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TIROS VORTICES AND LARGE-SCALE VERTICAL MOTION [1]

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ABSTRACT

TIROS cloud photographs and fine-scale quasi-geostrophic calculations of vertical motion are used in an attempt to gain understanding of the evolution of vortices and other aspects of large-scale cloud masses and to explore the usefulness of the pictures in diagnosis of the vertical motions.

Horizontal and vertical motions are found to be of roughly equal importance in the evolution of cloud patterns, except in the early phases of the storm, when the latter predominate. This circumstance complicates the diagnostic application of the pictures, but the evolution of cloud patterns is nicely accounted for.

Cloud vortices occur in a variety of large-scale motion environments and seem to depend on fine-scale variations of motion and moisture structure which escape detection in conventional sounding networks.

Quasi-geostrophic theory is found to yield at least qualitatively realistic vertical motions even in application to systems of smaller scale than can be justified a priori.

1. INTRODUCTION

PURPOSE AND APPROACH

The purposes of this study are to gain insight into the production and maintenance of large-scale cloud systems and to enhance the diagnostic value of TIROS cloud photography by calculation of large-scale vertical motion and comparison of the results with the cloud photographs. Little work of this sort has been done, though Deardorff [7] has commented briefly on measurements made in the vicinity of a cloud vortex, and Hansen and Thompson [8] have reported rather indifferent results in a summer study over the western and central United States in summer. Sherr and Rogers [14], moreover, have proposed a hypothesis concerning the effectiveness of vertical motions, but without the support of specific calculations.

Two important and not unrelated questions to which attention is here directed are (1) the relative importance of the roles of horizontal and vertical motion in accounting for the observed configuration of vortices and other large cloud systems, and (2) the degree to which presence or absence of cloud can be taken as an indication of local ascent or subsidence.

The main avenue of approach to these questions is a study of the relationships between calculated fields of large-scale vertical motion and cloud patterns observed by satellite for selected cases in middle latitudes. Clear-cut synoptic character was the criterion for selection of cases, subject to limitations imposed by availability of both conventional upper-level sounding data and TIROS observations.

Explanation of the diagnostic model used for calculating the vertical motion field and of the methods of analysis, and discussion of the results for the two cases studied are presented in succeeding sections of this paper.

DIAGNOSTIC MODEL FOR VERTICAL MOTION

A suitable equation for calculating the vertical motion is obtained by combining hydrodynamic and thermodynamic equations for large-scale quasi-geostrophic flow so

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as to eliminate local time derivatives. An appropriate form of the vorticity equation in the (x,y,p,t)-system is

$$\nabla^2\frac{\partial\Phi}{\partial t}=-f_0\mathbf{V}\cdot\nabla\eta+f_0^2\frac{\partial\omega}{\partial p} \quad (1)$$

where Φ is the geopotential, η is the absolute vorticity, f_0 is a constant value of the Coriolis parameter, and $\omega\equiv dp/dt$ represents the vertical motion. An appropriate form of the thermodynamic energy equation is

$$\frac{\partial}{\partial p}\frac{\partial\Phi}{\partial t}=-\mathbf{V}\cdot\nabla\frac{\partial\Phi}{\partial p}-\sigma\omega+H \quad (2)$$

where $\sigma\equiv(\partial\Phi/\partial p)(\partial\ln\theta/\partial p)$ is a measure of the static stability and is taken to be a function only of pressure, and $H\equiv(R/c_pp)(dQ/dt)$ represents the effect of diabatic heating. Other symbols have their customary meanings.

When (1) and (2) are combined to eliminate $\partial\Phi/\partial t$, the familiar ω-equation results:

$$\left[\nabla^2+\frac{f_0^2}{\sigma}\frac{\partial^2}{\partial p^2}\right]\omega=-\frac{f_0}{\sigma}\frac{\partial}{\partial p}(-\mathbf{V}\cdot\nabla\eta)-\frac{R}{p\sigma}\nabla^2(-\mathbf{V}\cdot\nabla T)-\frac{1}{\sigma}\nabla^2H \quad (3)$$

In arriving at (3) the equation of state has been used to express $-\mathbf{V}\cdot\nabla(\partial\Phi/\partial p)$ in terms of temperature advection. The interpretation of this equation has been discussed in detail by Sanders [12] among others. It suffices here to note that the left side of (3) is negatively correlated with ω itself. From examination of the terms on the right side of (3), we then find that ascent (subsidence) tends to occur in regions of upward increase of cyclonic (anticyclonic) vorticity advection, near maxima of warm (cold) temperature advection, and near maxima of diabatic heating (cooling).

As boundary conditions, ω is assumed to vanish at the top of the atmosphere and at the lateral boundaries of the volume over which calculations are performed. At the 1000-mb. surface, which is taken to represent the base of the atmosphere, it is assumed that

$$\omega_{10}=\rho_{10}\left[\frac{\partial\Phi}{\partial t_{10}}-\mathbf{V}_{10}\cdot\nabla\Phi_s-gK\zeta_{10}\right] \quad (4)$$

Here Φ_s represents the geopotential at the surface of the earth and $\mathbf{V}$ and ζ_{10} are the geostrophic wind and its relative vorticity at the 1000-mb. level.[4] The contribution from the first term within the brackets is relatively small. The second term represents the orographic vertical motion due to flow over sloping terrain, and the third term represents the vertical motion at the top of the surface friction layer generated by frictional divergence within the layer. The constant K was selected so that a 1000-mb. geostrophic relative vorticity of 10^{-4} sec.$^{-1}$ generates a frictional vertical velocity of 2 cm. sec.$^{-1}$, a value which may be somewhat excessive, particularly over relatively smooth ocean surfaces. While the boundary assumption (4) is not very realistic for various reasons, it is probably better than the assumption that ω vanishes at the lower boundary.

The input data are values of ground elevation (taken from Berkofsky and Bertoni's [1] smoothed topography) and of the heights of the mandatory pressure levels up to 50 mb. (excluding 200 mb. and 100 mb.) at a rectangular grid of 32 by 24 points, with a mesh length of 165 km. in middle latitudes. Values of σ are obtained from an estimated sounding representing a horizontal average over the grid area. Diabatic heating or cooling is ignored.

Values of geopotential at 950 mb., 850 mb., . . ., 50 mb. are calculated by the program either directly from the input data or by interpolation. A horizontal smoother is next applied to minimize the effects of small irregularities. The field of geopotential tendency is then calculated by three-dimensional relaxation of a tendency equation obtained by eliminating ω between equations (1) and (2), subject to boundary conditions consistent with those described above for $\boldsymbol{\omega}$. The field of $\boldsymbol{\omega}$ is then obtained from (2), rather than by a separate time-consuming relaxation. The results, of course, satisfy the $\boldsymbol{\omega}$-equation (3). In the computation procedure horizontal Laplacians at each point are calculated from the values at the point and at the four surrounding points. Jacobians are evaluated from data at the four corners of a grid square. Computed values of geopotential tendency and vertical motion therefore refer to locations at the center of each grid square rather than at the grid points at which the input height data are supplied. Finite differences in the vertical are calculated over pressure depths of 100 mb. so that geopotential tendencies are obtained at 950 mb., 850 mb., . . ., 50 mb. and vertical motions at 1000 mb., 900 mb., . . ., 100 mb. Further computation details are presented by Sanders, Wagner, and Carlson [13].

A word of warning is necessary concerning the interpretation of results. As Phillips [11] has shown, the geostrophic theory upon which (3) is based is most appropriate for synoptic-scale circulations, of hemispheric wave number four to eight. The small mesh length used in these computations permits vertical motion patterns more than an order of magnitude smaller in scale. Identifiable cloud elements in the TIROS photographs are at least two orders of magnitude smaller. We are therefore entitled to relate the calculated vertical motions only to the broader aspects of the observed cloud systems, which are usually adequately portrayed in the nephanalyses prepared from the original detailed cloud pictures. Moreover, the quantitative accuracy of the details of the computed fields of vertical motion must be viewed with reservation. Hopefully, in fact, the degree of success in explaining the observed cloud patterns by use of the vertical motions may be a measure of their accuracy. Lest this state of affairs seem like the blind leading the blind,

[4] Because of the mechanics of computation, all 1000-mb. quantities on the right side of (4) are taken at 950 mb.

however, we offer the impression, based upon experience, that the geostrophic model yields qualitatively correct vertical motions even on scales considerably smaller than those for which the results can be rigorously defended a priori.

No attempt has been made in our calculations to incorporate the effect of the release of latent heat of condensation in the cloud systems, though Phillips [11] suggests that it would be appropriate to do so within the framework of the geostrophic model provided the precipitation rate does not exceed about 0.03 inch per hour. Qualitatively, it is apparent from (3) that the effect of this heating would be to enhance the ascent in the precipitation areas and perhaps shrink the size a little. Danard's [6] calculations based on the ω-equation demonstrate this effect in a case study (in which in fact the observed precipitation rate was larger than the critical value given above), and suggest that little change of the area of ascent occurs except where the gradient of the "dry" vertical motion is weak.

METHODS OF ANALYSIS

The 1000-mb. analysis was derived from a surface analysis based on teletypewriter data and observations obtained from the Northern Hemisphere Data Tabulations. A difference of 8 mb. in sea level pressure was taken to represent a 1000-mb. height difference of 60 m. This equivalence is only approximate and is temperature dependent, but is not thought to introduce significant errors since the calculations are based on horizontal gradients of height and of thickness between constant-pressure levels.

The analyses at the higher levels were based on rawinsonde data obtained from the same sources and were performed in ascending order. Thickness patterns between levels were not explicitly obtained but the analysis for each level was guided by that for the level below. Considerable care was taken in this process to insure that the implicit thickness pattern was not unnecessarily complicated.

SELECTION OF CASES

Two synoptic cases were selected for study:

A. September 4–7, 1962, United States and southern Canada

B. April 19–20, 1963, United States and southern Canada

The first of these illustrates the formation and evolution of a spectacular and long-lived cloud vortex, associated with an occluding though weak surface cyclone. The second features a northeastward-moving Colorado cyclone at the surface with well-defined cloud structure as observed by TIROS, and a short-lived cloud vortex.

2. THE CASE OF SEPTEMBER 4–7, 1962

The case of September 4–7, 1962 was particularly well covered by photographs from TIROS V. In addition, the weather situation lends itself well to computations based on geostrophic theory. The storm occurred over the North American continent where there were sufficient synoptic data to prepare the 10-level model computations with some confidence. Perhaps most significant was the evolution of a classical cloud vortex pattern.

SYNOPTIC DISCUSSION

The early part of September was marked by a ridge over the Gulf of Alaska and a major trough over North America. A strong block was present throughout the period over the western North Atlantic. The effect of the Pacific ridge was to produce a cold surface High in northwestern Canada. This cold dry air moved southeastward across the Central Plains and eventually off the southern New England Coast.

The situation on September 4 at 1200 GMT (fig. 1), the first period in which vertical motions were computed, showed the leading edge of the cold air running from James Bay through the central Great Lakes to the Texas Panhandle and back into the Rockies. A young wave cyclone was just forming near Lake Michigan ahead of an upper trough moving through southern Canada. In the next 24 hr. (maps not shown) the system underwent development at all levels. The upper Low became cut off just west of James Bay while the surface Low deepened 4 mb. and moved to a point near the southeastern tip of James Bay. The cold front meanwhile moved eastward into Ohio.

By 1200 GMT on the 6th (fig. 2), the system had become occluded and nearly immobile behind the blocking High over the Maritime Provinces. Meanwhile another short-wave trough system had moved into the Lake Winnipeg area. This system was fairly shallow. It showed only a slight ripple at 500 mb. and warm advection in the middle

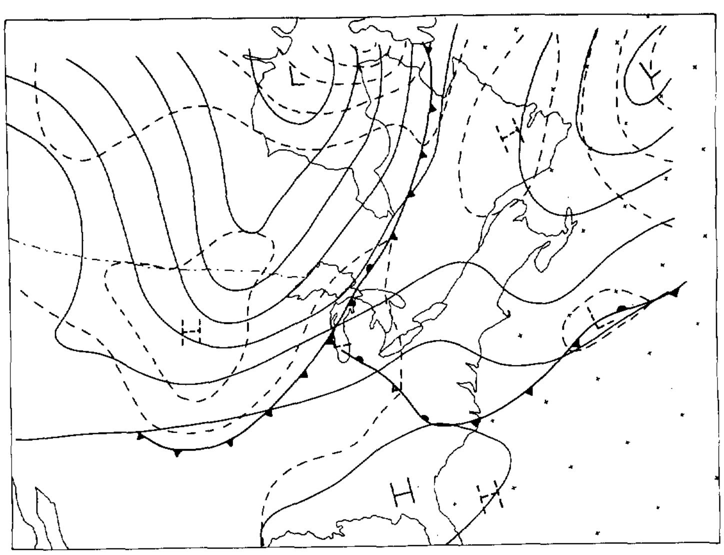

FIGURE 1.—Surface and upper-level analyses, 1200 GMT September 4, 1962. Dashed lines are 1000-mb. contours at intervals of 6 decameters. Solid lines are 300-mb. contours at intervals of 12 decameters. Surface fronts shown in conventional form.

