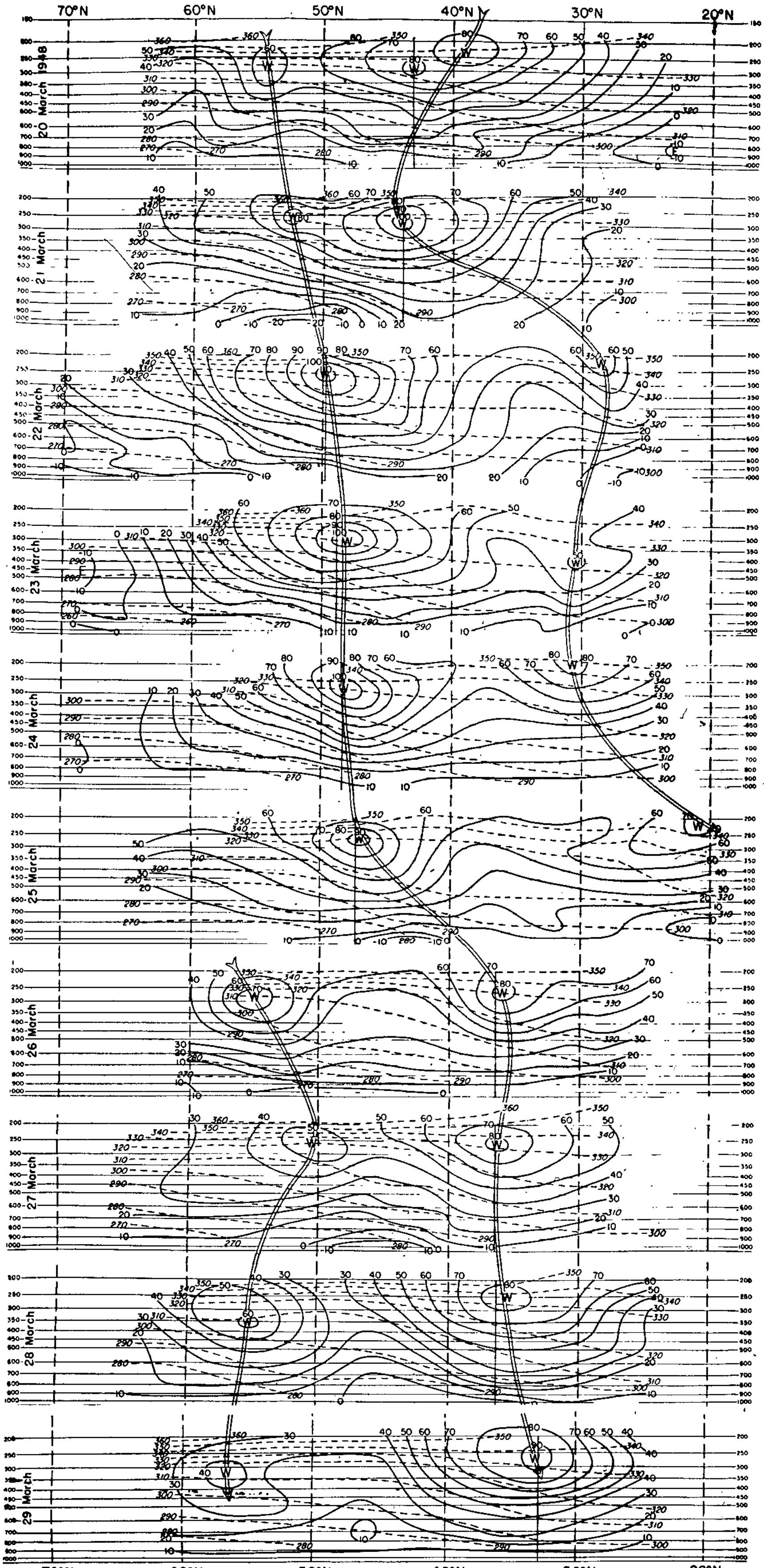

Fig. 1. Mean cross sections for the North American area. Solid curves are lines of equal geostrophic west-wind component in mph. Broken curves are lines of equal potential temperature.

The following observations can be made from fig. 1:

1. On each of the ten days there were two distinct maxima of west wind in the high troposphere.
2. There appears to be a disappearance of one maximum in the south and the appearance of a new maximum in the north. The east winds in the north on 23 March change to west by 25 March, and the new maximum appears on the cross section for 26 March.
3. A general net southward shift of the separate maxima is shown.
4. The jets in the south are found at higher elevations and in association with higher potential temperatures than those in the north.
5. The separate identity of each jet is most easily observed between 200 and 300 mb, but is often difficult to establish at 500 and particularly at 700 mb. This may be partly a result of the averaging process.

