Life History of Mobile Troughs in the Upper Westerlies

FREDERICK SANDERS

Marblehead, Massachusetts

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ABSTRACT

Increasing evidence indicates that surface cyclogenesis is predominantly a response to the approach of a preexisting trough at upper levels. A question then arises about the origin of the upper-level predecessor. As an initial approach to this question, mobile troughs in the major band of westerlies were crudely tracked in daily Northern Hemispheric 500-mb analysis during nine recent cold seasons. These troughs were identified only in the 552-dam height contour. Between 8 and 15 of them were present on a given day. Study of a particular cold season showed a median duration of 12 days and a mode of 5 days. Average zonal phase speed was 13 m s^{-1}.

Locations or origin and termination of individual troughs were distributed over all longitudes, but births greatly exceeded deaths over and east of the Rocky Mountains in North America and the highlands of central Asia. Trough terminations dominated over the eastern portions of the oceans. Within the quasi-steady planetary waves, origins and terminations of the smaller mobile troughs occurred preferentially in northwesterly and southwesterly flow, respectively.

More detailed studies of the structure during episodes of origin over North America showed prominent vertical and lateral shear in the time-averaged 500-mb flow, rapid growth of the perturbations through the depth of the troposphere, with a vertical tilt upshear only in the lower half, pronounced maximum amplitude near the tropopause, and a variety of circumstances in which troughs became organized in the belt of major westerlies.

1. Introduction

The geographical distribution of surface cyclones and cyclogenesis has received much attention for many years, from the comprehensive summaries of Petterssen (1950) and Klein (1958) to more recent regional studies, e.g., for the East China Sea by Hanson and Long (1985). The association of surface cyclones with upper-level troughs has also been studied for many years since Bjerknes (1937) and Bjerknes and Holmboe (1944).

Traditional thinking about cyclogenesis has been to regard it as a process in which the disturbance grows simultaneously at all levels from infinitesimal beginnings. Petterssen (1955), however, noted that over the United States cyclogenesis typically occurred when an area of upper-level cyclonic vorticity advection associated with an advancing, *preexisting* trough became superposed over a low-level baroclinic zone. He commented that this finding should not come as a surprise because numerous such upper-level features were typically available. Palmen and Newton (1969) indeed noted that substantial perturbations are typically present aloft prior to the development of lower-tropospheric disturbances.

Petterssen et al. (1962) distinguished between this mode of surface cyclogenesis and the more traditional sequence of events in which there was no upper-level predecessor and the flow aloft was more or less straight. These two types were said to be characteristic of the North American continent and of the North Atlantic Ocean, respectively. They were denoted B and A by Petterssen and Smebye (1971). In a study of 48 recent instances of explosive cyclogenesis in the western North Atlantic, however, Sanders (1986) found that a preexisting upper-level trough of substantial intensity played a crucial role in every case.

We may thus speculate that Type B cyclogenesis predominates everywhere and that the characterization of oceanic cyclogenesis as Type A was attributable to the relatively sparse oceanic data coverage at upper levels, which until recently has failed to reveal the near ubiquity of the upper-level predecessor. As to theory, Farrell (1985) has argued that inclusion of realistic Ekman damping in a model of cyclogenesis precludes significant exponential instability of cyclone-scale waves, but has shown on the other hand that strong transient intensification can result from an initial configuration resembling the Type B situation. So perhaps the predominance of this type is not only actually, but necessarily, observed.

Where then do the upper-level troughs come from? The question appears hardly to have been addressed in the literature. The presumption may have been that they arose in the process of Type A cyclogenesis. If this source is not available, then there must be another (if we can discount the possibility of the eternal life of a

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Corresponding author address: Dr. Frederick Sanders, 9 Flint Street, Marblehead, MA 01945.

set of primordial upper-level structures). This paper reports on an initial inquiry into this question.

2. The data

a. An approach

In an attempt to represent the gross features of the daily evolution of the circulation pattern at the 500-mb level with maximum economy, weekly compilations of the seven daily 0000 UTC positions of the 552-dam contour of the height of this surface around the Northern Hemisphere, taken from the analyses of the National Meteorological Center (NMC), have been accumulated (except during the summer months) from October 1976 until May 1984 in the synoptic laboratory at the Massachusetts Institute of Technology (MIT), and again during the 1985/86 cold season. When the map for 0000 UTC was missing, the position of the contour was interpolated, with guidance from other 500-mb maps for this time or for the adjacent 1200 UTC times. In all, 295 weeks were examined, as indicated in Table 1. The 552-dam contour was selected to represent in an optimum way the major band of circumpolar westerlies. Mobile troughs along this contour were identified each day, and note was taken of the dates and locations of their first and final appearances.

Whether or not a trough exists in a given map analysis is, of course, a subjective question. Some analysts' imaginations may be more vivid than others' (although most situations are unambiguous). This question seems never to have been asked in the identification of surface cyclones. The presence or absence of a low-pressure center is often defined by the presence or absence of a closed sea-level isobar around it, a seemingly objective criterion. But it is not that straightforward. What is the isobaric interval? For what pressure values are isobars given? Is the analyst (or analysis algorithm) given to showing numerous centers, or inclined toward a skeptical smoothing? It seems that in the case of surface lows the determination of existence is both subjective and arbitrary, yet we regard the results as robust. We hope for the same acceptance here.

A trough in a contour can be defined as either a local extreme in the equatorward deflection of the contour, or as a local maximum of cyclonic curvature of the associated geostrophic flow. We will use the latter definition, because we wish to associate the trough with a local maximum of geostrophic vorticity along the flow, because of its dynamical significance. On some occasions we regard a segment of straight contour flanked by ridges as a trough, provided there is good day-to-day continuity. At other times we choose to ignore a small but clear trough, provided there is little temporal continuity or if the feature occurs in a region where the quality of the data is felt to be less than satisfactory. These latter 2 disqualifying circumstances often occur together. We readily grant, however, that an element of subjectivity remains, and that another person, even given the same set of contours, would make some different judgments. We hope that these differences would not be numerous, however, and offer a sample for individual judgment.

TABLE 1. Periods of data collection.

2 October 1976–15 April 1977
10 September 1977–19 May 1978
9 September 1978–13 April 1979
29 September 1979–18 April 1980
6 September 1980–29 May 1981*
5 September 1981–28 May 1982
11 September 1982–27 May 1983
10 September 1983–21 April 1984
14 September 1985–18 April 1986

* Maps missing 27 March–4 April.

b. An example of mobile troughs

A 500-mb analysis, for 22 February 1986, appears in Fig. 1, while a continuity chart for the 7 days starting on this date is seen in Fig. 2. The analysis shows the major band of circumpolar westerlies between 30° and 40°N, with numerous undulations. These westerlies were broken and feeble across western and central Asia, where more vigorous flow surrounded a trough farther north at 75°E. Another break occurred over the Atlantic, where a weakly cutoff low was seen near 30°N, 60°W. Other more-or-less fragmentary bands of strong flow were seen in higher latitudes, associated with cellular cyclonic and anticyclonic circulation centers.

The 552-dam contour followed the major belt of westerlies, most closely across the Pacific and from the central Atlantic to the central Mediterranean Sea. Over much of Asia it followed the southern periphery of the northern belt of strong flow, while across North America it tended to lie in a region of weak flow between ill-defined maxima.

Those mobile troughs in the 552-dam contour for which continuity could be established for more than one day are denoted by letters. There were 12 of these, 2 of which were making their final appearance. These are the features whose life histories we wish to investigate.

Local maxima in the wind speed, which could be regarded as geostrophic jet streaks, were associated with troughs R, C^2 (the superscript arising because after a cycle through the alphabet the old C still survived), F, N, S, J, G and H. A number of other geostrophic jet streaks could be seen, both north and south of the 552-dam contour. In most instances they could be associated with troughs of limited extent in a direction transverse to the larger-scale flow. We will thus regard jet streaks and mobile troughs as synonymous in a sense, whether or not occurring on the 552-dam contour. (From geometric considerations, geostrophic jet streaks

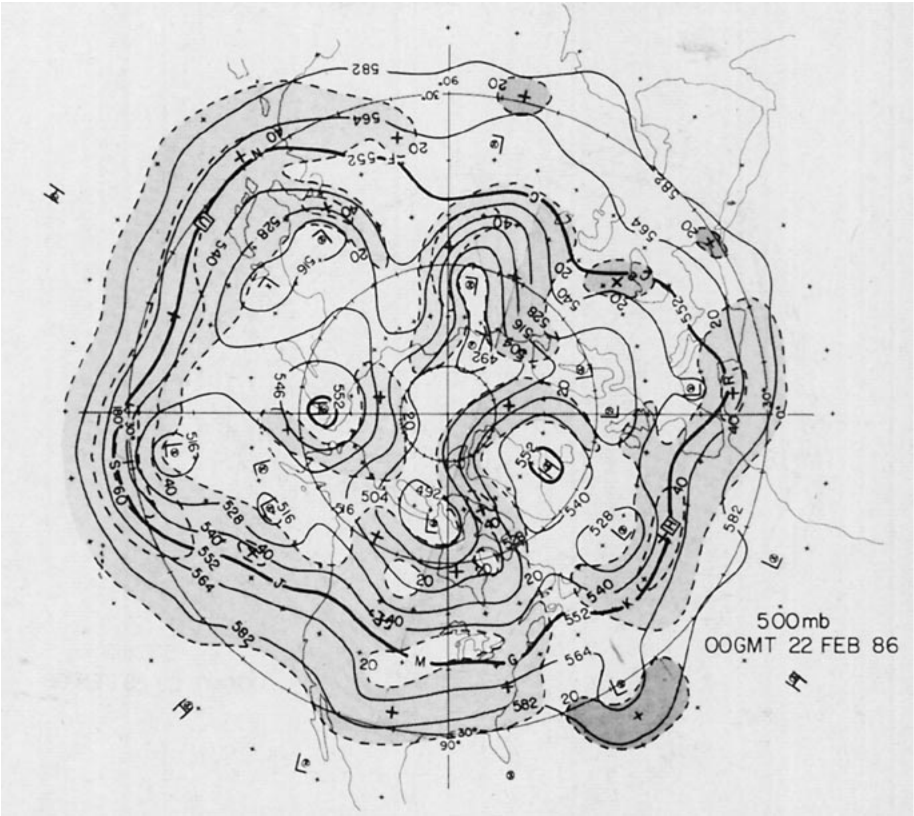


FIG. 1. Sample hemispheric 500-mb chart. The solid lines are contours of height, at intervals of 12 dam. The dashed lines are isotachs of geostrophic wind speed, at intervals of 20 m s^{-1}, with the area of speed more than 20 m s^{-1} shaded, and with a plus sign indicating a center of maximum speed. Positions of mobile troughs are denoted by letters. The box around a letter signifies that this day was the last on which the trough could be identified.

could as easily be associated with ridges of limited transverse extent, or with troughs and ridges in transverse juxtaposition, and one can see some examples in Fig. 1. The association with troughs, however, is more frequent.)