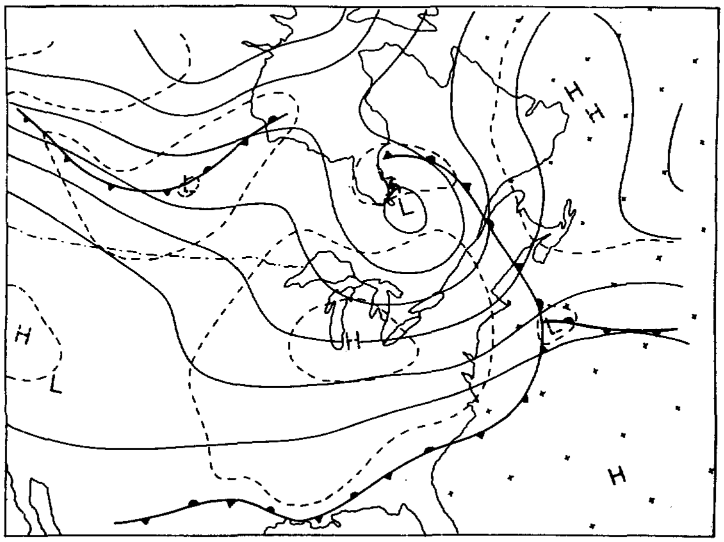

FIGURE 2.—Surface and upper-level analyses, 1200 GMT September 6, 1962. Position of TIROS vortex at 1325 GMT superposed.

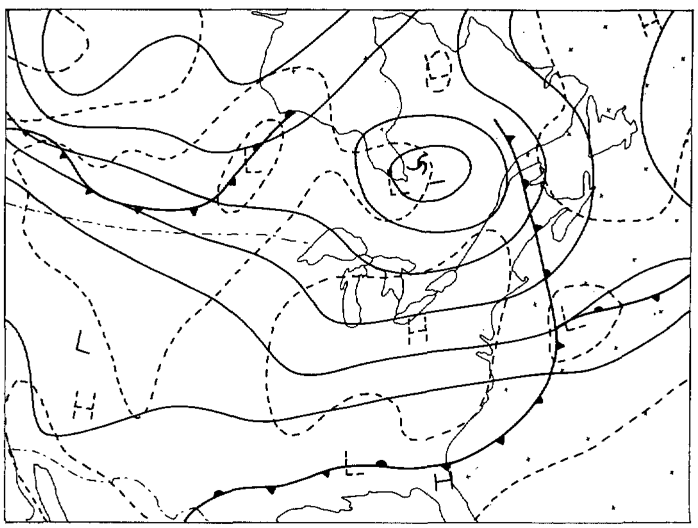

FIGURE 3.—Surface and upper-level analyses, 0000 GMT September 7, 1962. Position of TIROS vortex at 2027 GMT September 6, superposed.

troposphere gave it little chance of developing. The dry air had moved off the coast of the United States accompanied by secondary cyclogenesis southeast of Nantucket, and there was some push of cold air at the surface up the St. Lawrence River Valley.

During the next 24 hr. (figs. 3 and 4) the main cold Low drifted slowly eastward and maintained a healthy circulation above 700 mb. while the surface Low filled. The secondary surface cyclone moved eastward off the coast with little change of intensity. By contrast, a shot of cold air at the lower levels gave some character to the system near Lake Winnipeg. This was short-lived, however. By 1200 GMT on the 7th the long-wave upper trough was retrograding into another short-wave system just east of the Canadian Rockies, and by 0000 GMT on the 8th (maps not shown) the surface Low, with no support aloft, was filling as it moved over James Bay. The dry air, as indicated by dew points and synoptic reports, spread nearly up to the center of the primary Low by 1200 GMT on the 7th.

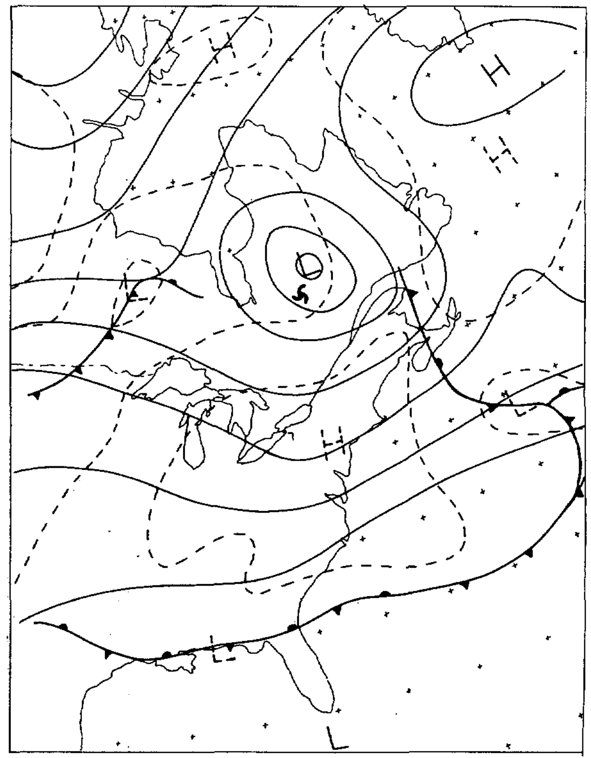

FIGURE 4.—Surface and upper-level analyses, 1200 GMT September 7, 1962. Position of TIROS vortex at 1250 GMT superposed.

FORMATION OF THE VORTEX

We are seldom fortunate enough to have TIROS photographs of a single storm from its inception as a small open wave disturbance to the fully occluded, dying stages. The case of September 4–7, 1962, was one of these rarities and because of this, it provides a valuable opportunity for study of the dynamics of the atmosphere. Several authors have recognized its value. Boucher et al. [3] made a careful synoptic interpretation of the cloud pattern. Tang et al. [15] looked at one stage of this storm in connection with the small-scale structure of the cloud band.

This study will present a mechanism for the formation of the vortex pattern based on dynamically calculated vertical motions and observed horizontal winds. In the following discussion only those features of the cloud pattern considered to be an integral part of the vortex formation will be discussed. Other interesting agreements and discrepancies between vertical motion and observed clouds will be presented in a later section.

a. September 4, 1200 GMT

The major feature here (fig. 5) is a frontal band from

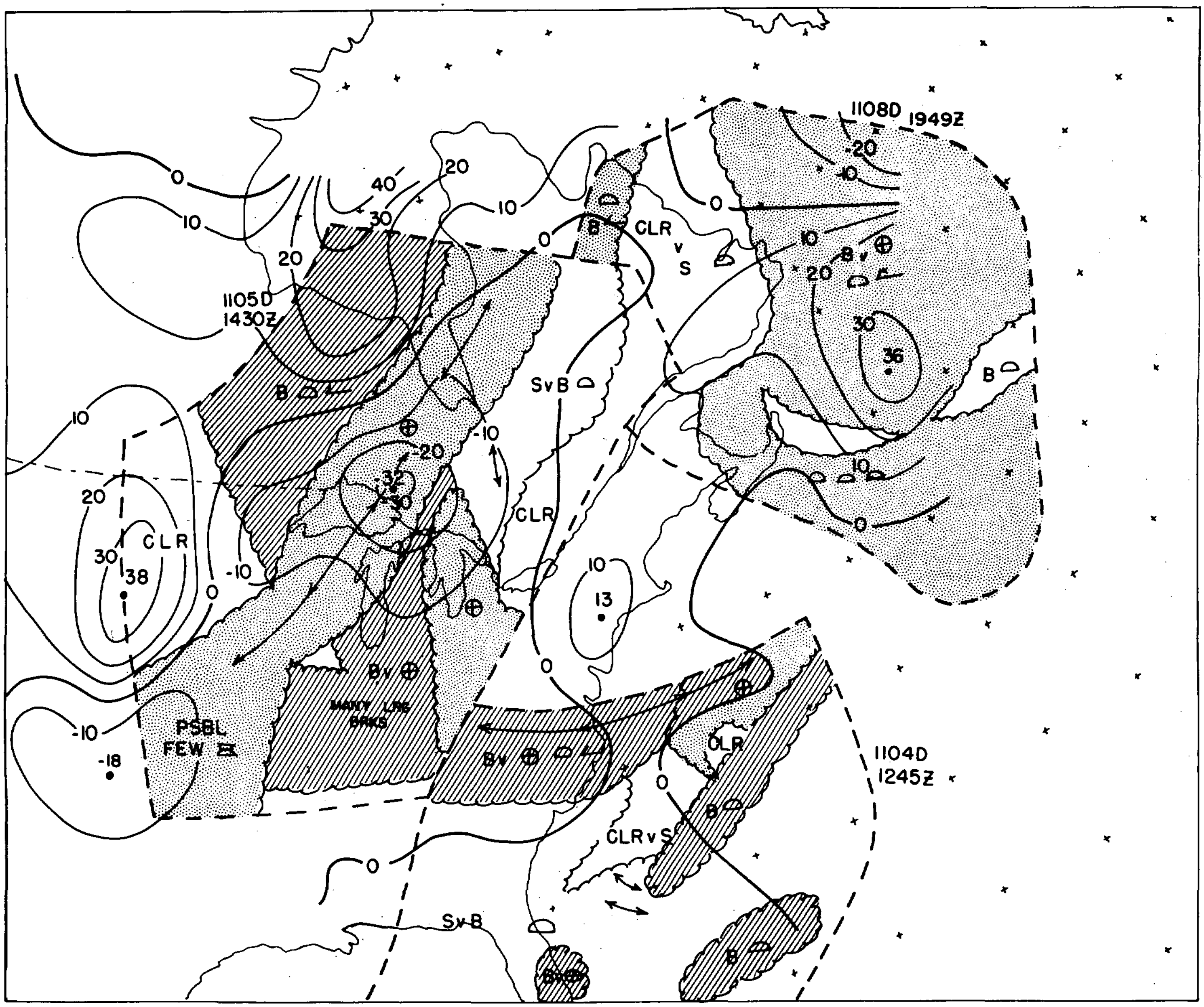

FIGURE 5.—Nephanalyses near 1200 GMT September 4, 1962. 700-mb. vertical motion superposed.

James Bay southeastward into Texas. A wave in the cloud band corresponds to the young disturbance in the Great Lakes. On the north side of the wave is an area of broken stratocumulus and altocumulus. West of this skies are clear. The vertical motions (fig. 6) correspond very well to the major cloud features. There is a westward tilt of the ascent region with height as observed by Sanders et al. [13], but the center of maximum descent remains nearly vertical. The result is to create a large gradient, almost a "shear zone" at middle levels between the strong downward and upward motions. If allowance is made for the difference in times between the pattern of vertical motion and the TIROS pass, this zone is found to correspond closely with the eastern edge of the clear area.

A kinematic experiment was made in which points on nephanalyses for pass 1109D 1532 GMT September 5 (not shown) were moved in 24-hr. trajectories based on observed 700-mb. winds. The resulting deformation of the cloud pattern from the 5th to the 6th, shown in figure 7, looked strikingly like the nephanalysis at the valid time (fig. 8). Another run between the 4th and 5th (not shown) gave equally good agreement. There is evidence from this experiment that a cloud band transported in a cyclonic circulation will develop a vortex shape including a narrow intrusion of clear air.

The successful use of the horizontal flow to account for the evolution of the cloud pattern depends on the parcels of clear or cloudy air maintaining their identity. Though winds at various levels were tried in the above experiment,

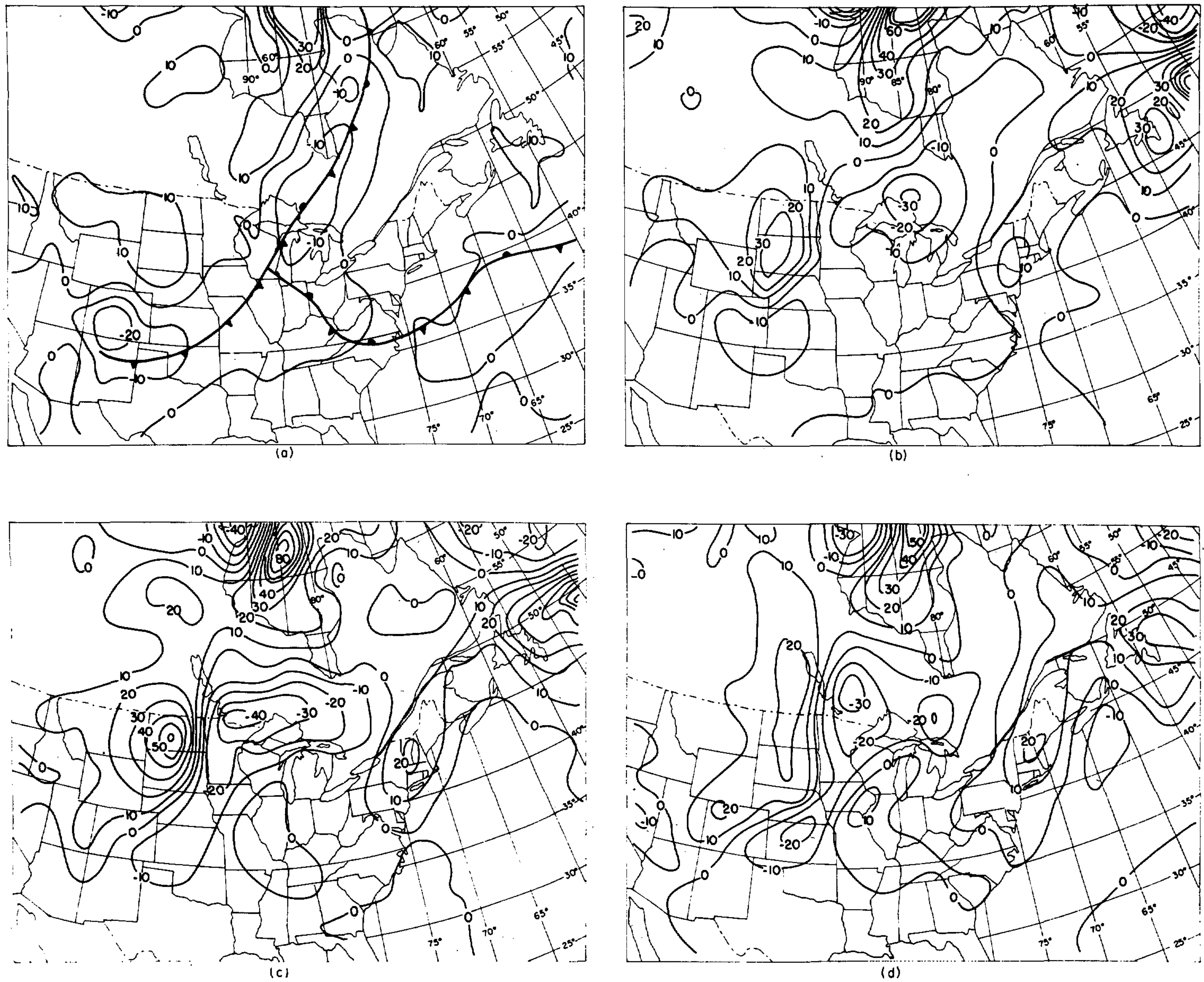

FIGURE 6.—Vertical motions (10^{-4} mb. sec.$^{-1}$), 1200 GMT September 4, 1962. (a) 900 mb., with surface fronts superposed; (b) 700 mb.; (c) 500 mb.; and (d) 300 mb.

the level which gave the best correlation with verifying nephanalyses was 700 mb. According to Younkin, LaRue, and Sanders [18] the effective "steering level" for the moisture from the surface to 500 mb. is about 800–833 mb., and since this integrated moisture is statistically related to cloud cover, regardless of height, the 850-mb. wind might ordinarily be expected to be better. In this case it turned out that between the 4th and 6th of September the vertical motion field moved with nearly the speed of the 700-mb. wind. As a result, cloud elements transported in that flow remained in the same type of vertical motion during most of the 48 hr. and retained their original appearance. A parcel moving faster would pass into a region of opposite vertical circulation. Clear air would rise and become saturated; clouds would sink and dissipate.