Several weaknesses are evident in the above study of mean cross sections. One could argue that the mean cross sections are not necessarily representative of conditions on a hemispheric scale.[4] Furthermore, a given ten-day period might prove to be unrepresentative of conditions in general. However, a geographical extension of the mean cross sections was not possible due to the lack of detailed high-level data over the oceans. It was not possible to extend the ten-day period because of the enormous amount of work necessary for the preparation of such mean cross sections.

3. Study of extended high-level constant pressure charts

Since the west-wind maxima are most pronounced near the 300-mb surface, a suitable analysis of their positions and shifts can be made for periods when extended 300-mb charts are available. The *Tyrena* project, sponsored by the Office of Naval Research, under the direction of Dr. H. Riehl, has prepared a series of very carefully analyzed 300-mb charts for the latter part of 1945 and the early part of 1946, when the greatest amount of high-level data was collected. Dr. Riehl has kindly made these charts, which cover most of the northern hemisphere, available for this study.

[4] Messrs. Phillips and Kuo of the Department of Meteorology, University of Chicago, have analyzed a series of daily cross sections along the 80th meridian for the months of January and February, 1948. Although their work is open to this same objection, they have found always more than one jet present. They have also found that during some of the time there was a net southward shift of all jets of the average order of magnitude of one to two degrees latitude per day. For other periods the jet streams showed much slower southward shifts. It is to be hoped that their results will be published as their study is, by nature of the smaller-scale attack, more objective than this one. In most cases their continuity can be seen easily.

This study was further extended with the aid of northern-hemisphere 500-mb charts prepared in the general circulation project, sponsored by the Office of Naval Research and being conducted by the University of Chicago. Although 500 mb is not as suitable as the 300-mb surface, care was taken to make use of all available 300-mb data. The period during which these charts were used extends from early October 1948 to early April 1949.

Two processes became evident in the course of the study. The first was the observation on a hemispheric scale of the process observed on cross sections, *i.e.*, the formation of west-wind maxima in the north, the southward shift of these maxima, and their disappearance in the south through breaking up into closed vortices.

An illustration of this process is shown in fig. 2. The chart for 27 July contains a suggestion of a circumpolar vortex in the polar regions. This vortex expands and is a distinct west-wind current on a hemispheric scale by 12 August. On 27 July there is also a faint suggestion of some lower latitude westerlies, except over North America. These are the remnants of a jet stream which broke up into vortices and became discontinuous. The main current of westerlies on 27 July has shifted southward with weakening by 12 August. It can be observed from figs. 2 and 3 that, although separate jet streams can easily be observed on a hemispheric scale, they occasionally appear to coalesce in one or more regions. This fact can be associated with the appearance of separate wave patterns of different wave lengths in the individual currents.

Such differing wave patterns at different latitudes have been described by Namias. A local coalescence of the two currents, which occurs in connection with perturbation phase differences in northern and southern currents, comes under the classification of *confluence*, which has been studied in detail by Namias, Clapp, and their associates [5]. The presence of such regions of confluence between the two streams means that there must be a certain amount of exchange of air and of momentum between the two hemispheric jet streams.

Fig. 3 illustrates another process which has been observed on the constant pressure charts. The chart for 22 February shows one well defined middle-latitude west-wind maximum. By 27 February this maximum has split into a double maximum on the west and east coasts of North America. By 4 March the splitting is evident over Europe, and by 9 March over the east coast of Asia. On 9 March the existence of a well defined double maximum on a hemispheric scale is shown very clearly at 500 mb. As shown in fig. 8, this double maximum proved to be a very stable arrangement.