The continuity chart for the 7-day period starting 22 February (Fig. 2) shows that the ten mobile troughs that survived the first day moved eastward at about 15 deg longitude per day, representing at 40°N a speed of about 15 m s^{-1}. Since the average zonal speed along the 552-dam contour was somewhat greater than this, the waves were propagating westward against the flow. During the week, four of the ten surviving troughs (S, G, R, and C^2) terminated, joining the two last seen on 22 February, but seven new ones (O, P, Q, T, U and a new R and S) developed. One of these could be identified on only 2 days, so that the next 7-day period would begin with 12 troughs, as did the one under consideration.

c. An example of quasi-stationary features

A different type of disturbance is also seen in Fig. 2, one which moves very little and has a relatively long wavelength. The most prominent example is a trough near 165°W, in which the positions of the 552-dam contour were far south of the long-term average on all 7 days. This longitude is one identified by Dole and Gordon (1983) as a favored site for height anomalies persisting far beyond the time period associated with the passage of transient disturbances of synoptic scale. Three of such disturbances (mobile troughs S, N, and F) in fact passed through this nearly steady large trough during the week.

Looking downstream we can see a number of additional nearly-stationary features: a ridge in western and a trough in eastern North America, a ridge in the central Atlantic, a broad complex trough across Europe, a ridge in central Asia and finally a small-amplitude doublet with trough south of Japan and ridge just west of the Date Line. The mobile troughs, and their undesignated ridges, are seen to move eastward on gently undulating paths through the quasi-stationary features. The stationary (hereafter dispensing with "quasi") features were larger on the whole than the mobile ones, although the distinction in places was slight. For example, the separation between mobile troughs N and

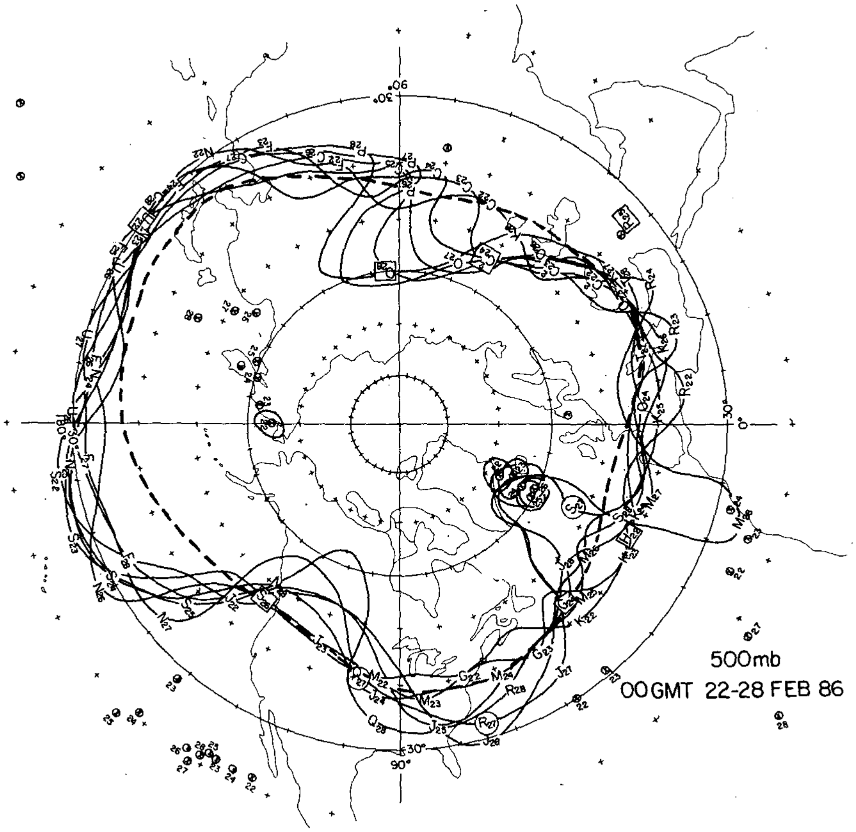


FIG. 2. Sample weekly composite of 0000 UTC positions of the 552-dam contour of 500-mb height. The positions of mobile troughs are denoted by letters, with a subscript indicating the date. A box (circle) around the letter signifies that this date was the last (first) on which the trough could be identified. The heavy dashed line is the long-term mean position of the contour for this week.

S in Fig. 1 was 60 degrees of longitude, while the distance between the stationary ridges over western North America and the central Atlantic was only 80 degrees. Our experience has been that it is more satisfactory to distinguish between mobile waves and stationary waves than between short and long ones.

Other slow-moving features are the cutoff highs of high latitudes and cutoff lows equatorward of the 552-dem contour. A number of these are seen in Fig. 2. Of the former, the anticyclone near 30°W was absorbed by the adjacent growing stationary ridge, while the one initially on the Date Line was seen in the last days of a lifetime which began in 11 February in a stationary ridge in the eastern Pacific and was about to end with merger into a mobile ridge near 150°E on the 28th. Of the cutoff lows of lower latitudes, only the one at 40°E derived from a trough (R) in the 552-dam contour, and its lifetime was atypically brief.

3. The duration, phase speed and scale of mobile troughs

During the period from 14 September 1985 to 18 April 1986, when a detailed accounting of mobile troughs was maintained, the number of them identified on Saturdays varied from 8 to 15, as can be seen in Fig. 3. The weekly sum of beginnings and terminations is seen (also in Fig. 3) to vary irregularly from 3 to 18.

The duration of the 153 mobile troughs during the 1985/86 season is shown in Fig. 4. The distribution is highly skewed, with a median at about 12 days, a mode near 5 and a few lasting more than a month. The senior attained 57 days, not we hope the result of sympathetic encouragement by the author. Although we are not aware of statistics on this point, our impression from synoptic experience is that the duration of individual surface cyclones is substantially less.

The journeys of two of the longest-lived troughs are illustrated in Fig. 5. For each date, a segment of the 552-dam contour is shown, encompassing the trough and the two flanking mobile ridges (or presumed vorticity minima).

The first, Trough M, was initially detected within a large-scale trough over western North America on 18 September. It traveled twice and nearly one-quarter around the hemisphere, terminating just west of the British Isles on 13 November. With an average latitude

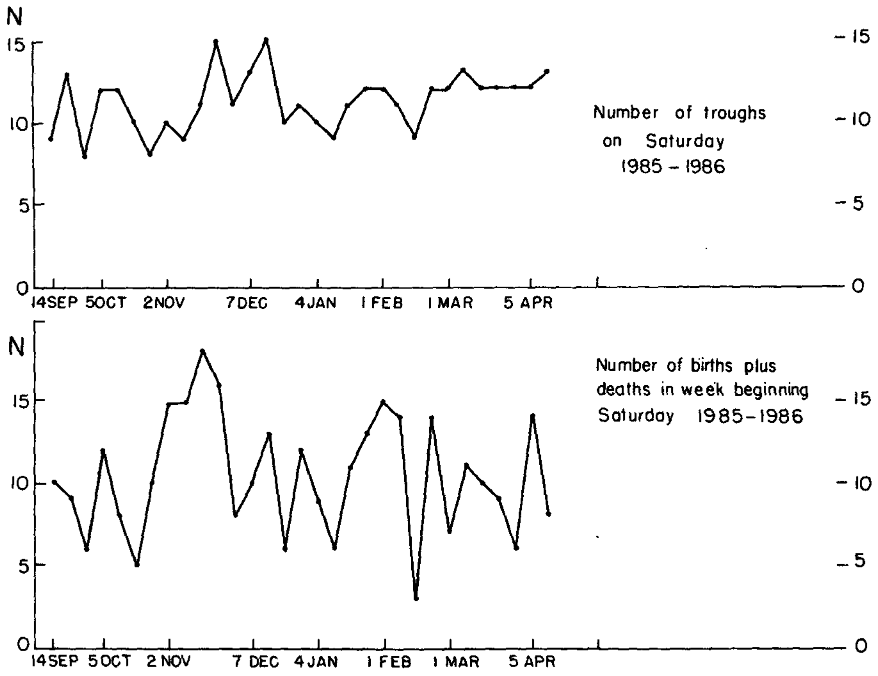


FIG. 3. Weekly number of mobile troughs and weekly frequency of trough origins and terminations, for the 1985/86 cold season.

of 49°N, the mean eastward phase speed of 14.3 degrees longitude per day represented a speed of 12.0 m s^{-1}. The steering effect of the planetary-scale flow can be seen in the poleward and equatorward meandering of M. On average but not in every case, successive passages across the same meridian occurred at a lower longitude, as the 552-dam contour expanded with the onset of the cold season.

The second, Trough C, appeared in a broad-scale ridge over western North America on 13 January and fell 20 degrees of longitude short of two complete revolutions, expiring off the west coast of Canada on 6 March, like Trough M in southwesterly flow west of a planetary-scale ridge. Its eastward phase speed was 13.5 degrees of longitude, or (at latitude 39°N) 13.4 m s^{-1}. As in the case of M, the effect of the broad-scale flow

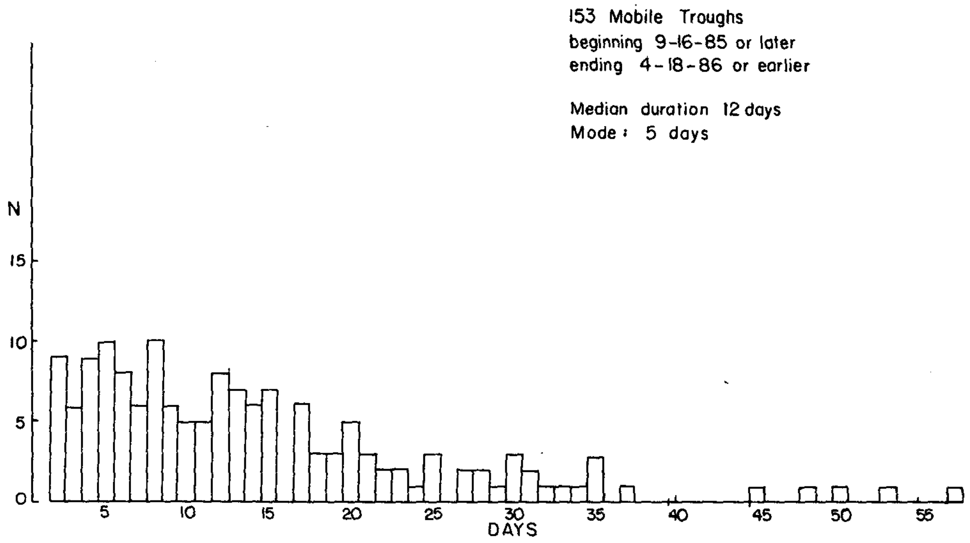


FIG. 4. Histogram of mobile trough durations during the 1985/86 cold season.