In summary, although individual cloud elements may move with a spectrum of horizontal velocities, the vertical-motion pattern and its movement relative to the flow single out a speed for the large-scale cloud mass by production and destruction processes at the boundaries.

It would appear that in the early stages of a storm's development, when the horizontal motion has not yet developed maximum character, the cloud cover should look most like a "snapshot" of vertical motions. Thereafter, tomorrow's clouds may reflect to some extent today's vertical motions deformed in a horizontal flow.

b. September 6, 1200 GMT

In the 48 hr. after the first open wave appeared, the cloud pattern formed a vortex as depicted in figures 8 and 9. The 24-hr. horizontal transport experiment, described previously, verifying at this time describes much of the character of the cloud pattern if the 700-mb. winds are used. There is actually more cloudiness on the west side of the vortex than indicated and the clear air is carried too far in the experiment into the frontal band over New England. Both discrepancies can be accounted for qualitatively by the computed ascent in these regions (fig. 10).

On the whole, the correlation between the vertical motion pattern and cloudiness is still excellent. Figure 10 shows an ascent maximum near James Bay with the ascent extending in an arc through Quebec and southward along the coast. The descent area connected with the cold Canadian air mass is centered over the eastern end of the Great Lakes above the northeast quadrant of the surface High. It is beginning to project a narrow finger northward into southern Quebec coinciding with a region of broken stratocumulus on the nephanalysis. These clouds are verified by surface observations. This is an area of northwesterly flow at low levels and the existence of cloudiness within descent can be explained by small-scale orographic effects and mechanical turbulent

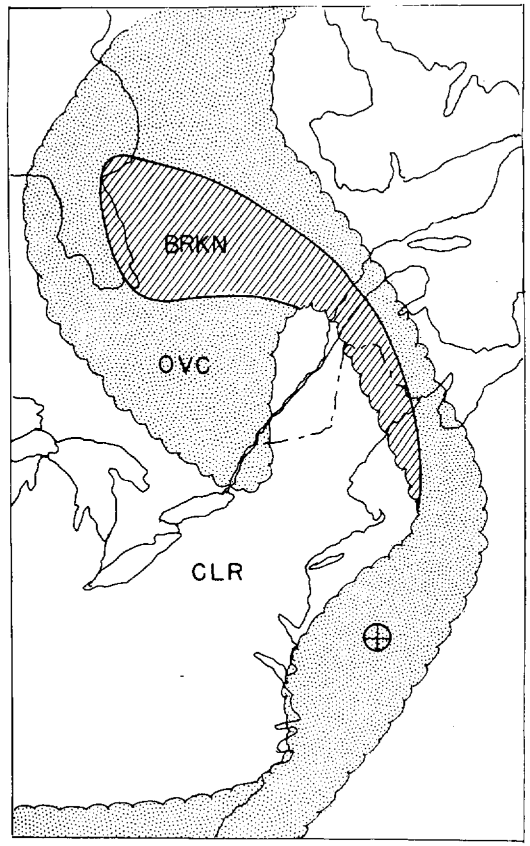

FIGURE 7.—Predicted nephanalysis for 1325 GMT September 6, 1962. See text for explanation.

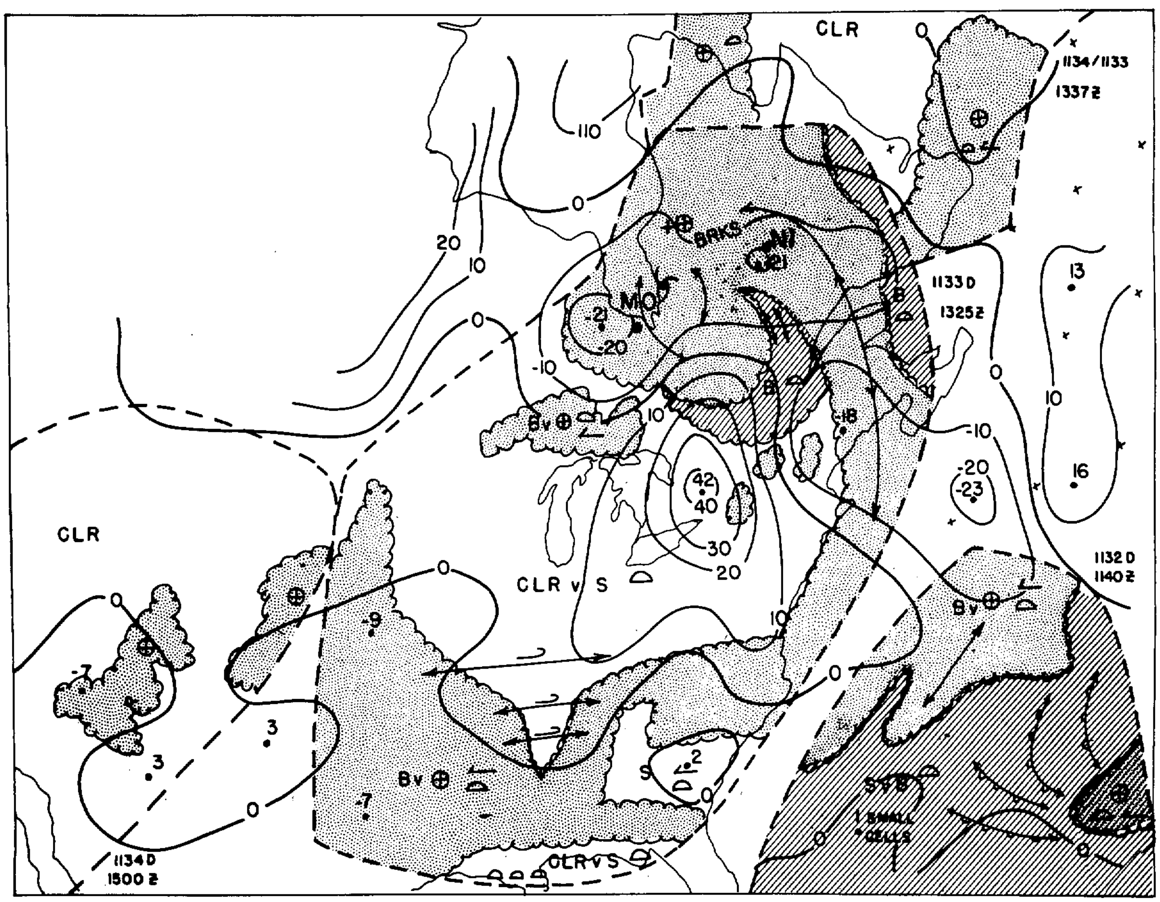

FIGURE 8.—Nephanalyses near 1200 GMT September 6, 1962. 700-mb. vertical motion superposed. Positions of Nitchequon (NI) and Moosonee (MO) shown.

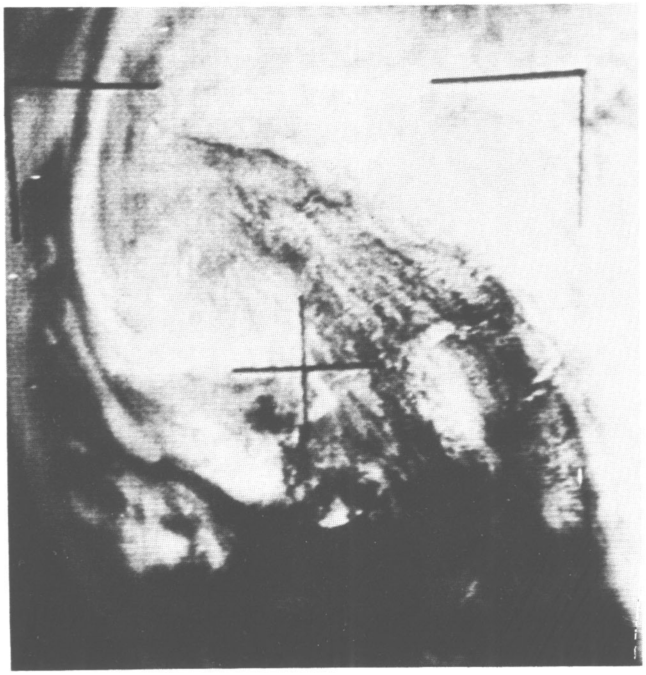

FIGURE 9.—TIROS V, pass 1133D, 1325 GMT September 6, 1962. Frame 10.

Below

FIGURE 10.—Vertical motions (10^{-4} mb. sec.$^{-1}$), 1200 GMT September 6, 1962. (a) 900 mb., with surface fronts and TIROS vortex at 1325 GMT superposed; (b) 700 mb.; (c) 500 mb.; and (d) 300 mb.

mixing. Flow normal to the Laurentians is probably producing instability clouds for which an explanation in terms of large-scale vertical motions should not be attempted. The important thing here is the absence of layered higher cloud. The region of maximum descent is clear as would be expected.

c. September 7, 0000 GMT

One of the biggest changes in the cloud patterns from 1200 GMT on the 6th to 0000 GMT on the 7th is the dissipation of cloudiness within the vortex. The nephanalysis and photographs (figs. 9, 11, and 12) show apparently solid overcast throughout the area early on the 6th and many large breaks developing later in the day. The deep moist layer over Nitchequon (NI) on the 6th has become just scattered cumulus and altocumulus clouds with tops below 630 mb. at 0000 GMT on the 7th. Similarly, Moosonee (MO), which is still near the center of maximum ascent, has gone from cloud tops at 330 mb. to low and middle clouds.

This drying can be accounted for by the vigorous small-scale pattern of vertical motion which has evolved (fig. 13). As in the previous time period, advection of the cold polar air mass accounts for the large area of moderate descent centered over eastern New York State. For the first time pronounced cold advection is reaching near the vortex center, creating an intense small-scale descent area in the northeast quadrant. This is a feature which the 10-level model brings out clearly, but which would be missed by a coarser grid. In the light of this spectacular pattern of vertical motion and the history of air parcels arriving at various points in the vortex cloud mass, the rather sudden drying in the upper levels appears reasonable. For example, Moosonee is near the upwind side of the ascent maximum. Twelve-hour trajectories at 700 mb. and 500 mb. ending there may have originated in descent. The presence of cloud at Nitchequon despite strong descent can be explained by noticing that a 12-hr. trajectory in the middle troposphere began in the ascent area. The average motion over the path may still be upward.

The horizontal cloud transport experiment fails to give good results at this stage of the storm since the ascent maximum becomes stationary, as does the circulation center itself. Although the major large-scale descent area has moved eastward, its movement does not coincide with any steering flow. As a result, the assumption of "conservation of cloud" is not valid. This method would move the clear area well north into the observed overcast.