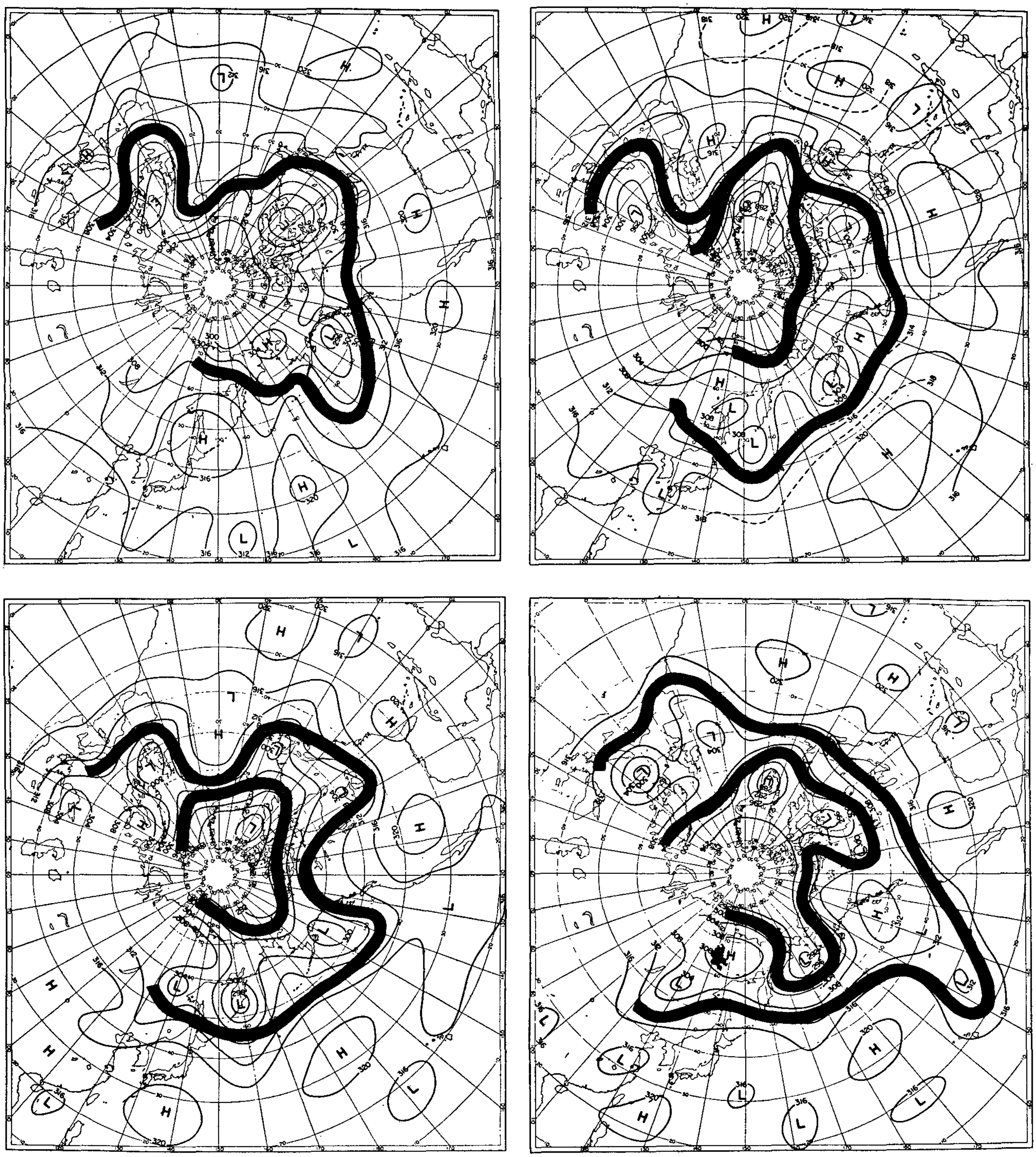

FIG. 2. 300-b charts for 0300 GCT at five-day intervals from 27 July (upper left) to 12 August (lower right) 1945. Upper right is 2 August; lower left is 7 August. These contain the 400-ft contours copied from the *Tyrena* project maps. The solid bands indicate approximate location of zones of maximum wind.

The existence and structure of *cut-off lows* or *kaltlufttropfen* has been discussed in detail in German and American publications; for examples, see [4] and [11]. The tendency of several of these to form at about the same time at widely separated places on the hemisphere was discussed in [2]. This present study has suggested that the splitting process, described above, leads to the formation of several cut-off lows within several days. They mark the trough positions of the long-wave pattern in the southern current. If the splitting and cyclone formation occur at relatively low latitudes, *e.g.*, about 40°N, the lower latitude jet stream would be most intense at or above 200 mb, and would be largely obscured at the 700-mb