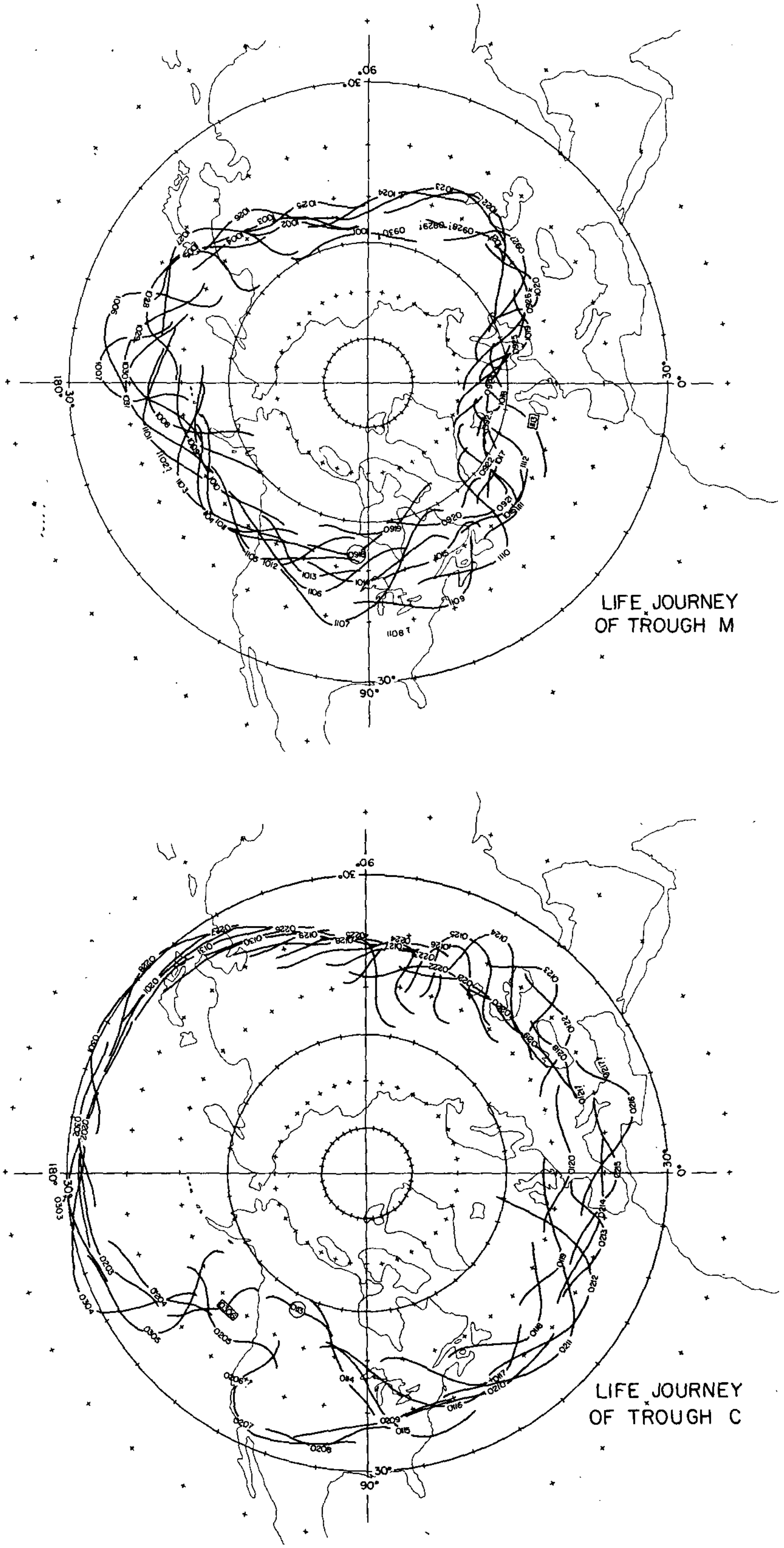


FIG. 5. Segments of 552-dam contours during the lifetimes of (a) mobile trough M and (b) trough C. The 4-digit number at each trough position indicates denotes the month and date.

was apparent, with meridional meandering of the mobile trough, especially in the eastern Pacific and over North America.

The amplitude of both troughs, but especially C, became small and the wavelength relatively long as the mobile feature approached a region of strong broad-scale westerlies, most notably in the western Pacific in March. At these times, the speed of the trough became relatively large (an extraordinary 32 m s^{-1} for C on 1–3 February). The converse occurred when the mobile trough approached a region of weak broad-scale flow. Note, for example, both passages of C over the longitude sector 50°–90°E.

Although no systematic attempt was made to measure phase speed and horizontal scale of the mobile troughs, the speeds cited above appeared to be representative. As for scale in the approximately zonal direction along the flow, inspection of Fig. 5 shows a variation in the distance between the flanking ridges from about 1500 km to somewhat more than 3500 km. If we presume that a zonal wavenumber of 12 is typical, as in Figs. 1 and 2, then the longitudinal wavelength at latitude 45° is slightly less than 2500 km, a midrange value for Troughs M and C, discussed above. Cursory examination of typical patterns indicates that the wavelength in the direction transverse to the planetary-scale flow is about 3000 km.

4. The origin and termination of mobile troughs

a. Geographical location

The position of origin of the approximately 1300 troughs during the 295 weeks studied were mapped, as shown in Fig. 6a. The raw count in each 10-degree latitude/longitude area was normalized to the area of such a square centered at 45°N (865 000 km^2). The normalized values were then smoothed by replacing them with 1/8 the sum of 4 times the value plus the sum of the values in the four surrounding areas. Analysis of the smoothed values yielded the contours seen in Fig. 6a.

We find a broad band of relatively high frequency of origin around the hemisphere following approximately the mean position of the 552-dam contour during the cold season, certainly no surprise. Along this band, however, a number of prominent centers of maximum frequency are seen. The largest is centered near 45°N, 100°E in east-central Asia, another nearly as intense is near 55°N, 115°W in northwestern North America, and a third, of somewhat smaller magnitude, lies near 45°N, 35°E just north of the Black Sea. Frequencies over the oceans are smaller than over the continents, except in the northeastern Pacific where there is a southwestward extension of the continental maximum, and in the northeastern Atlantic extending far southeastward from Greenland.

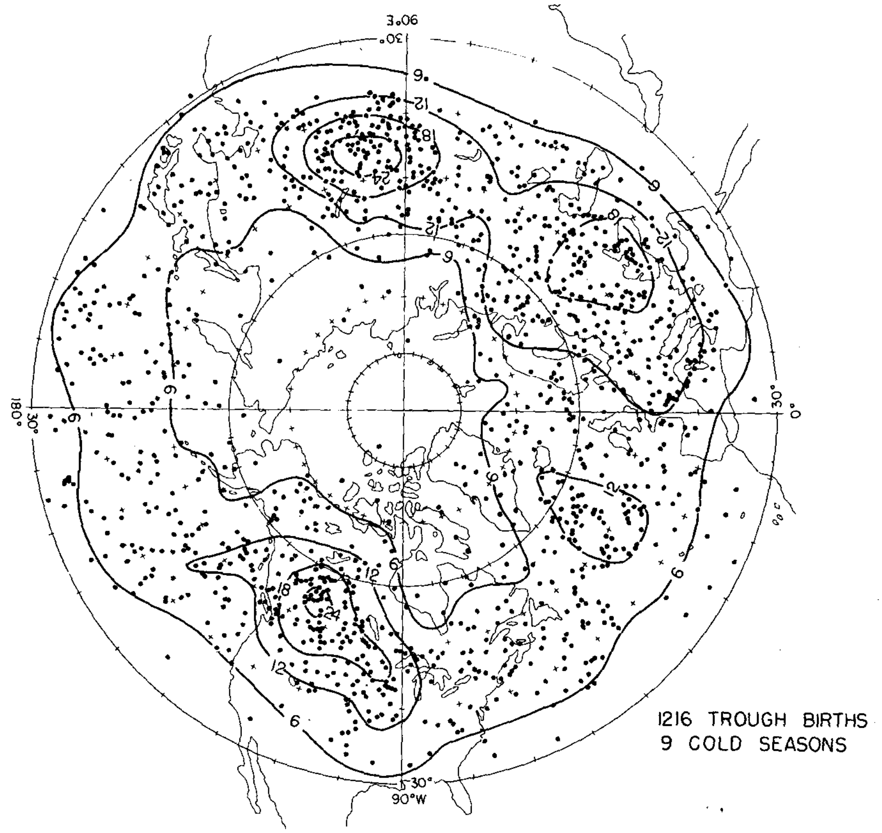
Comparison of this pattern with Petterssen's (1953) map of surface cyclogenesis frequency for the winter season shows little correlation. Only the center in northwestern North America matches a center in the surface data. The prominent regions of surface cyclogenesis in the western Atlantic and Pacific and in the Mediterranean have no counterpart in the upper-level data. This result indicates that a predecessor upper trough may play an important role in maritime cyclogenesis in general, as indicated in Sanders's (1986) results for explosive cyclones in the western Atlantic.

Instances of trough termination appear in Fig. 6b. There is a comparable band of relatively high frequency around the hemisphere, but the centers of maximum frequency are mainly oceanic. One of these is found just northwest of the British Isles, with an extension west-southwestward toward North America. Another is in the northeastern Pacific near 50°N, 140°W. A third region of especially high frequency covers the Near East and western Asia. This continental area contains maxima near 45°N, 70°E and over the Black Sea. The latter is not far from the location of one of the centers of high frequency of origin but extends substantially southward into the eastern Mediterranean.