In comparing the vertical motion field to the nephan-

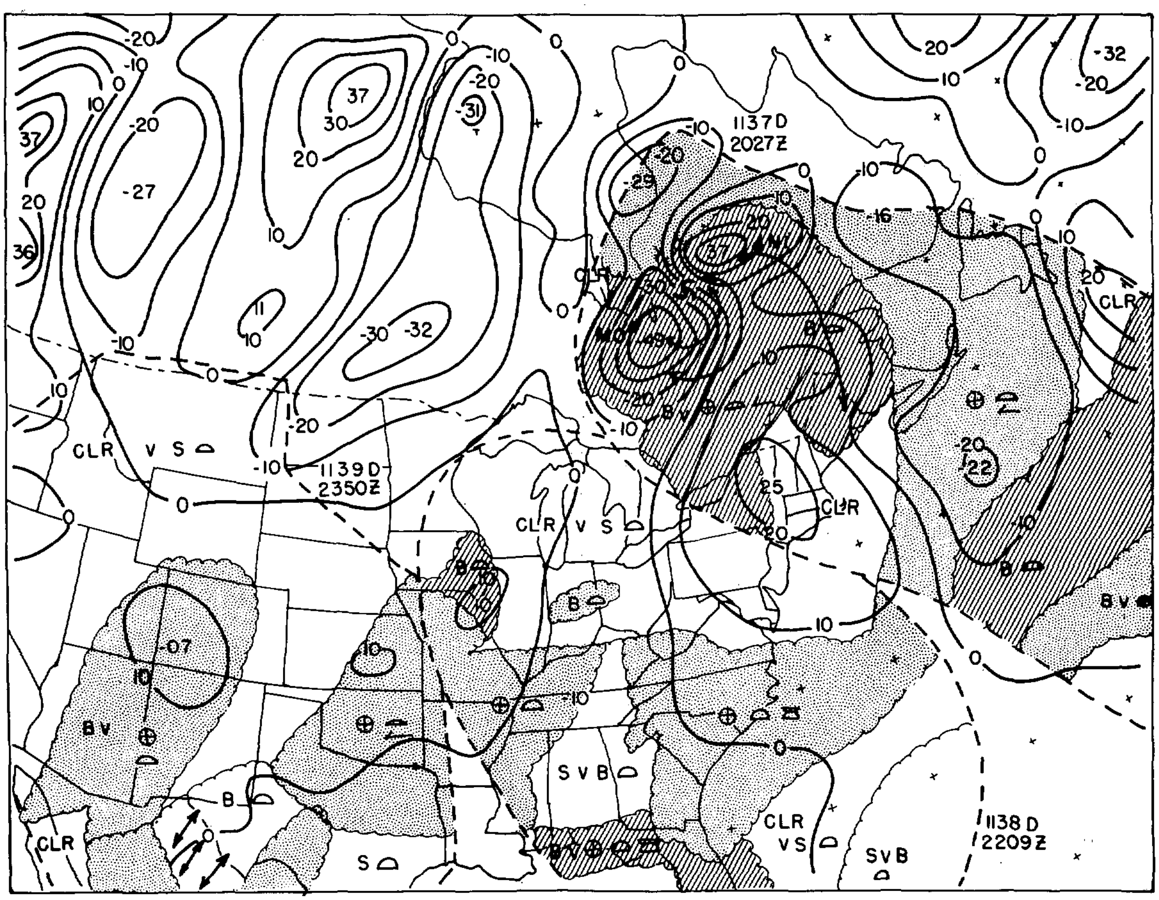

FIGURE 11.—Nephanalyses near 0000 GMT September 7, 1962. 700-mb. vertical motion superposed. Positions of Nitchequon (NI) and Moosonee (MO) shown.

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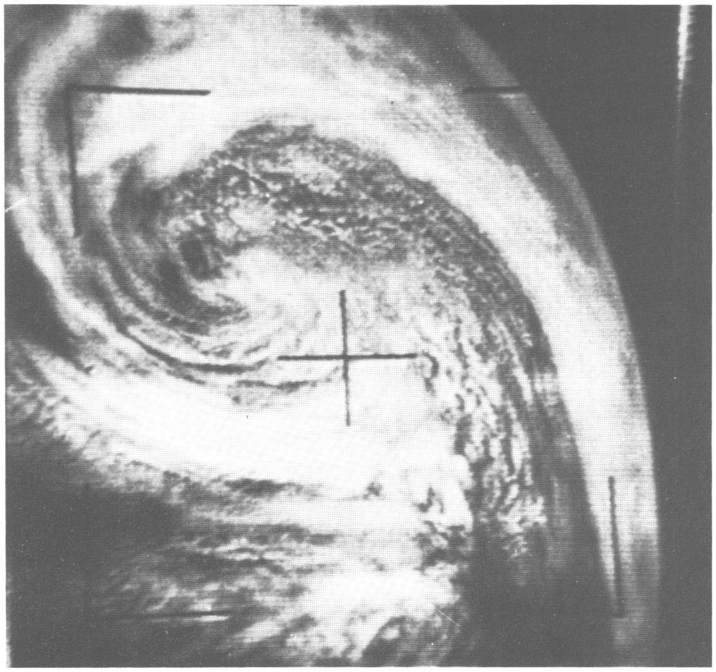

FIGURE 12.—TIROS V, pass 1137D, 2027 GMT September 6, 1962. Frame 1.

Below

FIGURE 13.—Vertical motions (10^{-4} mb. sec.$^{-1}$), 0000 GMT September 7, 1962. (a) 900 mb., with surface fronts and TIROS vortex at 2027 GMT September 6 superposed; position of Nitchequon (NI) shown; (b) 700 mb.; (c) 500 mb.; and (d) 300 mb.

alysis it is important to remember that pass 1137D occurred in mid-afternoon, 3½ hr. before the conventional data. Considerable convective cloudiness was present in the picture (fig. 12) over the Eastern Great Lakes, New York, and New England. These clouds dissipated by 0000 GMT as shown by surface observations. If this is taken into account, the cloud-free area very closely agrees with the zero line around the descent below 10,000 ft. The frontal band is still marked by moderate ascent and still maintains a hook shape around the north side of the strong subsidence (fig. 13c). Generally speaking, the vertical motion mechanism for describing the vortex is explaining things rather well. However, some knowledge of history of the air parcels is required. The cloud pattern is no longer the "portrait" of the vertical motion pattern that it was in the earlier stages.

d. September 7, 1200 GMT

The striking small-scale pattern of vertical motion is still present at this time (fig. 14). The ascent maximum has drifted northeastward about 180 n. mi. while the descent has moved slightly westward putting it on the north side of the ascent. This pattern appears to be significant for the evolution of the vortex. Figures 15 and 16 show the clear air intrusion as a narrow finger completely around the north and partially into the back side of the major cloud mass. The mechanism producing the descent is still almost entirely thickness advection. As the cold air works its way around the closed circulation, the strong descent accompanies it. This downward motion dries the air sufficiently to suppress even the instability stratocumulus which was present in the dry tongue earlier.

The central cloud mass has a mostly broken appearance except for a band of brighter cloudiness along the eastern edge (see fig. 16). It appears to coincide with a similar area of heavy cloudiness 12 hr. previous. In fact, if the vortex of 0000 GMT on the 7th were rotated about 45 deg. counterclockwise and the clouds in the dry intrusion erased, it would look very much like the vortex at 1200 GMT (cf. figs. 12 and 16). The angular rotation of the vertical motion pattern is very nearly the same (cf. figs. 13b and 14b). In the later stages of occlusion, the storm system is rotating as it drifts slowly eastward. The rotation of the dynamic system produces a similar behavior in the cloud pattern.

Within the band of heavy clouds, surface observations show mostly overcast and multi-layered clouds with several stations reporting rain. This contrasts with the remainder of the vortex area which has mostly broken clouds with no precipitation reported.

The cloud pattern appears to have most character, weatherwise, in the vortex region, aside from the major frontal band. It is worthwhile to ask why this does not correlate exactly with ascent, and why it extends in fact into a region of slight descent. Twelve-hour trajectories (not shown) terminating within the vortex mass have a history of strong ascent for much of the period, thus indicating cloud production over most of the route. A good indicator of the dynamic behavior in the band is Nitchequon (NI in figs. 13 and 14). At 0000 GMT it is moist below 700 mb. but drying out aloft. The 1200 GMT sounding shows saturation throughout as the clear tongue passes eastward and the vortex cloud mass moves over the station. In both periods, Nitchequon is under descent; however, the air over the station has undergone different three-dimensional trajectories.

Many details have been presented in this discussion in order to provide evidence that the small-scale features in the vertical motion field actually play an important role in the vortex formation. It is believed that this discussion shows that quasi-geostrophic theory may be capable of accounting at least qualitatively for the smaller details of synoptic-scale disturbances.

GENERAL DISCUSSION

There are a few details in the cloud and vertical motion patterns which are not an integral part of the vortex evolution and which, in many cases, are not time related. Yet there are interesting relationships which will be discussed disjunctively in this section.

At 1200 GMT on September 4, to the east of the main frontal band, a patch of cloudiness seen over lower Ontario in figures 5 and 17, and which Boucher et al. [3] refer to as a breakaway area, is associated with a weak but moist surface disturbance which later deepens off the Delaware coast and passes off to sea. The vertical motion calculations (fig. 6) show weak ascent in the lower troposphere but not enough to substantiate a large cloud mass. The cloud occurs within a deep moist tropical air mass and is largely convective, judging from figure 17. According to Curtis, Leese, and Valovcin [5], convective cloudiness is not well represented in calculations of this sort and often occurs in regions of near zero large-scale vertical motion.

A north-south band of vigorous ascent occurs above 600 mb. in the frontal zone (fig. 6c and d). It coincides with a line of thunderstorms in Nebraska and Kansas, 100 mi. behind the surface cold front. Soundings for Omaha and Dodge City (not shown) indeed indicate the bases of the cumulonimbus to be near 700 mb. rather than at lower levels. Here is some encouraging support to the idea put forth by Sanders et al. [13] that although convective activity is not well represented by large-scale vertical motions, the presence of ascent in a conditionally unstable air mass strongly favors the formation of a squall line.

Another feature of major significance in the cloud patterns of the last three time periods is the extensive cloudiness associated with the frontal band in lower latitudes (figs. 8, 11, and 15). For the most part it is supported only by weak ascent and often occurs in weak descent. The vertical motion field at lower latitudes does not display nearly as much character as at high latitudes. This is inevitable since thickness and vorticity advections are so weak in the South.

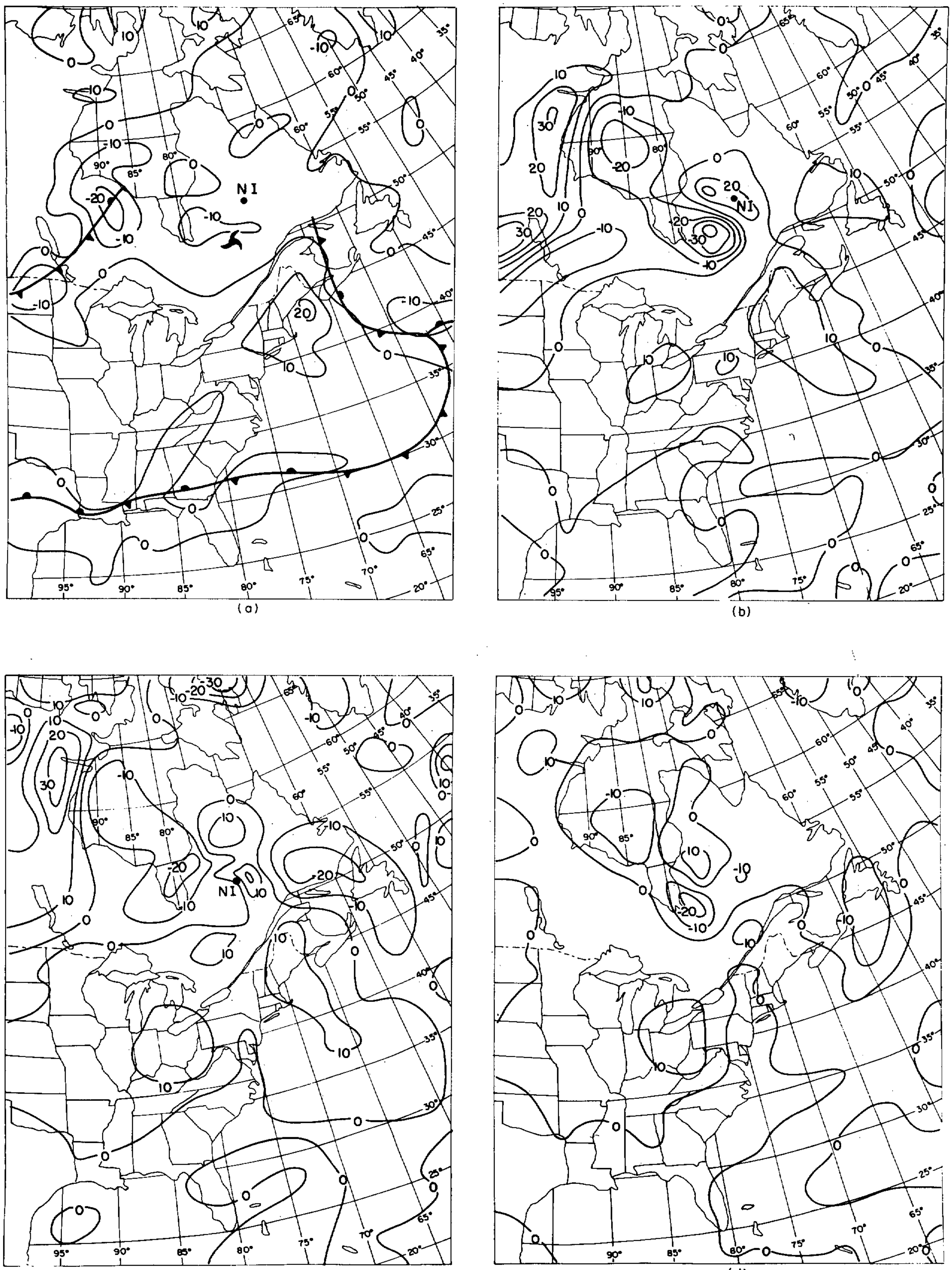

FIGURE 14.—Vertical motions (10^{-4} mb. sec.$^{-1}$), 1200 GMT September 7, 1962. (a) 900 mb., with surface fronts and TIROS vortex at 125 GMT superposed; position of Nitchequon (NI) shown; (b) 700 mb.; (c) 500 mb.; and (d) 300 mb.