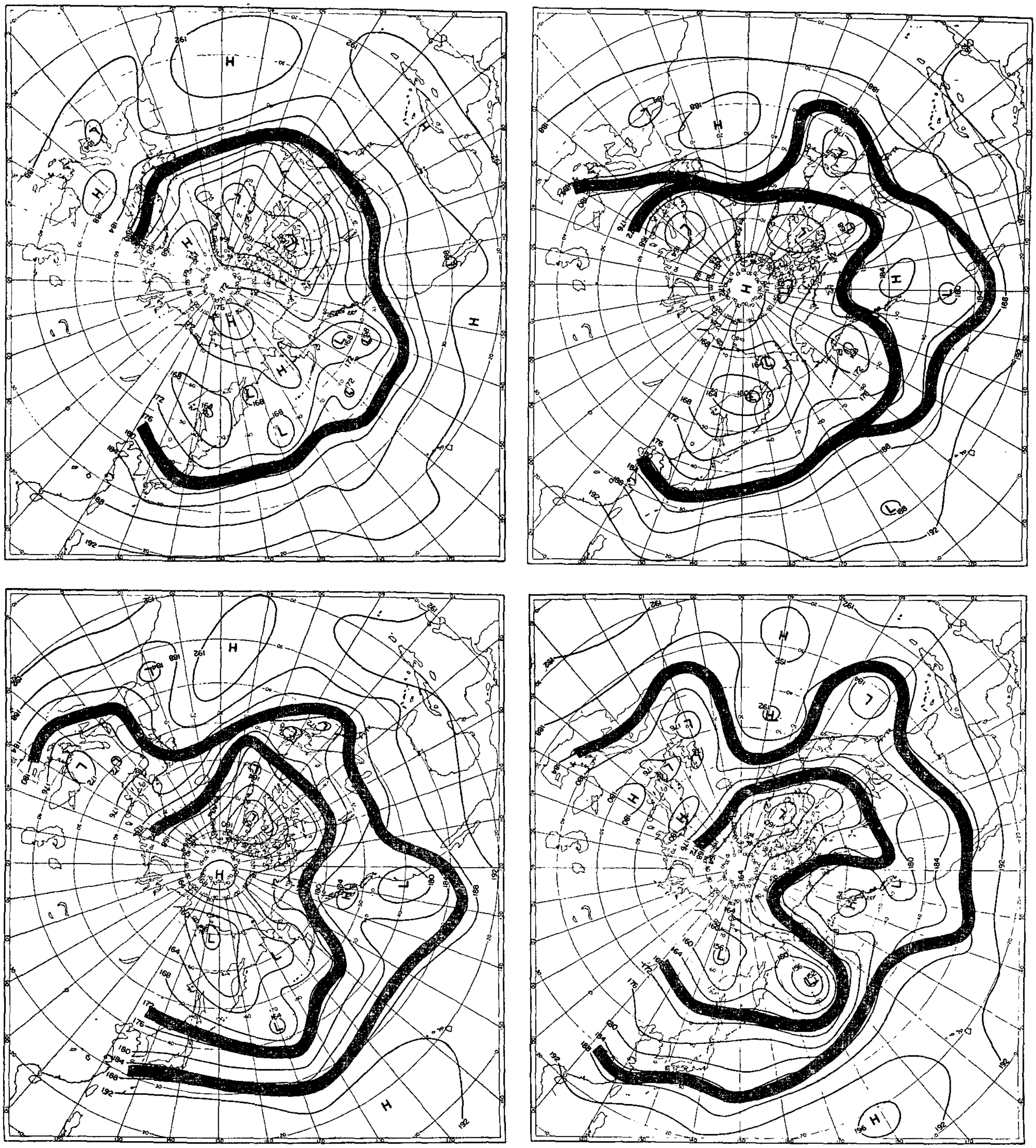

FIG. 3. 500-mb charts for 0300 GCT at five-day intervals from 22 February (upper left) to 9 March (lower right) 1949. Upper right is 27 February; lower left is 4 March. Solid bands indicate approximate location of zones of maximum wind.

surface. The cut-off lows would then appear to be isolated cyclones, without any connecting current at 700 mb.