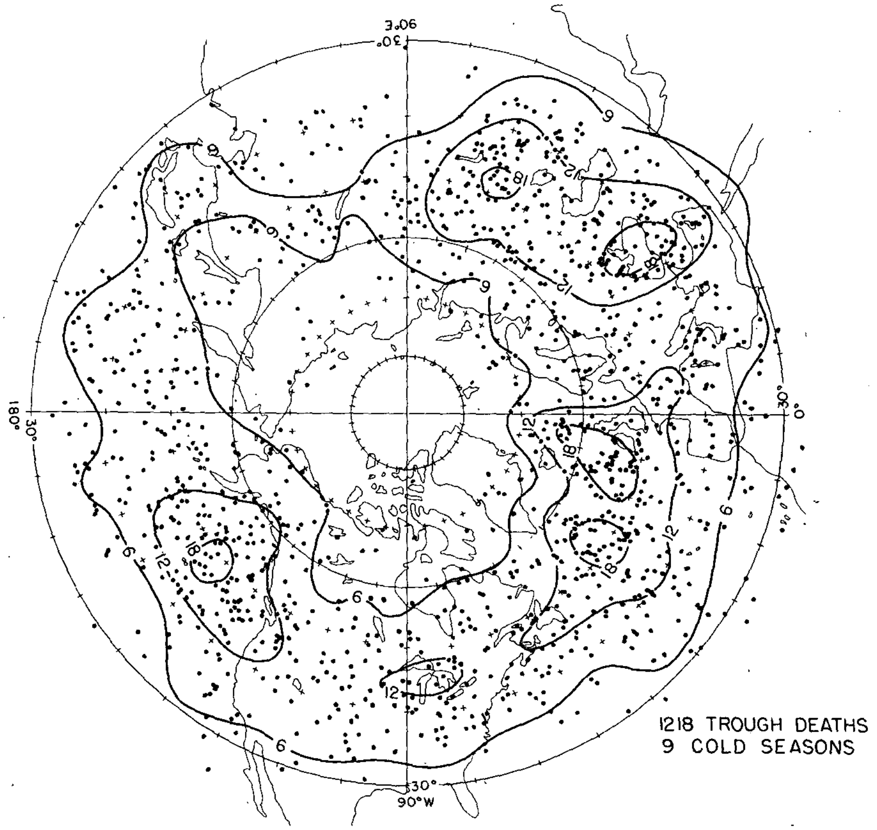
The excess of trough origins over terminations, derived from the smoothed normalized data, is shown in Fig. 6c. Overall, it is apparent that the regions dominated by trough origin are smaller and more sharply defined than the regions dominated by termination. The centers of origin in western North America and in central Asia stand out particularly strongly. Weaker centers lie east of Scandinavia and in southeastern Europe, and a small center is found just east of Greenland. Trough termination is the rule over the oceans, except along the mean winter position of the jet stream across all but the easternmost Pacific. Centers are found in the northeastern portions of both oceans, the one just northwest of the British Isles being very pronounced. Over land, termination dominates over the Near East and southwestern Asia, with notable centers near 35°N, 45°E and 40°N, 65°E.

b. Relationship to orography and planetary-scale flow

The position of centers of origin suggests an orographic effect. A smoothed representation of land elevation (derived from Berkofsky and Bertoni 1955) appears in Fig. 7, along with the long-term mean position of the 552-dam contour for selected months. From a comparison of Figs. 6c and 7 it is evident that the two major centers of trough initiation, in central Asia and in western North America, lie over and downwind from the two major mountain masses of the Northern Hemisphere, at latitudes close to where the mean position of the 552-dam contour crosses them. The three minor centers of birth lie east of mountainous areas: Scandinavia, central Greenland and the highest part of the Alps. The last two of these are far from the mean position of the selected contour and must be active



1216 TROUGH BIRTHS
9 COLD SEASONS



1218 TROUGH DEATHS
9 COLD SEASONS

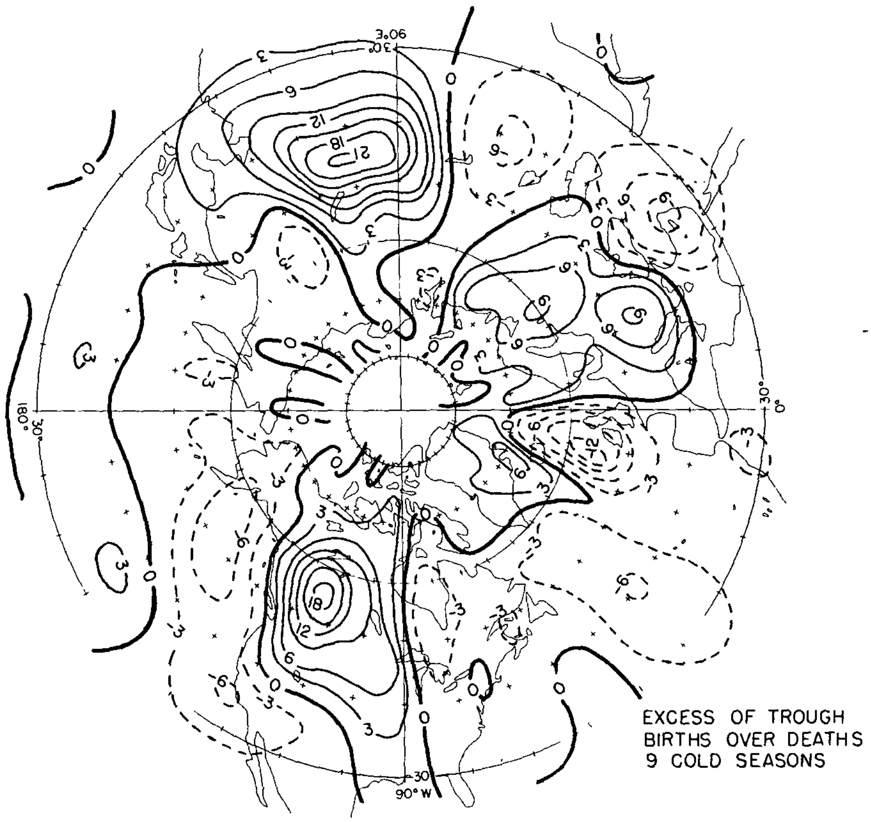


FIG. 6. Positions of mobile trough (a) origins, (b) terminations, and (c) excess of origins over terminations during the nine cold seasons examined. The solid lines are contours of smoothed normalized frequency in areas bounded by 10 degrees of latitude and longitude. See text.

only when there is a prominent perturbation in the quasi-steady planetary-scale flow.

Regions of excess trough death also show some indication of orographic effect. The centers, less well defined than in the case of excess birth, tend to lie roughly 1000 km upwind from major masses of elevated terrain.

In the process of accumulating the data a preference for position relative to the quasi-steady ridges and troughs became evident. The direction of this flow was estimated by observing the orientation of a line connecting the two ridges flanking each trough in the 552-dam contour. Results are summarized in Fig. 8. In the case of trough births this planetary flow displayed a northerly component twice as often as a southerly one. With trough deaths the opposite was the case: southerly components were present nearly twice as often as instances of southerly or purely zonal flow. This preference was seen on average in each of the calendar months of the study.

If a cutoff low south of the 552-dam contour originated as a trough in that contour, it continued to be identified as that trough despite its central height value until it no longer appeared in the analysis. A modest proportion of troughs, showing a seasonal peak in April and May, terminated in this way. On very rare occasions a trough originated in a cutoff low associated with a tropical cyclone. More typically these storms entered the westerlies by absorption into the flow in advance of a preexisting mobile trough.

The preference for deaths in southwesterly flow and births in northwesterlies on planetary-scales suggests that the trough initiations may actually represent rebirths or reappearances of features temporarily hidden. That is, the existence of the mobile trough may be hard to detect while it is superposed on a larger quasi-steady ridge and then may become increasingly prominent as it overtakes the downstream large-scale trough and moves into coincidence with it.

This possibility for deception was borne in mind during the daily analyses. The great majority of crossings of mountain barriers by mobile troughs did not result in a break in their continuity, despite weakening in transit. Only those in which the associated height-change field was practically obliterated were considered terminated. In a number of instances a new feature

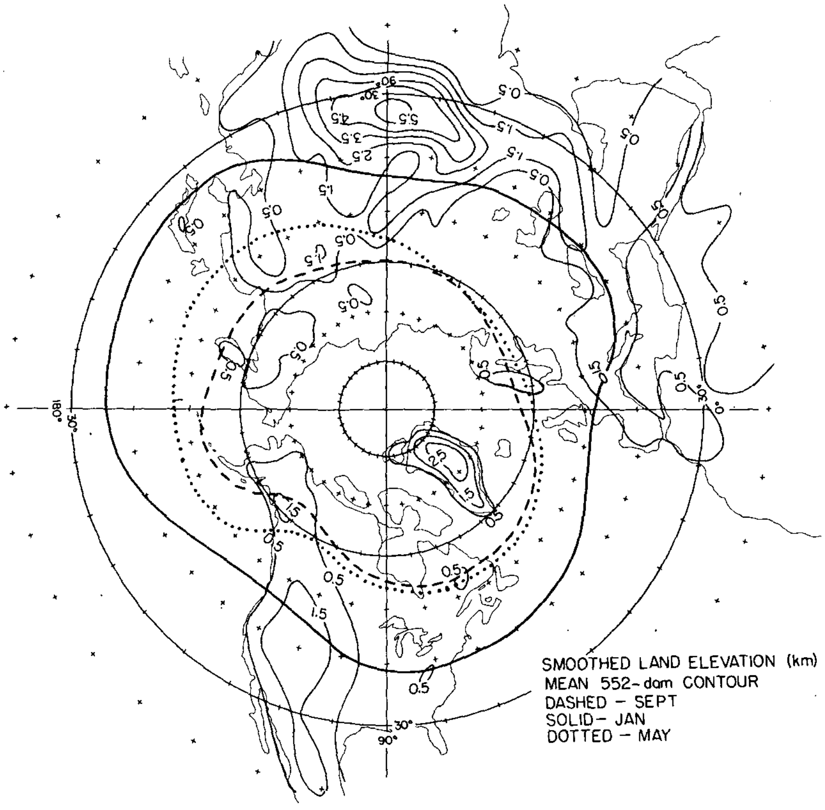


FIG. 7. Contours of smoothed land elevation and long term mean positions of the 552-dam contour for indicated months.

appeared on the lee slopes on the next day, but in many cases there was no reasonably-placed windward-slope predecessor.

Whether the height-change field is completely eliminated or merely weakened, of course, is a matter of degree. The modification during passage across the mountain barrier is of interest in any case.

5. Some examples

Seven episodes of trough initiation in or around the North American cordillera during the 1985/86 season were selected for illustrative study. The dates of these, and the letter designators of the 10 mobile troughs which originated during them, are given in Table 2. Their duration ranged from 3 to 6 days.

Two types of episode were immediately apparent, distinguished on the basis of the general direction of the planetary-scale flow: westerly, in which the mobile trough developed over or east of the mountains, and northerly, in which the development was over or west of the mountains. Five westerly episodes each produced a single mobile trough. The remaining two northerly ones, representing highly persistent blocking situations, were the setting for origin of the other five mobile systems.

a. Time-averaged flow patterns

An example of each type of episode is illustrated in Figs. 9 and 10. Composites of the daily positions of the relevant portions of the 552-dam contour, showing the locations of the initial trough appearances as well as other troughs present, appear as parts (a).