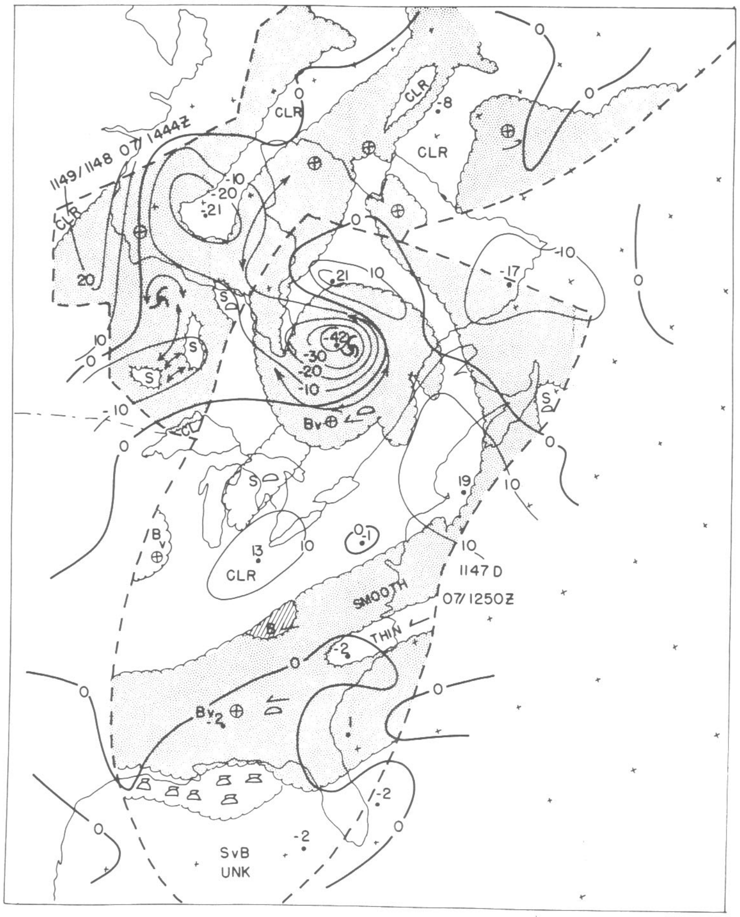

FIGURE 15.—Nephanalyses near 1200 GMT September 7, 1962. 700-mb. vertical motion superposed.

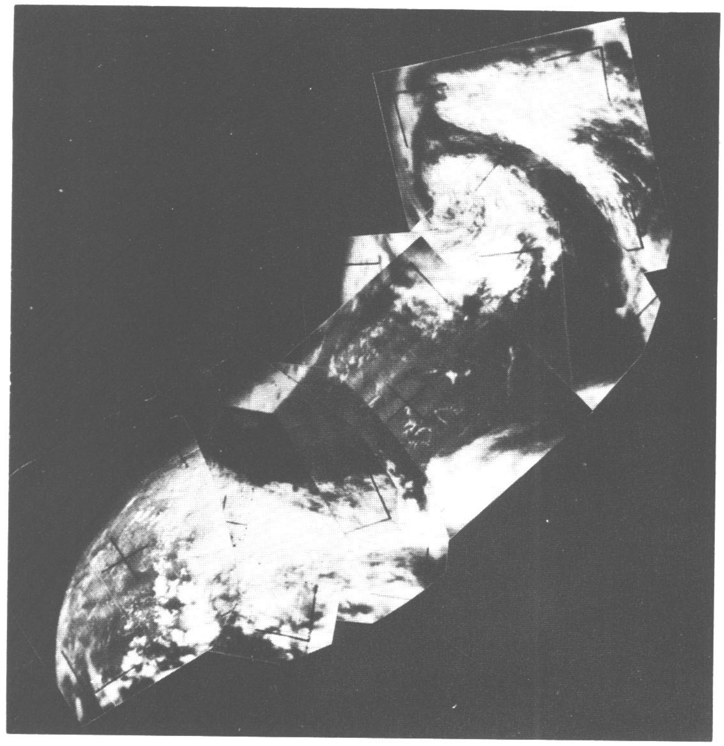

FIGURE 16.—TIROS V photomosaic, pass 1147D, 1250 GMT September 7, 1962.

The question arises why cloud cover appears so dense in this region. The answer probably lies in the convective nature of the clouds. Soundings and surface observations in the lower latitudes indicate convective cloudiness. Convection is especially noticeable at 1200 GMT on September 7. A distinct line of cumulonimbus is present in the warm air just off the Gulf Coast. There is a band of weak ascent in the area (fig. 14) which might encourage rather than suppress the growth of thunderstorms but apparently the large-scale vertical motions play a secondary role here.

One other feature of primary interest is that at both times on the 7th, descent seems to interrupt the frontal band along the east coast (figs. 13 and 14). This might cause some concern until one notices the weakening of cloud cover in figures 12 and 16. The effect is more evident at 1200 GMT. There is a storm developing southeast of Nova Scotia and tending to disrupt the frontal structure and also the vertical motion calculations.

3. THE CASE OF APRIL 19-20, 1963

Several passes over North America during the late afternoon of both April 18 and 19 by TIROS V produced good picture coverage of a large portion of the continent.

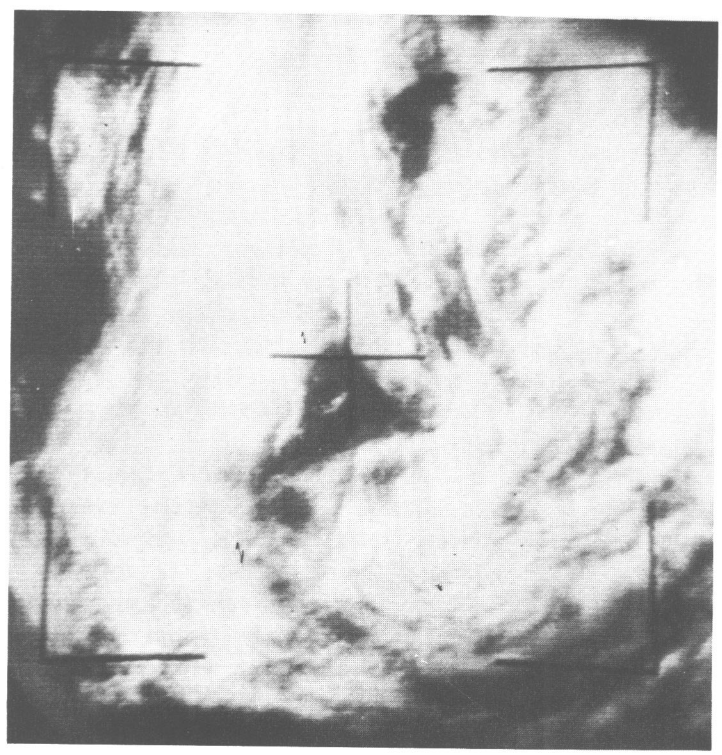

FIGURE 17.—TIROS V, pass 1105D, 1430 GMT September 4, 1962. Frame 1.

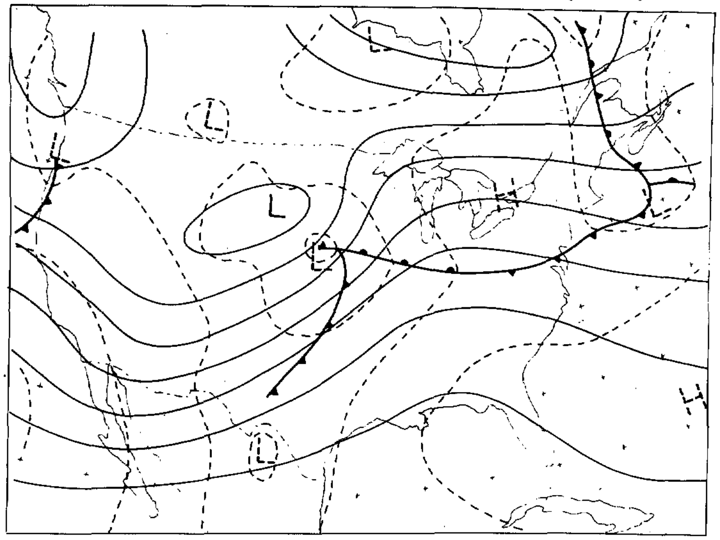

FIGURE 18.—Surface and upper-level analyses, 0000 GMT April 19, 1963. Dashed lines are 1000-mb. contours at intervals of 6 decameters. Solid lines are 300-mb. contours at intervals of 12 decameters. Surface fronts shown in conventional form.

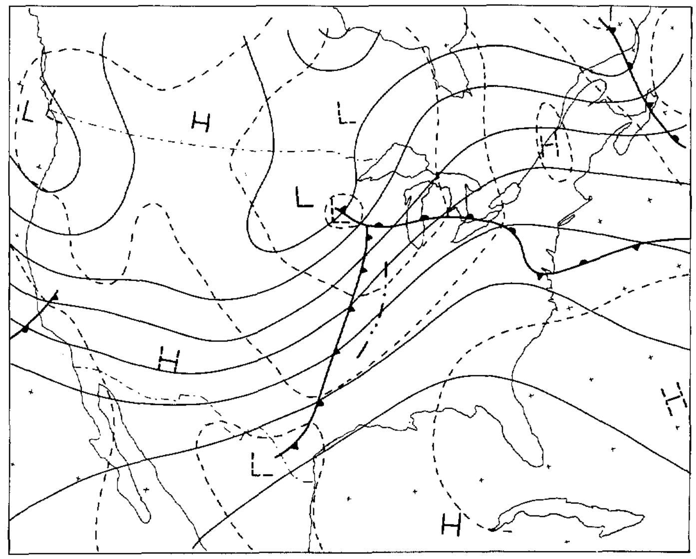

FIGURE 19.—Surface and upper-level analyses, 1200 GMT April 19, 1963.

Of major importance to this study is the observation of a pronounced vortex cloud pattern during part of the period. The time distribution of the satellite data suggested computation of the vertical velocity field for the following times: 0000 and 1200 GMT April 19, and 0000 GMT April 20. The 1200 GMT April 19 computation was made to allow for interpolation of the vertical velocity patterns. This was necessary to account for the difference between the time of the satellite pictures and the upper-air soundings, and to follow the evolution of the weather system that produced the observed cloud patterns.

SYNOPTIC DISCUSSION

At 0000 GMT of the 19th (fig. 18), a low pressure center which developed east of the Rockies is located in Nebraska. A cold front extends southward into Texas and a warm front eastward through southern Ohio. Thunderstorms are occurring along the warm front and a thin band of light snow and rain covers an area from Montana to Lake Michigan. Clear to partly cloudy skies are reported from Kansas southwestward into Mexico. High pressure predominates in the St. Lawrence Valley region where little cloudiness is reported.

Aloft, the Low maintains a closed circulation to high levels and tilts to the northwest. A tongue of warm air lies north of the Low in the middle troposphere causing warm air advection in the Montana area. High pressure aloft in the Gulf of Mexico ridges north and then northwest over the Great Lakes. A tongue of dry air embedded in southwesterly flow extends northeastward from the Texas Panhandle and is reflected by very low dew points at the surface behind the cold front.

By 1200 GMT of the 19th, the surface Low has combined with a Low from central Canada to form one large double-centered cyclonic circulation with the primary center in

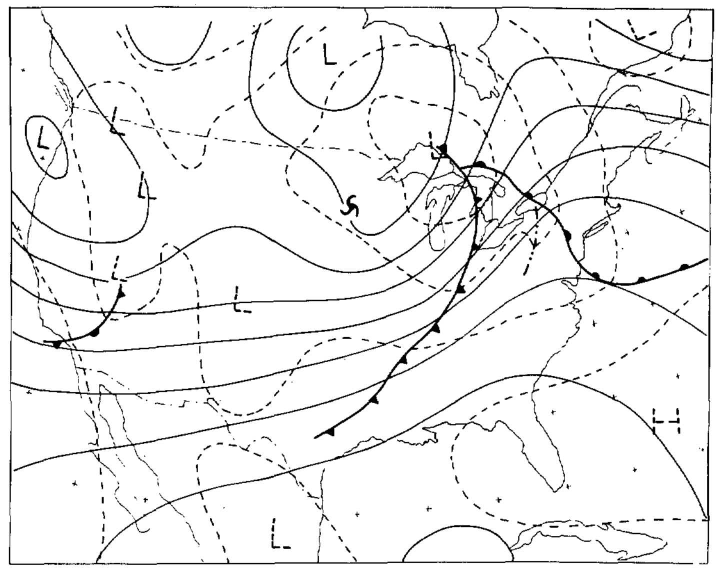

FIGURE 20.—Surface and upper-level analyses, 0000 GMT April 20, 1963. Position of TIROS vortex at 1925 GMT April 19 superposed.

Minnesota (fig. 19). Rain showers and a few thunderstorms accompany the warm front as it moves north and a band of continuous light rain and snow covers a narrow area from the Dakotas through the northern Great Lakes. The cold front has moved east and triggered a squall line from Indiana to Texas.

At upper levels two distinct circulation centers are maintained, one in the north-central United States and one in central Canada. Here also the merger of the two systems has begun.

At the final time period of this study, 0000 GMT of the 20th, the surface Low is over the central Great Lakes (fig. 20). The cold front is on a Lake Huron-Arkansas line and the warm front runs through New York and eastern Pennsylvania. The frontal system is occluding near the Great Lakes. Considerable thunderstorm activity continues in the warm sector and some light precipitation is found north and east of the Low.

The main upper-level feature is a large cyclonic circulation center northwest of the Great Lakes with a considerable northwest tilt in the lower troposphere. There is strong cold advection in the lower troposphere behind the cold front, and strong warm advection is occurring from southern Quebec through Pennsylvania. A deep upper-level trough lies over Wisconsin and Minnesota associated with an intense vorticity maximum which represents the remnant of the southern circulation center.