The splitting of a single, well defined jet stream is an extremely important process from both synoptic and theoretical points of view. Before the splitting takes place, the extended upper-air maps have an unusually uncomplicated and simple appearance. The splitting occurs very rapidly, and the original simple synoptic patterns change their aspect completely within a very short time. This study has suggested that a synoptic pattern consisting of a single high-level west-wind maximum, containing long waves of small amplitude, such as is found in the 22 February chart in fig. 3, is in itself unstable, and must necessarily break down into a more complicated pattern by means

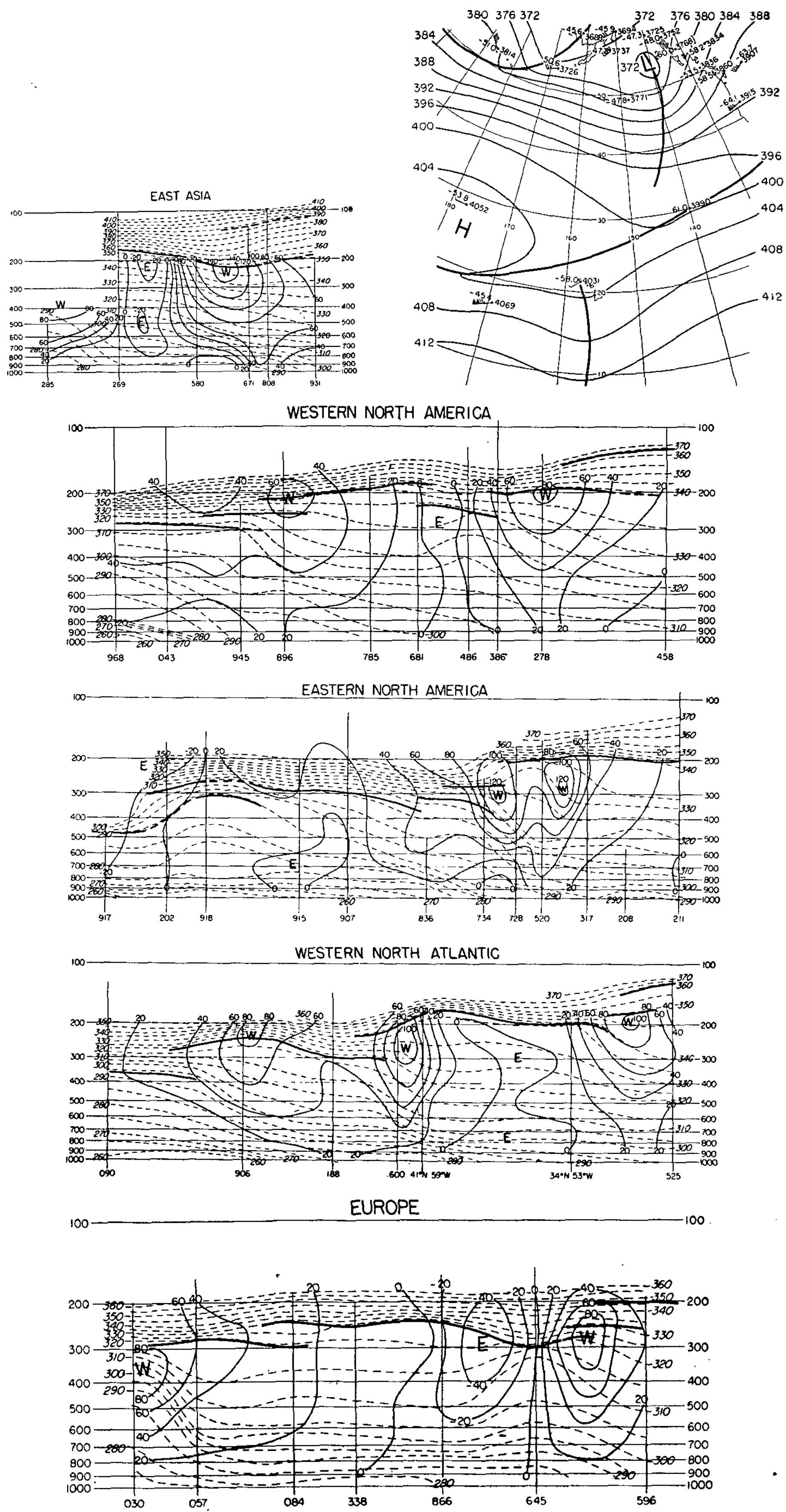

FIG. 4. Meridional cross sections and 200-mb chart for 0300 GCT 27 April 1949. On the cross sections dashed lines are isentropes; solid lines are lines of equal geostrophic wind speed in knots perpendicular to the sections; heavy lines are tropopauses. Fronts are omitted. Vertical lines represent vertical extent of soundings used.

of a splitting of the maximum. Further investigation of this problem seems desirable.

4. Horizontal extent of the jet streams

The maps available for this study did not contain enough consistently good data for central or southern Asia for a complete study of the horizontal extent of the wind maxima. Therefore, when a *hemispheric wind maximum* is discussed here, it should be understood that the above regions were not included in the study.