Time-averaged regional fields of 500-mb height and absolute vorticity were derived from NMC initial analyses and are shown in parts (b) of Figs. 9 and 10. In the northerly case there was a blocking ridge near 150°W and a deep trough near 110°W, showing little overall change over the 6-day period. There was a pronounced mean northerly wind maximum, highly concentrated and flanked by vorticity minima and maxima about 1500 km apart. The mobile troughs formed in this wind maximum. The averaged flow for the westerly case, in Fig. 10b, showed a ridge-to-trough distance of about 30 degrees of longitude, implying a zonal wavelength of about 5000 km. As seen in Fig. 10a the new mobile trough N was relatively difficult to distinguish from its immediate predecessor B, but was clearly separate in the vorticity and height-change fields. The wind maximum was not as strongly concentrated as in the northerly example, but the vorticity field still showed extrema with a lateral separation of 1500 or 2000 km.

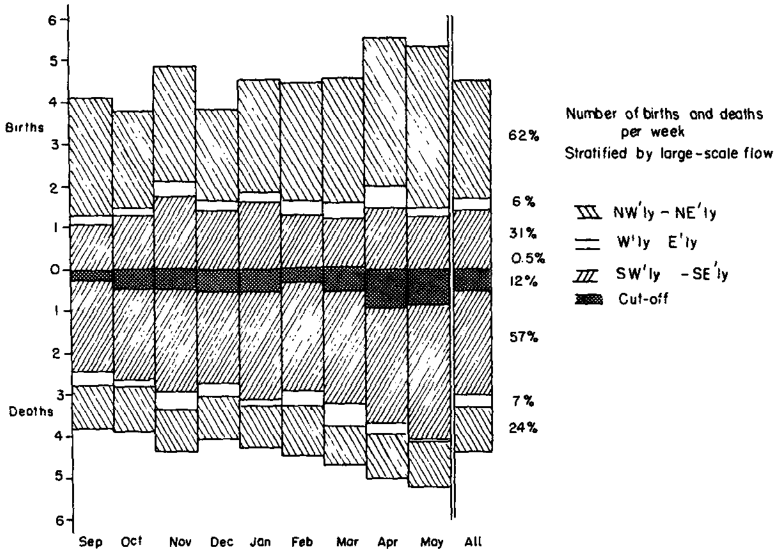


FIG. 8. Mean weekly frequency of trough origins and terminations, stratified on the basis of the large-scale flow in which they are embedded.

A string of rawinsonde stations was selected for each episode, extending 4000–5000 km approximately along the quasi-steady flow at this level and as near as possible to the centers of height rise and fall associated with the initiating troughs. These strings of stations lay reasonably near the mean 552-dam contour except for the episode from 4 to 7 January 1986, when the major height changes occurred about 1000 km poleward, along the 534-dam mean contour. They also tended to lie along the axis of maximum wind speed at 500 mb.

Vertical cross-sections of direction and speed of the mean observed wind for the sample episodes are shown in Figs. 9c and 10c. Wind maxima in the range from 30–50 m s^{-1} are seen, somewhat stronger in the northerly case. The vertical shear in which the troughs originated varies from 4–6 m s^{-1}/km.

The patterns for the other episodes resembled these, except that the mean wind speeds in the other northerly case resembled the relatively weak ones for the westerly case in Fig. 10, while two of the other westerly episodes showed strong mean winds, with jet maxima near 50–60 m s^{-1} near the 250-mb level. Half-wave lengths from ridge to downstream mean trough varied from 30–40 degrees of longitude, and absolute vorticity maxima and minima at 500 mb tended to lie along the flanks of the axis of maximum wind. Thus, the environment for origin of mobile waves showed a potential for growth by both baroclinic and barotropic processes.

TABLE 2. Dates of episodes studied, and troughs initiated.

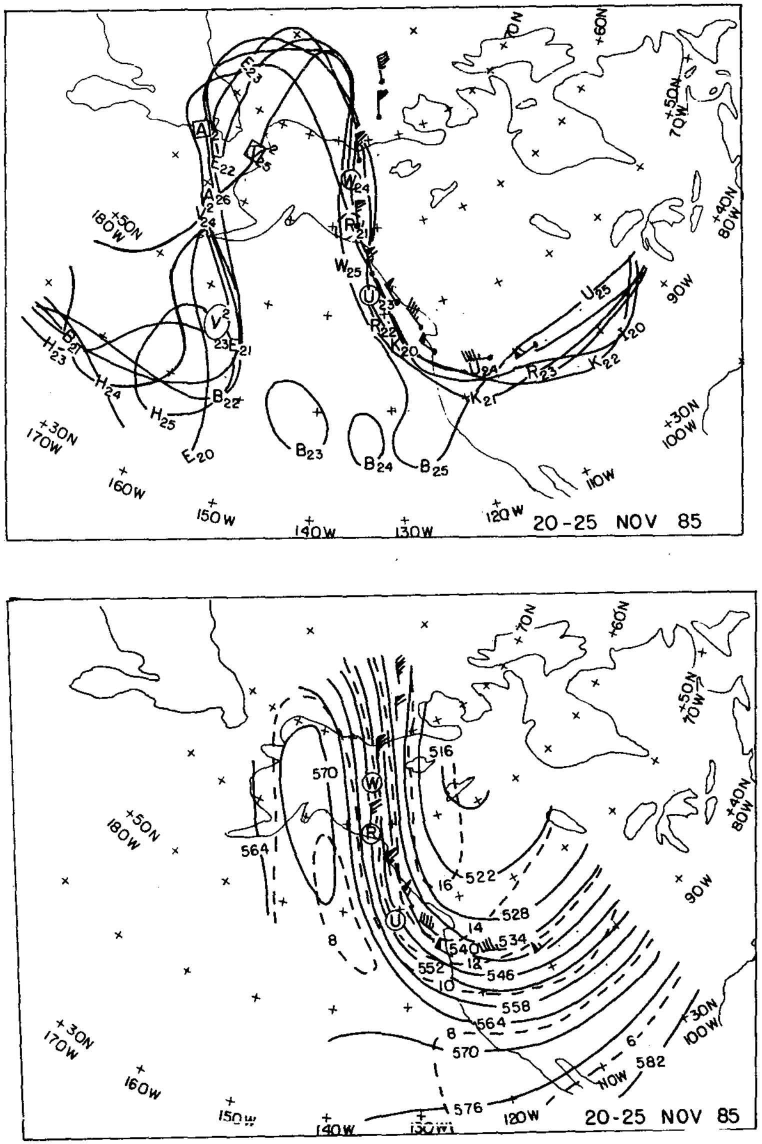
Dates	Troughs
20–25 November 1985	R, U, W
16–19 December 1985	Q
4–7 January 1986	Y
24–26 January 1986	N
6–11 February 1986	B, C^{2}
25–27 February 1986	Q
5–7 April 1986	S

b. Temporal evolution of the mobile troughs

To study the development of each of the ten mobile troughs, we considered that the observed height change on constant-pressure surfaces might be regarded as the effect of a moving oscillation. Over a wavelength its mean value would be zero. If the wave amplitude were increasing both the rises and the falls would be increasing with time. A nonzero average value over a wave length would be taken as evidence of a larger scale variability against which the wave oscillation is occurring.

With this interpretation in mind, we prepared 12-h height-change fields from the NMC analyses at 850, 700, 500 and 250 mb at intervals of 12 h throughout each episode. A series of 51 vertical cross sections of 12-h height change was made along the string of rawinsonde stations for each episode, examples of which were shown in Figs. 9c and 10c. Qualitative examination was made of the surface analyses and of the fields of 500-mb vorticity advection.

It was difficult to summarize the mass of detail. On a number of occasions, a weak vorticity maximum, distorted and convoluted and fragmented into more than one center, was seen to migrate across the mountains from the Pacific to become reorganized and strengthened on the lee side. No center of height fall



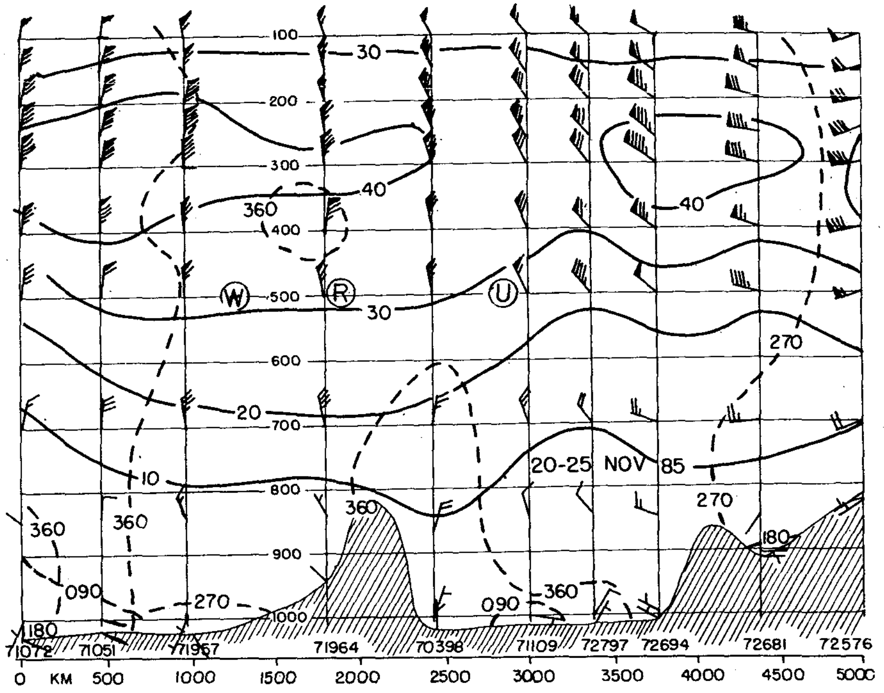


FIG. 9. Illustrating the episode of 20–25 November 1985. (a) Composite of 0000 UTC positions of the 552-dam contour, with daily positions of mobile troughs denoted as in Fig. 2. (b) Time-mean fields at 500 mb, the solid lines being contours of height at intervals of 6 dam and the dashed lines being isopleths of absolute vorticity at intervals of $2 \times 10^{-5}\ \mathrm{s}^{-1}$. (c) Vertical cross section of mean observed wind along the line of sounding stations for which the mean winds appear in (b). In the wind plots, a half-barb, a full barb and a triangle represent speeds of 5, 10 and 25 $\mathrm{m\ s}^{-1}$, respectively. Solid lines are isotachs of mean wind speed, at intervals of 10 $\mathrm{m\ s}^{-1}$, and the dashed lines are the cardinal isogons of direction of the mean wind.