Although some heavy precipitation from thunderstorms was observed during the 24 hr. of interest, the overall precipitation pattern associated with the storm system is consistent with quasi-geostrophic formulation.

ORBITAL PASS 4348T: 1955 GMT, APRIL 18

There is no recognizable cloud vortex at this time (fig. 21), although close examination of figure 22 indicates a possible circulation center in western South Dakota. This is supported by the position of the upper-level low center (fig. 19).

The boundary between the clear area behind the frontal band and the cloud-filled area is very well defined. Also there is a noticeable asymmetric bulge in the frontal cloud mass toward the Iowa-Wisconsin area. This bulge actually extends into Montana (determined from a photograph not shown) and is verified by surface reports. Eastern Montana is seen to be a region of ascent (fig. 23). This upward motion is caused by warm advection which was mentioned in the synoptic discussion.

Eastern Colorado, slightly upwind from the approximate middle of the clear area, is the center of a region of moderate descent. The small band of cloudiness observed in Colorado is not consistent with the vertical motion field. However, examination of figure 22 reveals that this is convective cloudiness. Also, these clouds dissipate later on, as the area is clear by 0600 GMT of the 19th according to surface reports.

The broken-to-overcast cumuliform clouds northwest of New Mexico in figure 22 are also in conflict with the vertical motion pattern. The photograph reveals detailed structure which suggests that these clouds are produced by an orographic effect. Small-scale streets oriented east-west roughly coincide with the west- to northwesterly flow at 700 mb. and 500 mb. at this time. This flow is normal to the mountain ranges in this area. Large-scale bands within this cloud mass are oriented north-south. This feature can be related to the general north-south character of the individual mountain ranges.

The coincidence of the zero-line of vertical motion at 700 mb. (fig. 23b) with the boundaries of the main cloud mass in the north-central United States is quite marked. If, however, account is taken of the time difference between the TIROS photographs and the vertical motion calculations, it is apparent that the upwind cloud boundary lies within substantial ascent while the downstream boundary extends into weak descent. Apparently, parcels of dry air are moving from an area of descent to one of ascent and do not reach saturation for some time. Similarly, high clouds are being advected from ascent to descent and are taking some time to evaporate. The fact that the leading edge of the cloud system moving into Michigan and Ohio is composed of cirrus is verified by surface reports. Also, the photograph (fig. 25) reveals that the easternmost clouds appear to be cirriform while the western portion of the cloud shield has a more sculptured appearance with a shadowy effect as if this portion were composed of a much deeper cloud structure with an irregular upper surface.

Surface reports at 1800 GMT of the 18th and 0000 GMT of the 19th were utilized to determine the movement of the leading edge of the cirrus clouds. Figure 26 illustrates this movement. Surface reports were in good agreement with the nephanalysis. The northern half of the leading edge moved from Lake Michigan to central New York, a distance of about 400 n. mi. The southern half moved from eastern Ohio to central Pennsylvania, about 200 n. mi. The vertical motion at 300 mb. at 0000 GMT of the 19th indicates that the leading edge was undergoing slight descent during the 6-hr. period, varying from 2 to 6 mb. per 3 hr.

Six-hour trajectories were computed using the 300-mb. observed winds at 0000 GMT of the 19th (also in fig. 26). The starting points of the trajectories were selected along the 1800 GMT position of the leading edge of the cloud. The ratio of the 6-hr. observed cirrus movement along the trajectory to the length of the trajectory was used to determine how long the leading edge of the cirrus took to dissipate while undergoing descent. It varied from 2 hr. at the southern end to 4½ hr. in the north. Use of the vertical velocity patterns mentioned above shows that dissipation of the leading edge of the cirrus required approximately 1 to 10 mb. of descent. Examination of a thermodynamic diagram indicates that in order for 2 mb. of descent to dissipate an ice cloud, the water content of this cloud must be on the order of 0.005 $gm./m.^3$, a value so small that there is doubt whether such cloud could be seen by TIROS (Wexler et al. [16]). Since in this case, however, the TIROS picture was supported by surface observations, we might infer that the calculated vertical motions are somewhat too small. In any event, the role of horizontal advection in the horizontal distribution of high clouds, except the most tenuous cirrus, is seen to be very important.

Figure 21 shows significant cloudiness over Hudson Bay and part of Quebec. The vertical motion field (fig. 23) shows moderate to strong descent in central Quebec at all levels up to 400 mb. Even though moderate ascent is computed at 200 mb., surface reports indicate that there was no appreciable high cloudiness, so we are left with a discrepancy that invites further investigation.

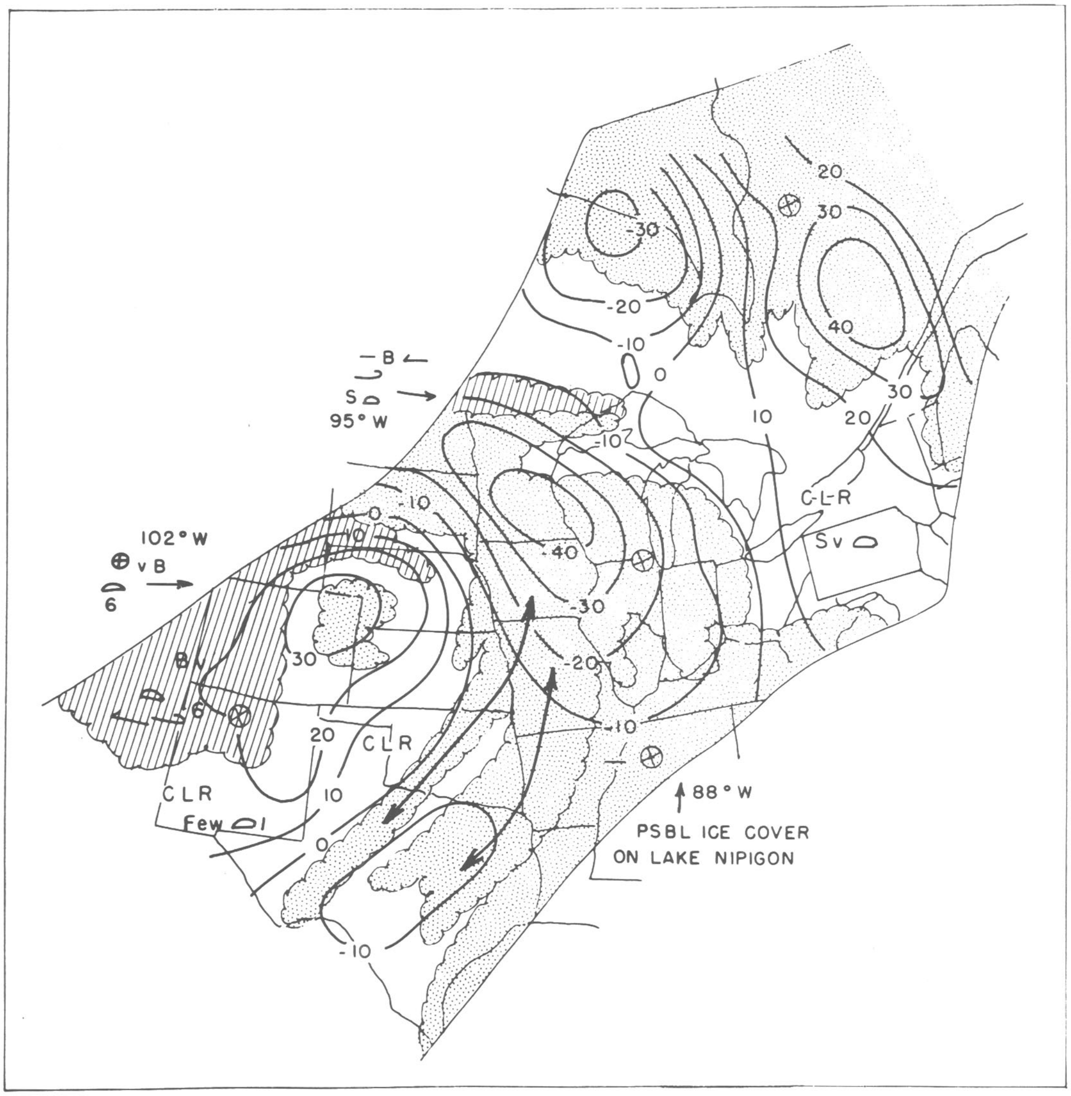

FIGURE 21.—TIROS V nephanalysis, pass 4348T, 1955 GMT April 18, 1963. 700-mb. vertical motions for 0000 GMT April 19 superposed.

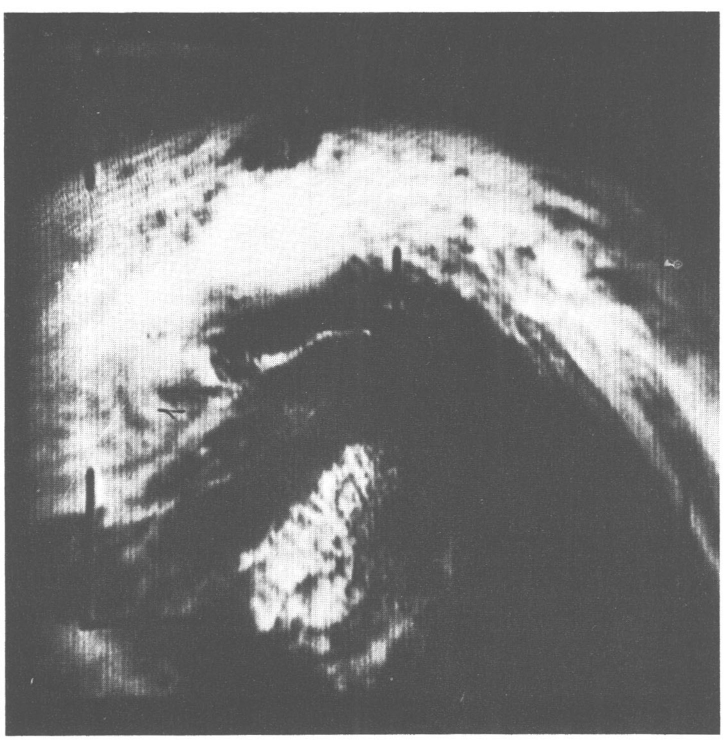

FIGURE 22.—TIROS V, pass 4348T, 1955 GMT April 18, 1963. Frame 10.

The photograph from which this portion of the nephanalysis was made is shown in figure 27 and this is the best view available of the area in question. A continuous cloud mass appears to be indicated, but the high nadir angle permits doubt about the interpretation. The few surface reports available in this region at 1800 GMT of the 18th and 0000 GMT of the 19th show a definite clearing trend, so that the 4-hr. difference between picture and calculation may partially explain the discrepancy. However, the best explanation is found in the close agreement between the boundary of the analyzed overcast region on the nephanalysis and the southern boundary of observed heavy snow cover at this time. Conover [4] has stated

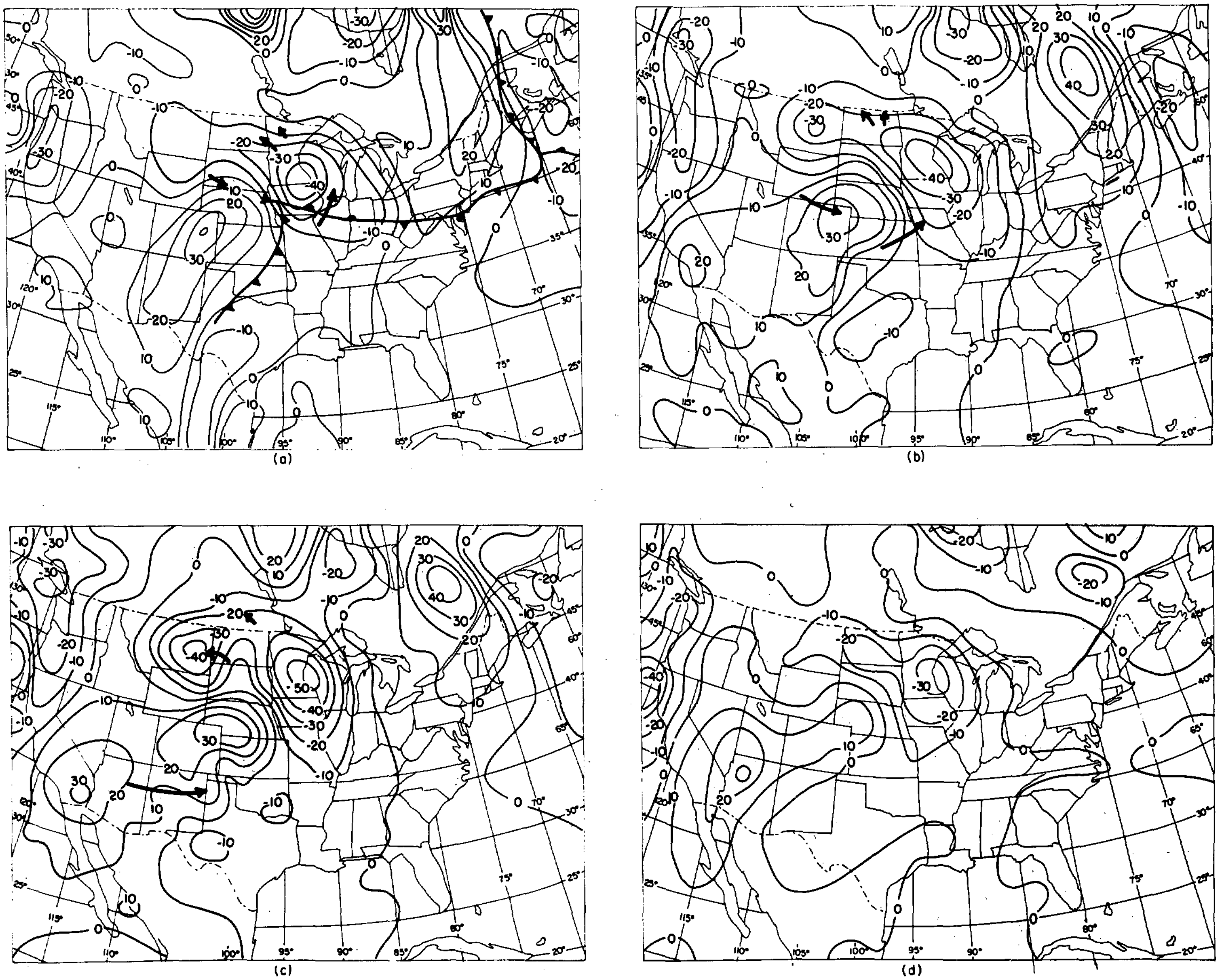

FIGURE 23.—Vertical motions (10^{-4} mb. sec. $^{-1}$), 0000 GMT April 19, 1963. Heavy lines on these and on succeeding vertical-motion fields are trajectory segments. (a) 900 mb., with surface fronts superposed; (b) 700 mb.; (c) 500 mb.; and (d) 300 mb.

that snow cover has about the same reflectivity as cloud and boundaries of clouds over snow are often impossible to delineate.