An ideal way to investigate the horizontal continuity of the various wind maxima would be to draw north-south cross sections of geostrophic wind and potential temperature at close intervals around the hemisphere. Although this is not entirely possible, an approach to this technique was attempted for 27 April 1949. All the data available permitted the analysis of five extended cross sections approximately along the longitudes 10°E, 60°W, 80°W, 115°W, and 135°E. Since no north-south cross section could be constructed for the central Pacific, a 200-mb chart for that region is included in fig. 4.

The high-level constant-pressure charts for this date indicate a well-defined double maximum of west wind. The charts in fig. 4 show that all the meridional cross sections which could be constructed for this date also contain this double maximum. The western Atlantic cross section shows a third maximum, in the north, but this is either a local phenomenon or else too far north at other longitudes to appear on the other sections. The 200-mb chart for the Pacific shows very clearly the existence of the double wind maximum in this region.

It is impossible to say how accurately the maximum wind speed can be represented in cross sections such as those in fig. 4. However, with this fact in mind, it can be seen that there is a variation from 80 to 140 knots in the highest speed in the southern jet. The maximum speed of the northern jet is not shown on the east Asia cross section due to lack of data, but elsewhere the highest speed in this jet varies from 60 to 120 knots. Although the geostrophic wind component perpendicular to the cross section is used in each case, this represents nearly the total geostrophic wind speed, since all the cross sections are nearly perpendicular to the streamlines. The cross sections also show that the wind maxima in the south are found at slightly higher elevations and in association with higher potential temperatures than those in the north. However, potential temperature is not even approximately constant along the centers of the jet streams.

The wind maxima are found in the vicinity of the tropopause and are much less distinct at 700 mb. These sections show that no adequate picture of the structure of the westerlies can be gained from the 700-mb chart. The ideal chart for that purpose would be the 300-mb or the 200-mb chart.

5. Time variation of the position of the maxima

In order to study the shifts of the hemispheric wind maxima over long periods of time, an average latitude and an average speed for each jet stream were determined from the maps prepared by the *Tyrena* project. These were determined from measurements of the latitude and speed of each hemispheric wind maximum at its intersection with the ten-degree meridians. The averages then represent the speed and latitude of each jet from 120°E eastward to 20°E. Occasionally a map would appear on which the locations of the hemispheric wind maxima were obscure, due to missing data or other reasons. In such cases, continuity from day to day was the guiding principle for the solution of the difficulty.

Fig. 5 shows the average latitudes of the hemispheric jets which were found on the *Tyrena* maps as a func-

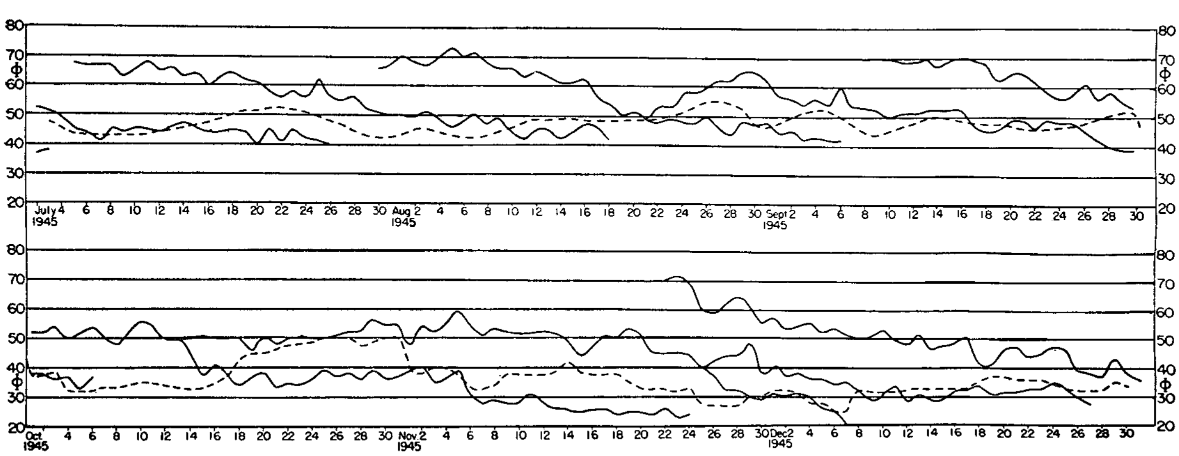

FIG. 5. Average latitude (solid lines) of hemispheric jet streams measured from the 300-mb charts for 1945 from the *Tyrena* project. The broken line represents the maximum of the 300-mb geostrophic west-wind profile for the area from 110°E eastward to 20°E. averaged with overlapping three-day averages.