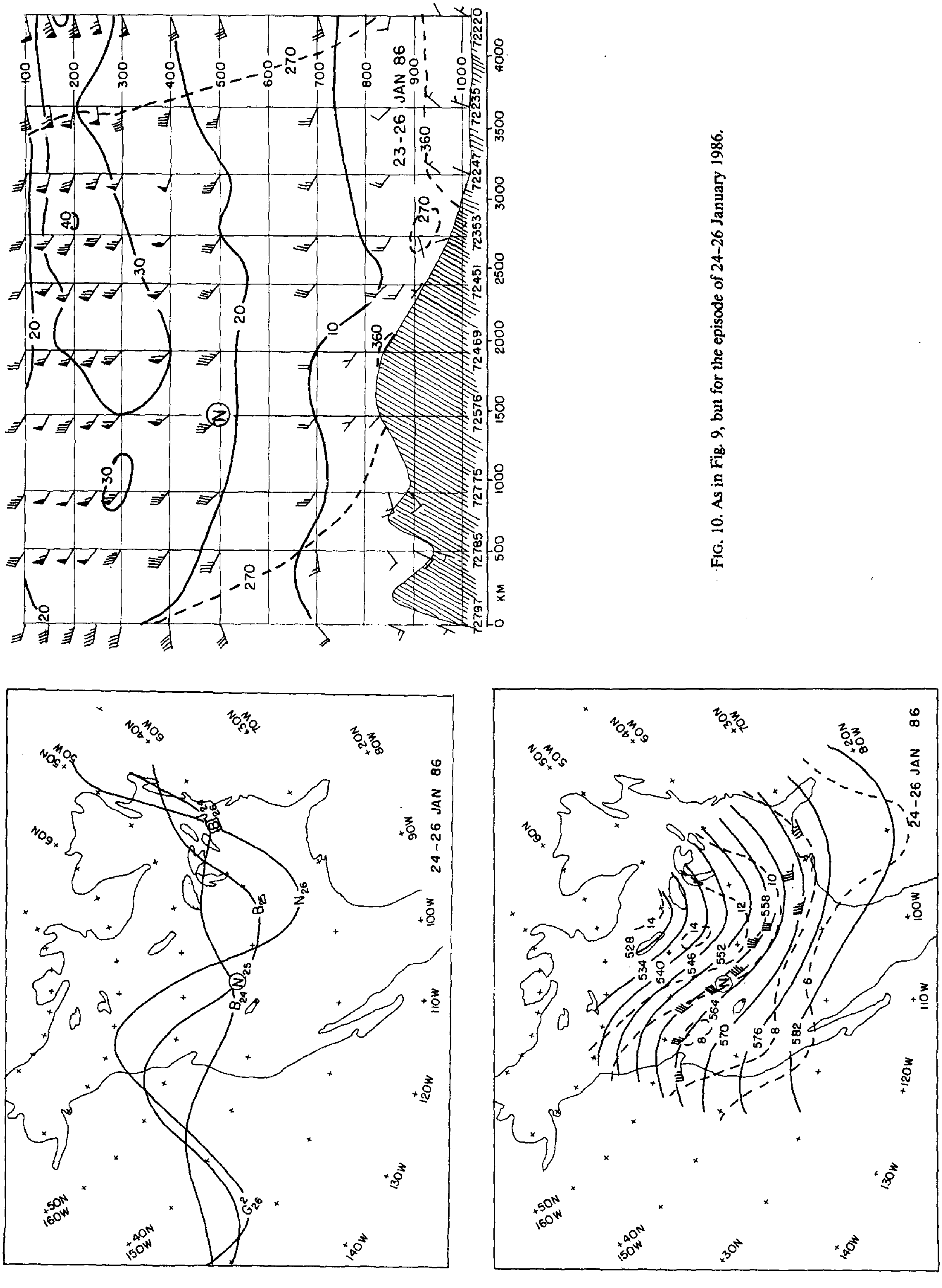


FIG. 10. As in Fig. 9, but for the episode of 24–26 January 1986.

could be followed across the mountains in these cases, but one became clearly evident during reorganization.

At the surface, lee trough development occurred in most cases, with a cyclonic center appearing in about half. These centers could be identified for more than a day on only three occasions (one of them accompanying trough N illustrated in Fig. 10) and none intensified strongly.

The cross sections showed examples in which the origin of the height falls was clearly at the surface and the system could not be identified through the depth of the troposphere until 12–24 h later. In other cases, however, the falls were first evident in the upper troposphere, subsequently extending down to the 500-mb level but not being identifiable in the lower troposphere. The most reliable predecessor seemed to be a region of strong 12-h rises through the entire troposphere upstream from the subsequent trough development.

In the search for common characteristics, and despite the evidence of different kinds of development mentioned above, we prepared composite cross sections centered on the position of the mobile trough at 500 mb for the day of origin and for the day following. A further section was prepared for all later times, including data for troughs on the section line in addition to those originating there. Finally, a section was prepared for the day prior to the appearance of each trough. The central point for this section was obtained by proceeding backward in the time-averaged flow for the episode a distance equal to the 24-h displacement of the trough which subsequently formed. This distance was about 1300 km on the average.

Data for the composite sections were taken from the strings of rawinsonde stations, except for the "day before" section, where upstream rawinsondes, or NMC analyses in the case of oceanic areas, were included as data sources. The time of origin was nominally taken as 0000 UTC on the first day of trough identification, but data for 12 h earlier was used if the trough was evident at that time in the height-change field. Data were subsequently taken at 12-h intervals so long as the trough was present along the section line. Changes were taken at all available standard pressure levels from the surface to 100 mb. Data were statified according to station location into contiguous 500-km segments extending from 1750 km ahead to 1750 km behind the location of the trough, and averages were formed for each segment and standard level. Mean temperature changes for the layers between levels were derived hydrostatically from the averaged thickness changes for each 500-km segment. The values of height and temperature change for each segment were attributed to its center. Results appear in Fig. 11.

First, we find in Fig. 11a that on the day before initiation, the new trough would form in an environment that was changing on large scales. There was a substantial height rise over the domain, increasing almost monotonically with elevation up into the stratosphere. The initiation site was bracketed by upstream rises and downstream falls, suggesting a wavelength of about 4000 km. These rises and falls were associated, respectively, with tropospheric temperature rises and falls. The implied temperature wave displayed a prominent downshear tilt with elevation, intersecting the implied geopotential wave well below the tropopause, so that it likewise tilted downshear in the upper troposphere.

On the day of initiation, we see in Fig. 11b the sudden appearance of a region of height falls associated with the new wave on a smaller scale, with a wavelength of perhaps 2000 km. Again, temperature waves accompanied the height oscillations, with both tilting downshear, this time in the middle as well as upper troposphere. The new system displayed a prominent upshear tilt in the layer from 850 to 500 mb, with relatively strong cooling just upstream from the fall center. This cooling was weakly foreshadowed, in fact, at a similar location a day earlier. Also as on the preceding day, there was a substantial average height rise over the domain, centered this time near the tropopause.

On the day after initiation, Fig. 11c shows an enlargement of scale, since the centers of height rise flanking the falls are on or beyond the boundaries of the domain. We see also a substantial increase in the height falls. The strongest gradients adjacent to the fall center, however, were still separated by only about 1250 km, however, indicating a large contribution from a 2500-km wavelength. The increase in falls, moreover, reflects mainly a substantial difference in the domain-average height changes, which were now modestly negative. The temperature waves again tilted downstream for the most part, although a branch of cooling extended west of the fall center up to the tropopause. This was the only instance in the series of composites in which the disturbance tilted upshear through the depth of the troposphere.

The last composite, Fig. 11d, contains data from any subsequent days for the originating troughs and also for any other 500-mb troughs present along the section lines, but with an origin outside. The height and temperature changes suggest a predominant wavelength of about 3000 km. There was again downshear tilt in the temperature wave, intersecting the geopotential wave in the middle troposphere. In the implied geopotential perturbation, there was therefore an upshear tilt favorable for baroclinic development only below the 500-mb level. The domain-average height change was small, mainly negative.

The relative vorticity field of the mobile system can be estimated from the composite field of height change by measuring its gradient along constant-pressure surfaces. We wish to estimate

$$v = (g/f_0)(\delta Z/\delta s),$$

where the s-axis is along the section line, δs is 500 km and v is the geostrophic perturbation velocity component normal to it. We assume that

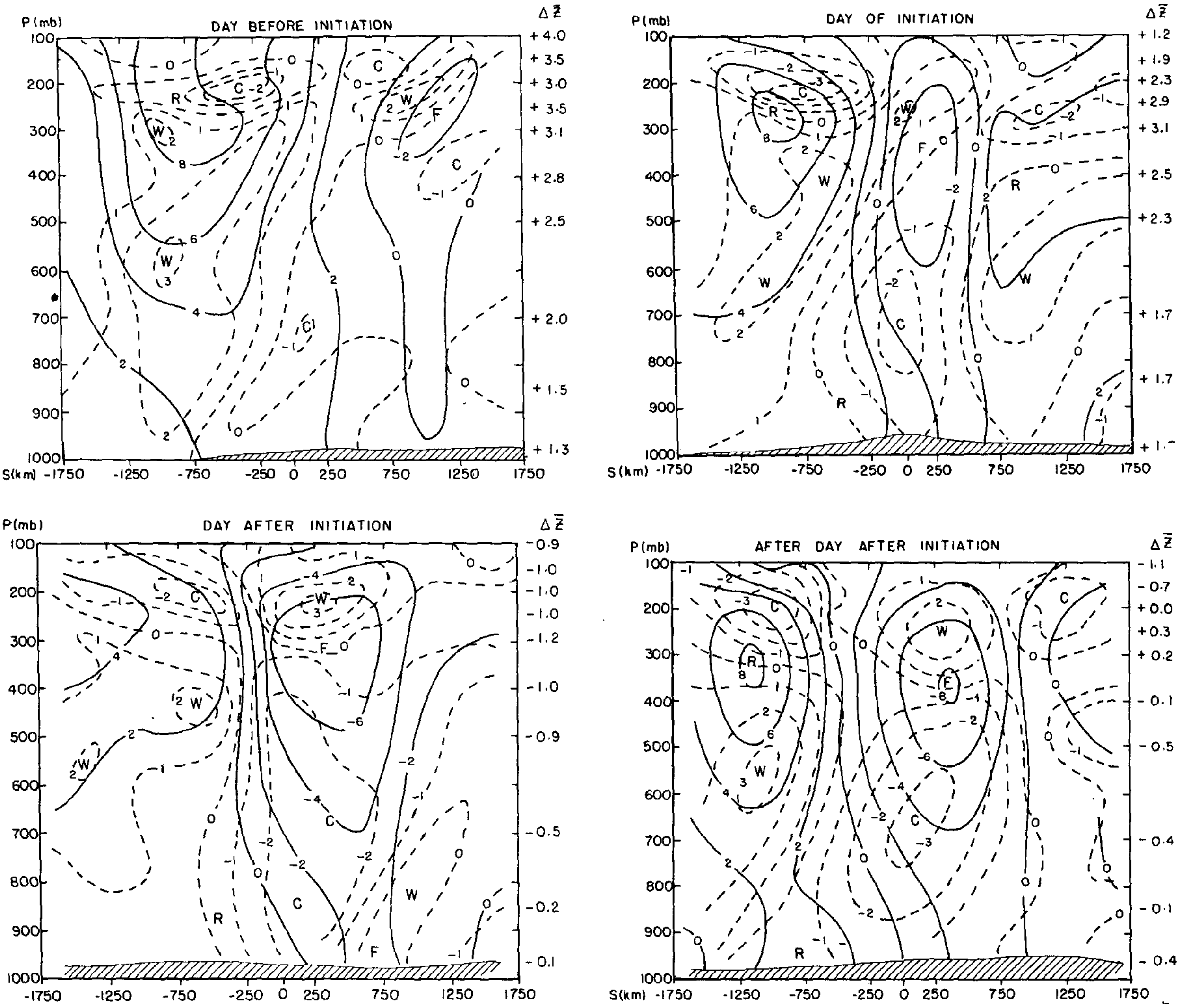


FIG. 11. Composite vertical cross sections of 12-h height change (solid lines) at intervals of 2 dam and of 12-h change of mean temperature between standard levels (dashed lines) at intervals of 1 K. See text. (a) For the day before trough initiation. (b) For the day of initiation. (c) For the day after initiation. (d) For days subsequent to the day after initiation.