To summarize the foregoing discussion, a cloud system which is known to develop into a vortex pattern within 24 hr. has been examined. The vertical motion pattern and cloud pattern are in good agreement with little indication of the influence of horizontal advection processes, except for cirrus advection. It has been less than 24 hr. since the storm responsible for the cloud formation began its development east of the Rockies. Note that the September 1962 case also exhibited similar good agreement in the early phase.

One can relate the stage of development of the cloud system under discussion to a five-stage model depicting the evolution of a cyclonic vortex pattern (Boucher and Newcomb, [2]). Stage two of this model, the "occluding wave cyclone," is characterized by a "noticeable asymmetry in the cloud pattern due to the intrusion of the clear air behind the cold front." It is also expected that the first signs of the "vortex signature" should appear as a spiral streakiness in the cloud pattern. The asymmetry of the present case has been discussed and is clearly a major feature of the system. Whether or not the "vortex signature" is present at this time cannot be determined with confidence. However, the possibility of such a feature has been noted over South Dakota.

ORBITAL PASS 4362: 1925 GMT, APRIL 19

This pass offers a good look at the cloud system under discussion, which at this time contains a well-defined vortex. Frames from this pass are shown in figures 28 and 29, while figure 30 is the nephanalysis for this pass.

The presence of the vortex in Minnesota is unmistakable.

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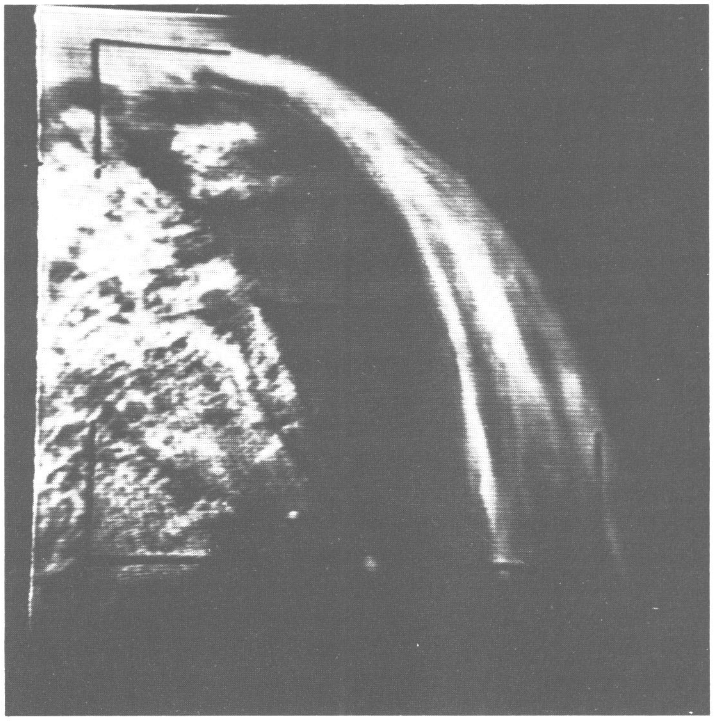

FIGURE 24.—TIROS V, pass 4348T, 1955 GMT April 18, 1963. Frame 14.

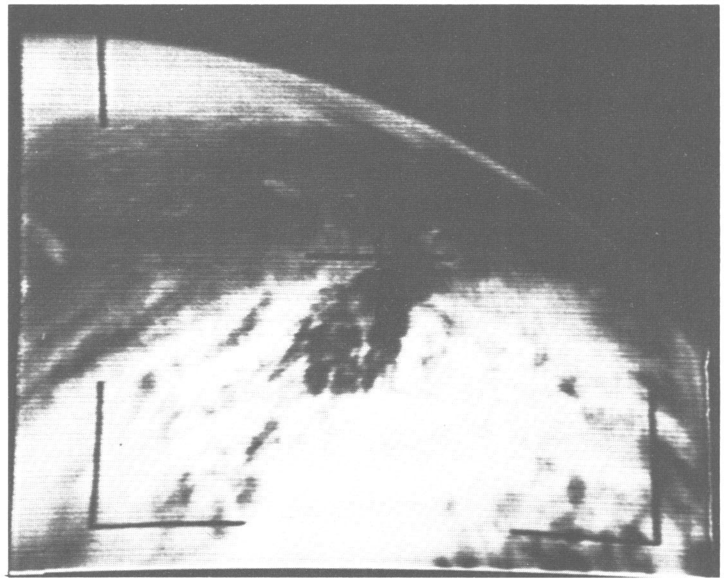

FIGURE 25.—TIROS V, pass 4348T, 1955 GMT April 18, 1963. Frame 7.

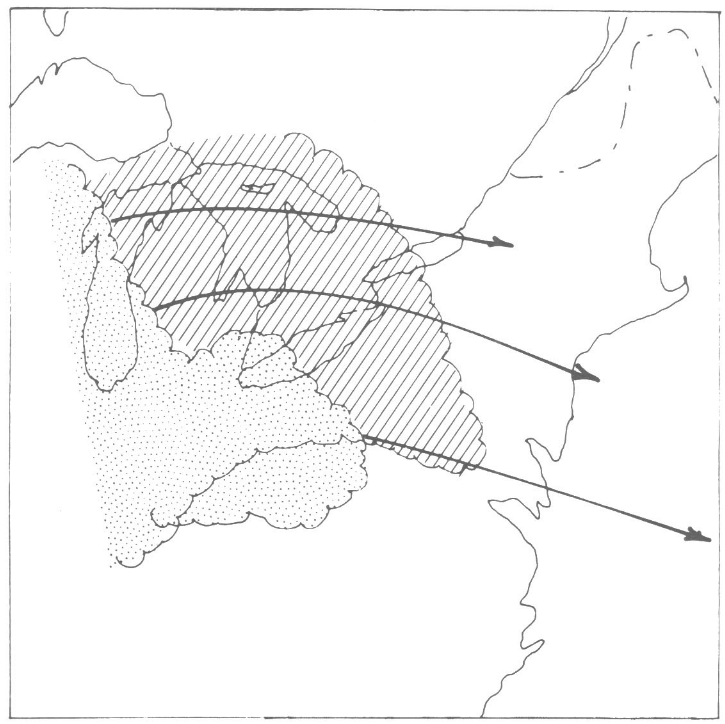

FIGURE 26.—Observed cirrus movement and 300-mb. trajectories, 1800 GMT April 18, to 0000 GMT April 19, 1963.

The leading edge of the tongue of clear, dry air is located east-northeast of the vortex center. Lack of agreement between the cloud pattern and the vertical motion pattern (fig. 31) is quite noticeable. An estimate of the 500-mb. vertical motion field for 1925 GMT of the 19th is shown in figure 32. This analysis was made by subjective interpolation between the 500-mb. vertical motion fields of 1200 GMT of the 19th and 0000 GMT of the 20th. Note that the vortex center in Minnesota is in a region of descent although a tongue of rising motion tends to be oriented in the direction of the vortex. This conclusion is required by any reasonably linear interpolation. The overlapping of the clear-air tongue with an ascent region is also evident.

The existence of part of the vortex cloud system in an area of moderate to strong descent is suggestive of a finding of Sanders et al. [13]. Using the 10-level model in a case study, they found that "there was fairly good correlation between clouds and vertical motion in the expected manner except in the region of strong descending motion behind the cold front." It was suggested that mixing, convection, and strong horizontal advection of moist air are possible explanations for this finding. Examination of surface observations at 1800 GMT of the 19th and 0000 GMT of the 20th indicates showery precipitation and convective cloudiness near the vortex center to the south and west. There is a need to consider horizontal advective processes to account for the observed misfit of vertical motion and cloud cover. Twenty-four-hour upwind geostrophic trajectories were computed starting at selected points of interest at 0000 GMT of the 20th. The trajectories were computed at the 850-, 700-, and 500-mb. levels and were related to the 900-, 700-, and 500-mb. computed vertical motions. The 6-hr. segments are indicated on the appropriate vertical motion charts. It is realized that these trajectories are somewhat crude, since a parcel of air does not remain at the

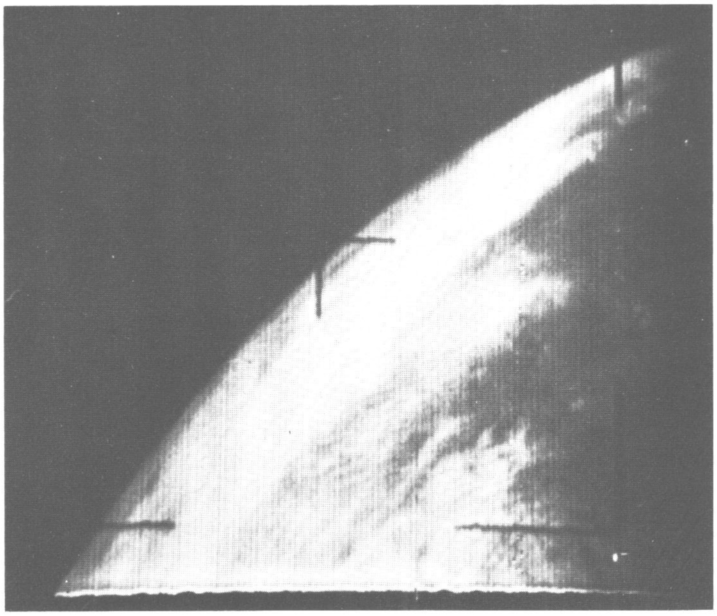

FIGURE 27.—TIROS V, pass 4348T, 1955 GMT April 18, 1963. Frame 1.

same pressure level when it is subjected to vertical motion. However, this source of error is damped to some extent, since each trajectory undergoes both ascent and descent during the 24-hr. period.

Trajectories were taken from the approximate vortex center in Minnesota. At all three levels, the final 6 hr. of the trajectories were generally in light descent and the first 18 hr. in light to moderate ascent. This may help to account for the existence of portions of the vortex clouds in a descent region at picture time. None of the air below 500 mb. in the immediate vicinity of the vortex descended more than about 40 mb. in the 24 hr. prior to picture time. If we assume a liquid water content of 0.5 gm./m^3. for these clouds, about 100 mb. of descent in the lower to middle troposphere would be required to dissipate them. Thus, it is possible that insufficient descent has occurred to destroy the vortex.

Similar trajectories were determined for a point in southern Iowa which is the southern boundary of the cloud mass associated with the vortex. At all levels, the air parcels underwent moderate to strong descent in the final 6 hr., with descent increasing with elevation. In the first 18 hr. moderate ascent predominated. Thus, in this area it is not surprising to find only convective clouds with clear skies farther downwind.

By interpolation among the synoptic charts the vortex center at 1925 GMT of the 19th is found to lie most probably, though not certainly in view of the uncertainties involved, several hundred miles west of the surface Low and west of the upper trough position. It is thus probably experiencing west- to north-northwesterly flow at all levels. This, in conjunction with the computed vertical motion pattern, indicates that there is no longer a sig-

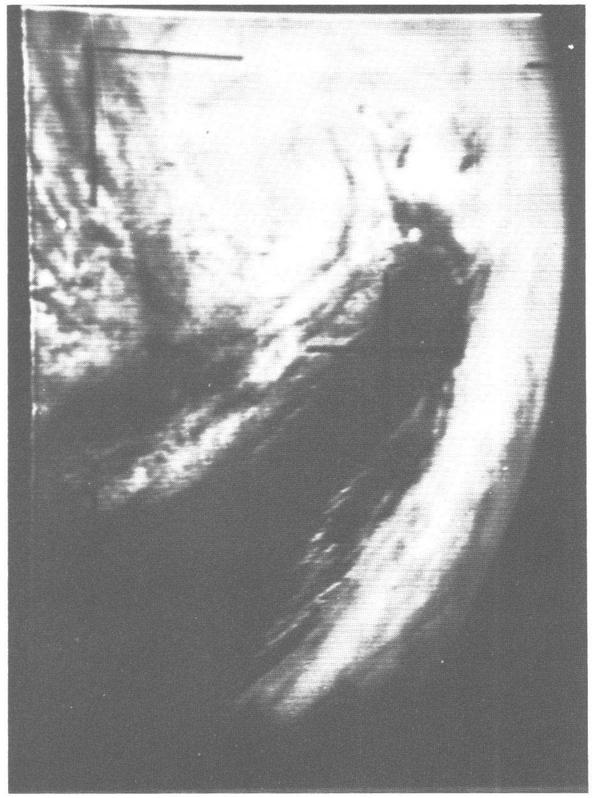

FIGURE 28.—TIROS V, pass 4362T, 1925 GMT April 19, 1963. Frame 13.