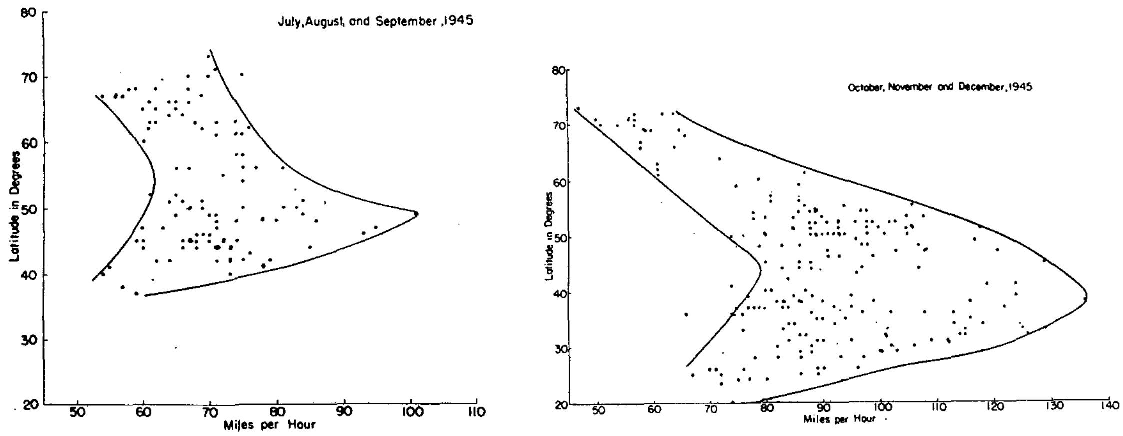

FIG. 6. Average speeds of the jet streams at 300 mb, which are shown in fig. 5. Each point represents the average speed of a jet stream on a given day plotted against its average latitude for the same day. The solid lines are approximate envelopes of the points.

tion of time. A fairly regular southward shift of all jet streams can be observed, with the exception of periods immediately following the splitting of one maximum into two. The speed of the southward shifts appears to be approximately one-half degree of latitude per day. During the latter part of August, after the splitting of the jet stream, the resulting northern wind maximum shifted about fifteen degrees of latitude northward before its southward shift began. Stagnation of the maxima occurred in late October. However, the southward shifting was under way again by mid-November. These renewed southward shifts brought the strong wind maxima to much lower latitudes than observed previously, reflecting the normal seasonal changes in the westerlies.

In general it can be seen that with few exceptions the shift of the latitude of a wind maximum is a slow, long-term process. This fact has some possible value in the field of long range forecasting, since extrapolations of the shifts of the various wind maxima should usually yield good results for five or ten day periods.

Fig. 6 shows the speeds of the jet streams at the various latitudes for two successive three-month periods. Since the jet streams were shifting southward more or less continuously, it seems permissible to conclude that they increase in speed until they pass a certain latitude, and then further southward shifts are accompanied by decreases in speed. The southward shift and increase in speed of the region corresponding to the maximum jet speed as the season advanced compare well with results given by Fultz, summarized in fig. 18 of [3].

Fig. 7, representing the changes of speed of two individual jet streams during their southward shifts, shows the same seasonal change. The changes shown here agree with the conclusions drawn from fig. 6 with respect to the changes in the individual jets and also with respect to the seasonal variations. This figure is suggestive of the theoretical curves computed by Rossby, shown in fig. 3 of [9].

The curves shown in fig. 8 represent the changing latitudes of the hemispheric wind maxima from early October 1948 to the middle of April 1949, as measured from northern-hemisphere 500-mb charts from 120°E eastward to 30°E. The 300-mb charts for North America, the North Atlantic, and Europe were also used for the location of the jet streams. During the period covered by fig. 8 there was much more stability of the position of the jet streams than during the period covered by fig. 5. The continuous southward shifts were observed from late December to early March, their order of magnitude being about one degree of latitude per day. Otherwise there was very little shifting of the jet streams except for a week or two after a splitting was observed.