$$\delta Z/\delta s = -(1/c)(\delta Z/\delta t),$$

where c is the phase speed of the wave. If δZ is the 12-h change and we use the mean 12-h displacement of the originating wave (650 km) in evaluating c, then, approximating the relative vorticity by $(\delta v/\delta s)$, we have

$$\zeta = -(g/f_0)\,(650\ \mathrm{km})^{-1}\,(500\ \mathrm{km})^{-1}\,\delta(\delta Z),$$

where $\delta(\delta Z)$ is the difference of the height change over 500 km. If we take $f_0 = 115 \times 10^{-6}$, corresponding to the mean latitude of trough origination, and the height change is measured in decameters, then

$$\zeta = -2.624 \times 10^{-6}\,\delta(\delta Z)$$

This expression is almost certainly an underestimate of the vorticity because it neglects any contribution from perturbation velocity shear in a direction normal to the section line, because grouping all data in a 500-km line segment suppresses the extreme value in a given case, and because the 12-h height change does not represent the largest instantaneous rate. The error is likely by a factor of somewhat more than 2. Nevertheless we use this expression because it is easily obtained and because the pattern is not likely to be seriously in error. The results obtained from the composites presented in Fig. 11 are given in Fig. 12.

Maximum vorticities were in the upper troposphere throughout. Before initiation of the new trough, the vorticity was weakly cyclonic through most of the domain. The new feature in the height field was foreshadowed by the maximum near the tropopause and by negative values near the upstream boundary, re-

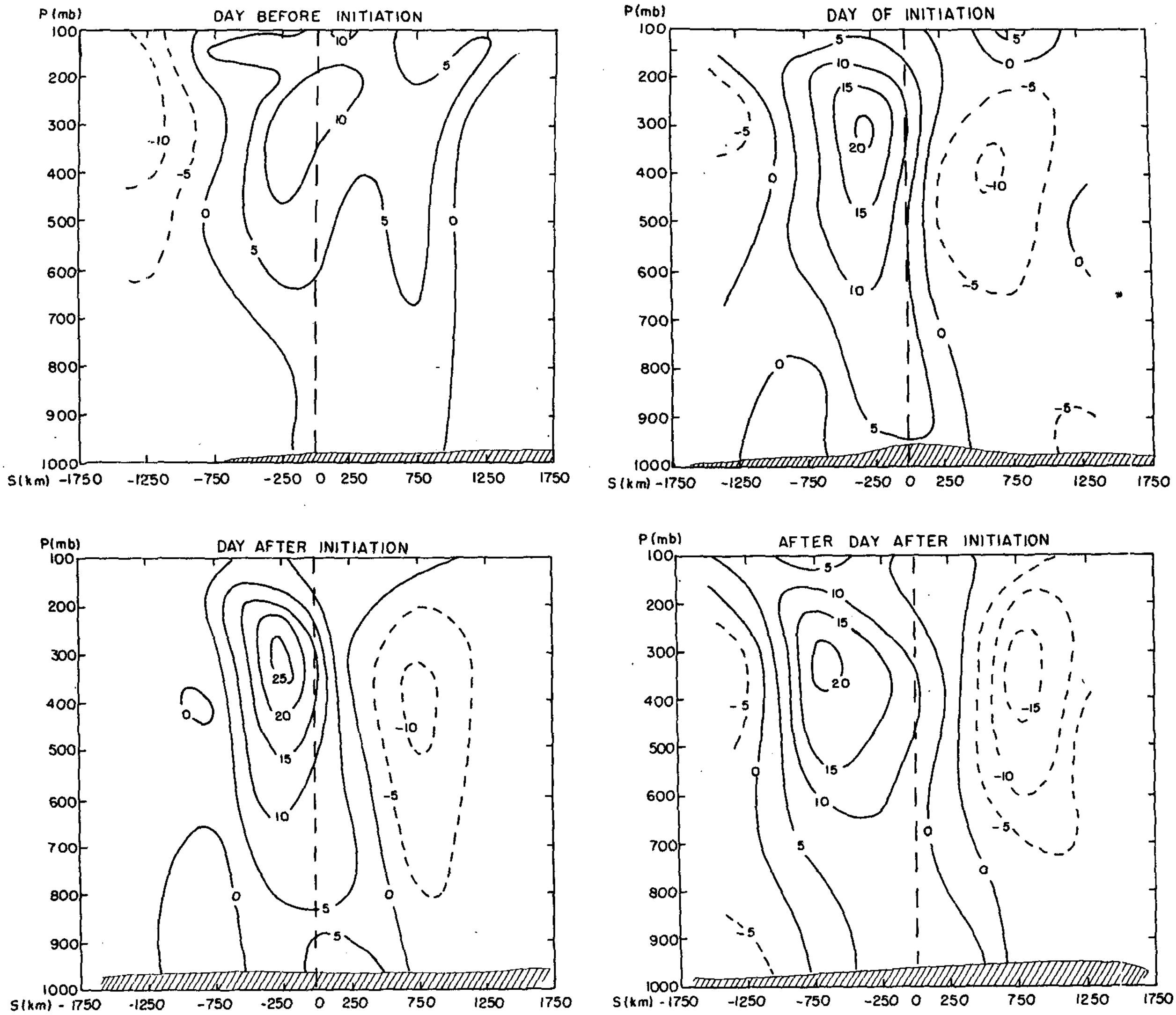


FIG. 12A. Composite vertical cross sections of $\delta v/\delta s$ at intervals of 5×10^{-6} s^{-1}, evaluated geostrophically for the same days as illustrated in Fig. 11. Fig. 12B, 12C, 12D.

flecting a predecessor ridge. On the day of initiation the vorticity field attained nearly the maximum strength it would ever display, and a vorticity minimum appeared downstream from the new trough. The wavelength indicated by the vorticity field was about 2000 km during initiation and on the day following. Subsequently, the scale was larger, but still no more than 3000 km. The magnitude of the vorticity maximum once the new system had developed, even in this substantial underestimate, was not small compared to the value of f_0.

Note that the maximum cyclonic vorticity did not coincide at 500 mb with the zero-line on the s-axis. This discrepancy arose because the 12-h changes referred to a period ending at the time the 500-mb trough position (and the zero line) was determined. The discrepancy should therefore represent at 6-h trough displacement (or about 325 km) and it does so, by and large.

c. Vertical structure of the mobile troughs

The vertical structure of the disturbances is not accurately portrayed by these composites because of the way they were prepared. They were centered on the trough at 500 mb. Any variability in trough tilt above and below this level in the individual vertical cross sections would then dilute the mean value of the changes at other levels compared to the mean value at 500 mb. To improve the representation of the vertical structure of the height changes, we went back to 21 of the individual sections, for conditions on the day of initiation, and tabulated individually the values of the associated maximum fall and maximum rise associated with the new trough at each standard level.

There was little difficulty identifying the rise center, apart from seven instances when it lay upstream from the end of the section line, and apart from two cases where no maximum could be found in the lower troposphere. Mean values of the maximum rise, normalized by the mean value at 500 mb, appear in Fig. 13a. Nearly uniform values of about 0.75 extended from the surface to 700 mb. Above, there was a sharp increase to a value approaching 1.65 near the 300-mb level and then a rapid decrease in the lower stratosphere.

In the case of the falls, there was more variability. Although the associated falls were always shown within the section line, a center could be identified at all levels in only 14 of the 21 cases. In 7 others (all of the westerly type), the maximum falls were at the surface. A center could be identified only with difficulty at 500 mb and not at all above. (The following day the fall extended through the entire troposphere.) In another 2 cases, also of westerly type, the falls were an upper tropospheric phenomenon and could not be identified below 500 mb. Profiles for these three categories of situation are shown in Fig. 13b. The case in which the center was identifiable throughout the depth of the domain displayed a profile resembling the one for height rises. The other two differed as might be expected. The low-level one was normalized by the surface value because the mean 500-mb value was so small. The upper-level case had a substantial value at 500 mb and a strong peak at 300 mb. This last profile, as mentioned above, was based on only two sections.

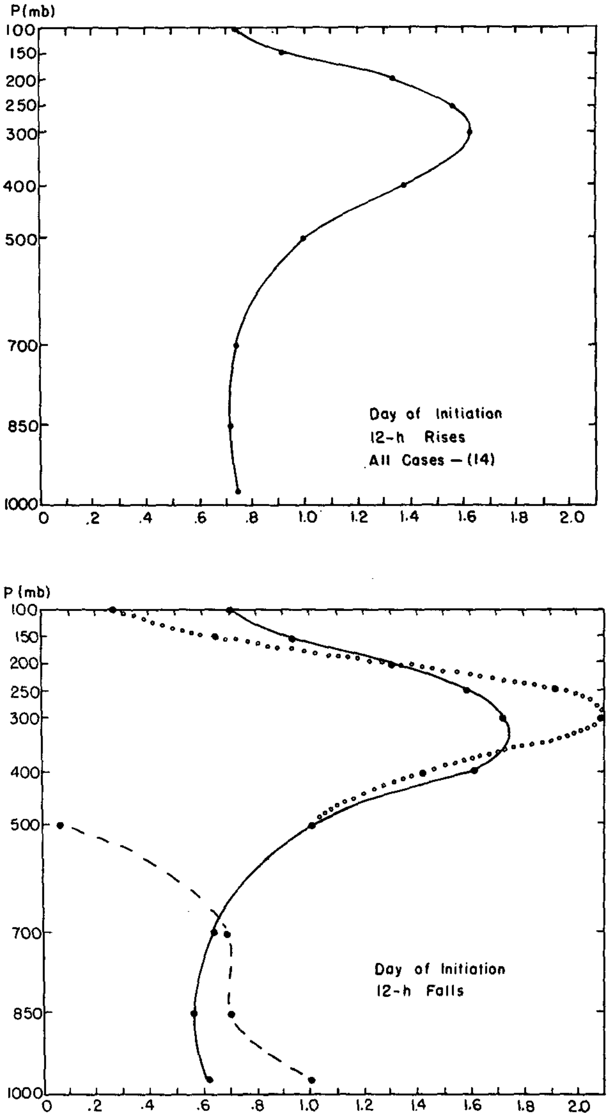


FIG. 13. Normalized vertical profiles of 12-h height change for the day of trough origin. (a) Maximum height rise. (b) Maximum height fall, the solid line representing the 12 cases in which a fall center could be identified at all standard levels, the dashed line the 7 cases in which the center could not be identified above 500 mb, and the dotted line the 2 cases in which the center could not be identified below 500 mb. The normalizing factor was the value at 500 mb, except for those cases when no center could be detected above 500 mb, when the surface value was the normalizing factor.