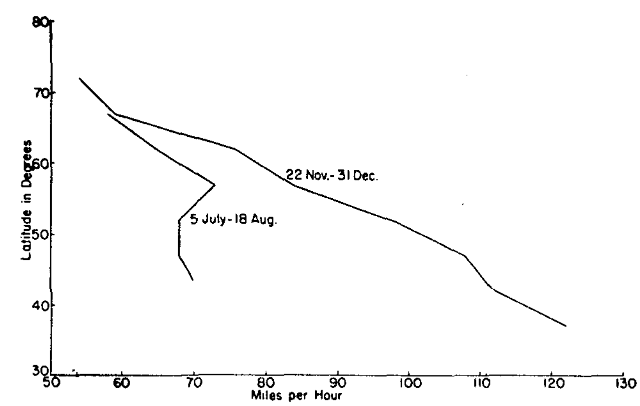

FIG. 7. Relation of the average speeds to the average latitudes for two separate jet streams at 300 mb. The jet streams shown are also represented in fig. 5, the one appearing at high latitudes on 5 July and the other appearing at high latitudes on 22 November. The average speeds of the individual jets for separate days were averaged according to the average latitudes of the jets for the separate days, grouped into class intervals of five degrees latitude. The final fate of the second jet is not known, as it was still strong and pronounced on 31 December 1945, when this analysis was stopped.

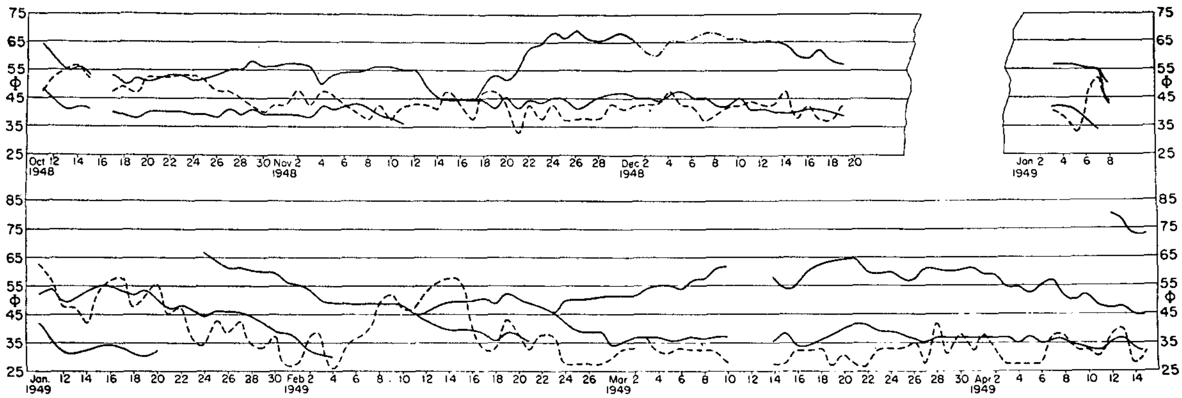

FIG. 8. Average latitudes (solid lines) of hemispheric jet streams measured from the 500-mb charts, supplemented by 300-mb charts for late 1948 and early 1949. The broken line represents the maximum of the 500-mb geostrophic west-wind profile for the area from 125°E eastward to 30°E. Individual daily values are shown.

Changes of the latitude of the maximum west wind, as observed on the north-south profile of west wind over a large area, appear to be related to the changing latitudes of the jet streams in a fairly clear manner. Figs. 5 and 8 indicate that the maximum on the west-wind profile shifts southward in coincidence with the southward shift of a pronounced jet stream. Northward shifts of the maximum on the west-wind profile are associated with the weakening and disappearance of a jet stream in the south, and the beginning predominance of another jet stream farther north. It seems likely that the northward shift of the maximum on the west-wind profile could occur in coincidence with the northward shift of a jet stream, after the splitting process has occurred, but this has not yet been observed.

In addition to the long-period shifts of the hemispheric wind maxima described above there seems to be a process whereby a jet will split locally, with one of the resulting maxima shifting rapidly northward or southward, and becoming involved in a closed vortex with its eventual disappearance. It is emphasized, however, that this is a relatively local process of an entirely different magnitude, both in space and time, from the processes described above.

6. Conclusions

This study has shown that the upper tropospheric westerlies are usually composed of two hemispheric maxima, or jet streams. These maxima form in high latitudes, gradually shift southward, and disappear in low latitudes. Splitting of the jet streams is occasionally observed, when a single jet stream in middle latitudes separates into two distinct jet streams. The southward shift of the jet streams occurs at a speed of one-half to two degrees latitude per day, but is occasionally interrupted for periods of several weeks or longer, when little or no shift of the west-wind maxima is observed.

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