d. A mean proximity temperature sounding for trough initiation

For the cross sections on which a new trough appeared for the first time, including two for some instances as explained above, the sounding location nearest the position of the trough was determined. Standard-level temperatures were obtained from observations at this station at the beginning and end of the 12-h period to which the section referred, 39 soundings in all. The profile of average temperature appears in Fig. 14. A mean inversion from the surface to 850 mb gave way to a nearly uniform lapse rate between 700 and 300 mb. Potential temperature increased with elevation in this layer at the rate of 4 K $(\mathrm{km})^{-1}$. Above 250 mb, conditions were nearly isothermal in the lower stratosphere. The square of the Brunt-Väisälä frequency, N^2, for this mean profile is shown in Fig. 14. It was evaluated, for unsaturated air, over the layer from the surface to 1 km elevation, and over 1-km layers above. Relatively large values occur in the lower troposphere and in the stratosphere, while a minimum is seen in the upper troposphere.

Lapse rates in the layer from the surface to 850 mb were extremely variable. In 10 observations the inversion was at least 10°C, but in 15 others the temperature decreased with elevation. No effort was made to examine the temperature structure in the region of geo-

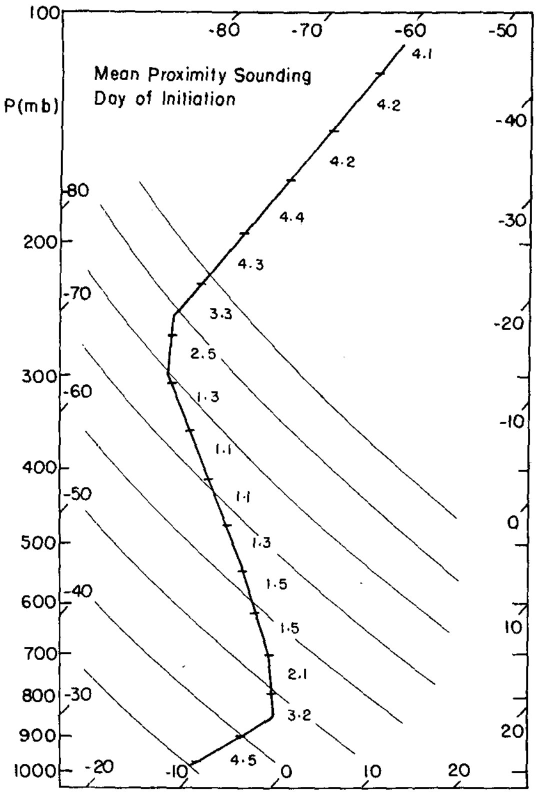


FIG. 14. Sounding of temperature on the day of origin, averaged over the sounding nearest the point of origin for each instance. The plotted numbers are the values of N^2, in units of 10^{-4} s^{-2}, over each 1-km layer, except from the layer from the surface to 1 km, for which the average depth was 650 m.

potential falls near the surface, or in the flanking ridges at any level. A more extensive study would be required to establish the character of the temperature profile firmly.

e. Some aspects of lateral structure

Although the emphasis in this study has been on features along the core of the main western current at upper levels, a cursory examination was made of conditions away from the key 552-dam contour of 500-mb height. In particular, the cross-stream tilt of the centers of maximum height rise and fall over the layer from 850 to 250 mb was briefly studied. For the 19 map times during the seven episodes when such centers were unambiguously associated with the new trough throughout this layer, the average displacement of the centers of both rise and fall was slightly (less than 100 km) toward lower height from the bottom to the top of the layer. The scatter of the individual cases about this mean was large, however, and the tilt was toward higher height in nearly 30% of the instances. Thus the lateral tilt does not seem significantly different from zero.

The two-dimensional vorticity field in the NMC analyses at 500 mb also received some attention, from just prior to trough initiation until the system left the limited domain studied. In all cases an absolute vorticity maximum either formed as the trough developed on the 552-dam contour or was present beforehand somewhere within about 1000 km of the point of initiation. This finding is perhaps not remarkable, given the considerable number of maxima that are seen on any map.

The center in 9 of the 10 cases of trough initiation, however, lay initially at a lower height than 552 dam. In all of these the center migrated toward higher height as development occurred. In the remaining case the vorticity maximum lay initially at a higher height and migrated toward lower. In all cases but one, the vorticity maximum increased slightly as this migration occurred.

In 5 cases, the vorticity center lay initially at heights from 540 to 550 dam, only modestly lower than the key value. These centers had either just developed as an offshoot of a more prominent Pacific system during its transit across the mountains, or represented the system itself, in a much weakened state. The trough initiation on the 552-dam contour in 4 of these 5 then constituted on organization of an irregular vorticity field into a coherent system with prominent regions of cyclonic and anticyclonic advection. In the remaining case a previous trough on the 552 contour plunged southward to become cut off from the main body of westerlies, while farther to the north a remnant of the original trough continued eastward with an independent new identity.

In 4 cases, the vorticity center lay initially at heights between 514 and 525 dam. Then a trough, usually well-developed, propagated laterally from the inner portion of a cold vortex outward so as to involve the main body of westerlies. In the single case of an initial vorticity center at a higher height, this feature appeared at the edge of the available map, evidently having an earlier history over the Arctic Ocean before rounding the crest of a blocking ridge and heading southward.

In this great variety of individual circumstances, none of which were analyzed in detail, the only common feature was that in *no* case did the new trough originate as a "development from scratch" out of undisturbed zonal flow, or even out of a simple wave of planetary scale. Evidently, the organization and growth of the system out of the small-scale chaos of the vorticity field is the most important process.

6. Concluding summary

Since much significant surface cyclogenesis occurs by interaction of a preexisting mobile upper-level trough and a lower-level baroclinic zone, a question of origin of the upper-level feature arises. Daily positions of all identifiable troughs were marked along the 552-dam contour on the 0000 UTC NMC Northern Hemispheric analysis during a 9-year period from October 1976 to April 1986 (June–August and the entire 1984-1985 season omitted). A single contour was examined to keep the work within practical limits, and this one was selected because it as well as any other represented the band of maximum westerlies.

On any particular day, between 8 and 15 mobile troughs, distinct from the larger quasi-steady planetary-scale troughs, could be identified. A mean zonal wavelength of about 2500 km is implied. Cursory examination of the complete charts indicated a comparable meridional wavelength. The weekly sum of origins and terminations of such individual features varied from 3 to 18. The duration of 153 mobile troughs during the 1985–1986 season showed a median of 12 days and a mode of 5 days. A few lasted longer than a month. Mean phase speed was about 13 m s^{-1}.

The distribution of birthplaces for these features was wide but showed a strong preference for high terrain. The Rockies and the mountains north of the Tibetan Plateau were the primary regions of origin with another in Eastern Europe. Deaths occurred principally over the eastern Atlantic and Pacific Oceans, in the Middle East and west of the mountains of central Asia. In reference to the planetary-scale flow, "births" occurred preferentially with northerly components and "deaths" with southerly components or as cutoff systems south of the major westerlies.

Examination of individual episodes in the vicinity of the Rockies, with durations ranging from 3 to 7 days, showed that the mobile trough appeared initially within a quasi-steady wave of substantially larger scale. When this larger wave had only modest amplitude (westerly type), the trough formed over or east of the mountains. When the wave was unusually prominent (northerly type), multiple troughs tended to form over or to the west of the mountains. The flow pattern averaged over the duration of the episode showed prominent vertical and lateral shear, with a jet maximum in the upper troposphere.

Often there was one or more weak predecessor vorticity feature with a Pacific or Arctic origin, scarcely visible in the height-change field, but the organization of the system occurred in the lee of the mountains.

Composite vertical sections of 12-h geopotential and temperature change, taken along the large-scale flow, showed that the smaller mobile features grew quite quickly, achieving most of their development in one day. The vertical slope of the implied perturbations was consistently upshear only up to the middle troposphere. There and above, the tilt was slightly downshear on the average, but with large case-to-case variability. There was no consistent cross-shear tilt of the implied perturbations, although tilts upward toward the colder air were somewhat more common than the other way.

Amplitude in the geopotential-change field showed an identifiable structure throughout the troposphere in most cases, with a pronounced maximum near 300 mb. A tendency in most cases toward a weak maximum at the surface reflected modest cyclogenesis accompanying the development of the upper feature. A few examples were seen in which the initiation began near the surface, or entered the analysis area only in the upper levels. The disturbance quickly spread through the depth of the troposphere in either case.

The mobile trough did not initiate as a simple development in zonal flow, or even in a simple planetary-scale wave. The process proceeded rather along one of three lines: 1) the organization of an irregular vorticity field into a coherent one on a scale of 2500–3000 km with prominent fields of advection, or 2) the propagation across the flow of a preexisting trough near the center of a large cold vortex, or 3) the fracture of a trough with substantial meridional extent, the feature previously tracked plunging southward as a cutoff cyclone and a remaining portion of the trough continuing eastward with a new and independent identity. Both baroclinic and barotropic processes are probably operating in all these situations.

These descriptions of how troughs are initiated on the 552-dam contour make clear the limitation of looking at a single contour. This choice was made in order to make feasible an investigation of hemispheric scope over a substantial period of time. We might alternatively have chosen to examine absolute vorticity maxima at 500 mb as being less arbitrarily selected. Had we done so, we would probably have seen large numbers in polar latitudes, where the vorticity is high and the gradient (of the Coriolis parameter at any rate) is weak. Vorticity perturbations of greater dynamical significance might occur farther south but not appear as centers owing to the strong gradients of vorticity flanking the major belt of westerlies. To deal with this difficulty, we might consider calculating the Laplacian of the vorticity field, or we might return to the simple approach we in fact selected.

We wish only to defend our choice, not to suggest that this study exhausts the possibilities for describing how upper-level disturbances form. To the contrary, more detailed studies of particular cases are needed, as is a theory for these types of development.

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