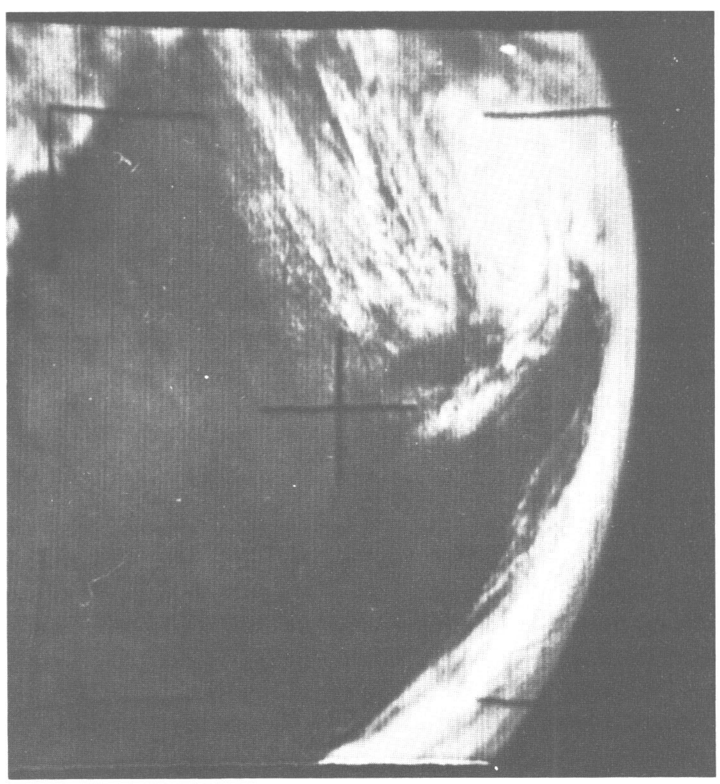

FIGURE 29.—TIROS V, pass 4362T, 1925 GMT April 19, 1963. Frame 16.

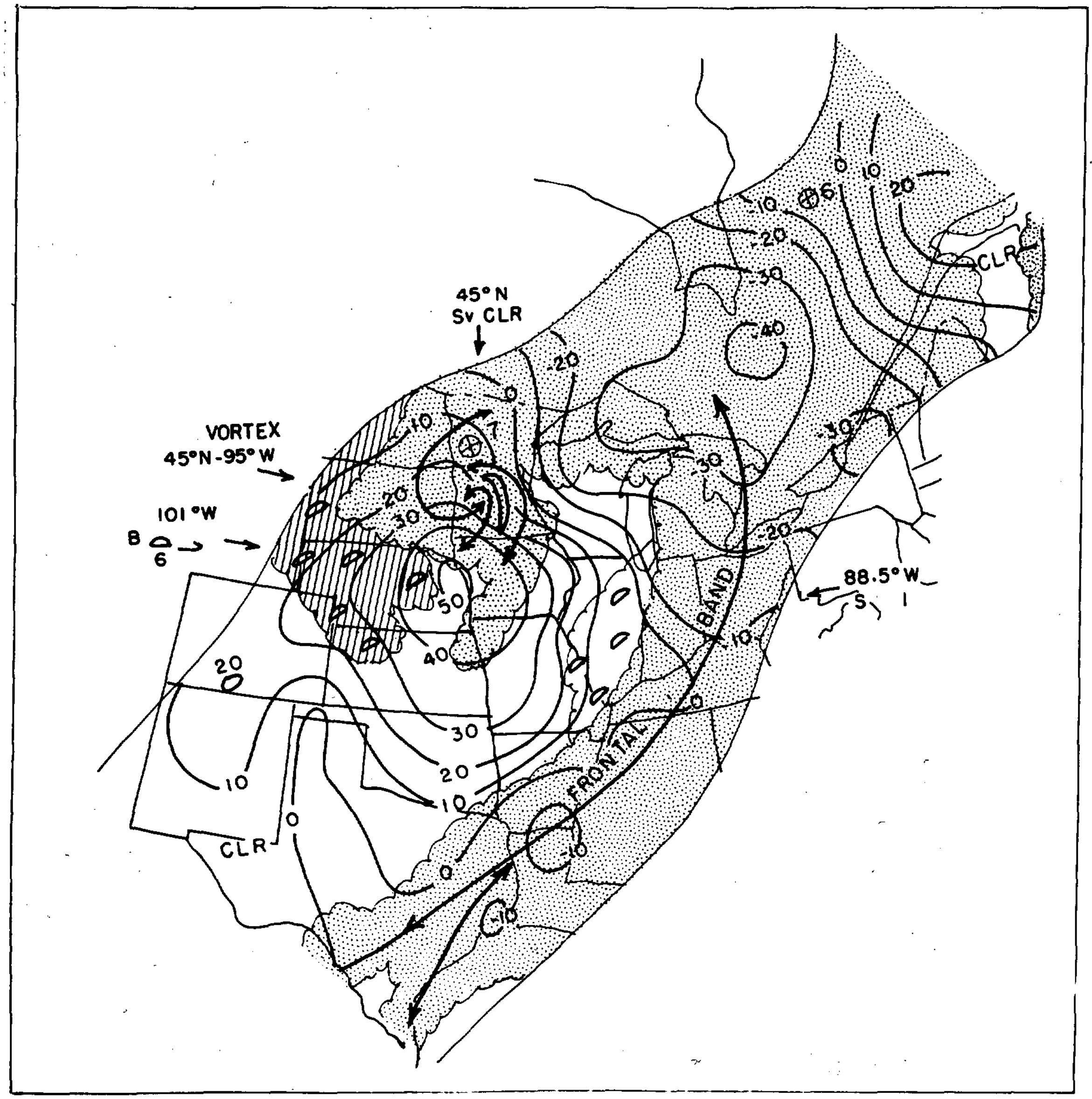

FIGURE 30.—TIROS nephanalysis, pass 4362T, 1925 GMT April 19, 1963. 700-mb. vertical motion for 0000 GMT April 20 superposed.

nificant horizontal advection mechanism supplying moist air to the vortex system to counteract the descent that it is experiencing. These factors indicate that the vortex cloud pattern, at picture time, has already reached a peak of organized circulation and is in a dissipative stage. A pass by TIROS VI at 1606 GMT of the 20th over the eastern United States supports this conclusion (picture and nephanalysis not shown). This pass shows a rather disorganized cloud mass from western New England to the eastern Great Lakes and in southern Quebec. Only the clear air zone has maintained its identity having moved eastward well off the coast behind the frontal system. It is believed that this disorganized cloud mass and the related clear air zone are the remains of the vortex circulation that has been under consideration. The primary frontal system and upper trough moved rapidly eastward, leaving the cloud vortex behind.

REMARKS

Recent models of satellite-observed vortex cloud patterns (Boucher and Newcomb [2], and Widger [17]) include the conspicuous curvature of the dry air, spiraling inward around the vortex. This feature is thought to indicate that the cyclone has reached the occluded mature stage, just prior to fullest maturity. As far as can be determined from the available TIROS coverage, the vortex in this study never exhibited this feature, even though the associated storm had a strong closed circulation throughout the troposphere in its early phase.

What appears to distinguish this storm from the classical evolution of a vortex is the difference in size between the vortex cloud system and the cyclonic circulation of the low-pressure cell with which it is associated. Throughout almost the entire history of the vortex, it appears to be related to a short-wave disturbance which amalgamated

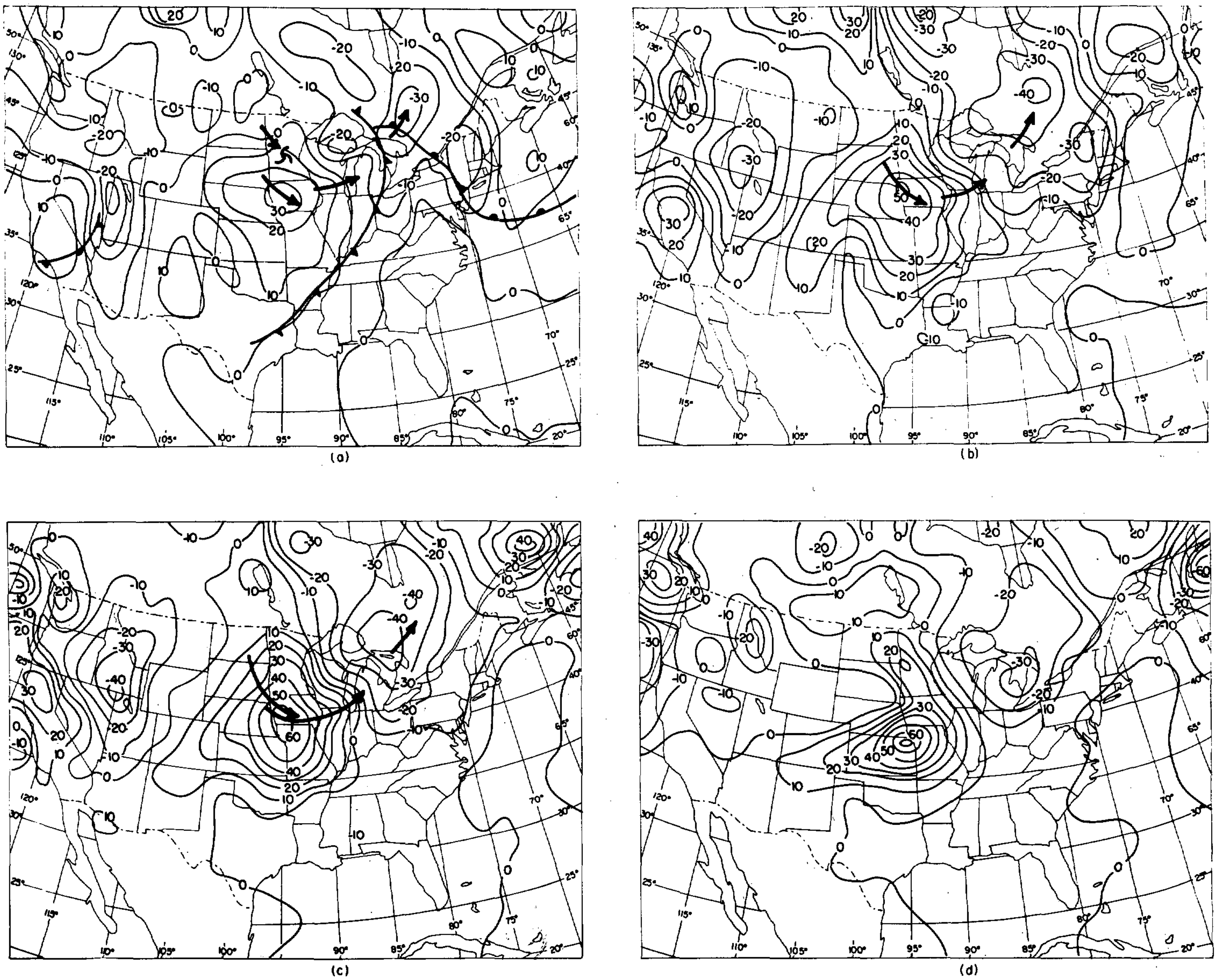

FIGURE 31.—Vertical motion (10^{-4} mb. sec.$^{-1}$), 0000 GMT April 20, 1963. (a) 900 mb., with surface fronts and TIROS vortex at 1925 GMT April 19 superposed; (b) 700 mb.; (c) 500 mb.; and (d) 300 mb.

with a much larger system located in central Canada. Thus, the classical occlusion process in which the cyclonic circulation, closed at least through the middle troposphere, becomes relatively vertical with little or no baroclinicity, has not been allowed to occur. In the case of September 4–7, 1962, it is this occlusion process that allows the arrangement of the vertical motion pattern in such a way as to promote the curvature of the clear air tongue around the center of the Low.

Also worth mentioning is the apparent rapidity of the development and decay of the vortex system in question. The entire evolution occurred in less than 48 hr. Whether or not a vortex is able to complete the evolutionary cycle may depend on the speed of development of the associated storm.

We find that the vortex system seen on the 19th failed to complete the classic evolutionary cycle described by

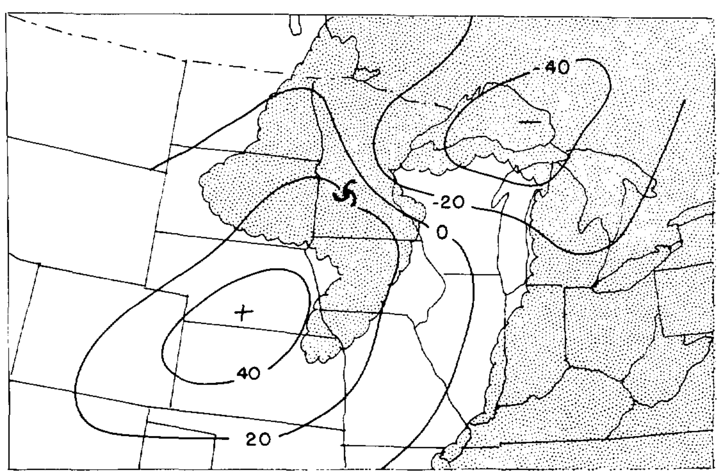

FIGURE 32.—TIROS vortex position, 1925 GMT April 19, 1963, and interpolated analysis of 500-mb. vertical motion for the same time.

recent cloud vortex models. The one time it was viewed from a satellite and recognized as a vortex, there was little indication that it would behave differently from vortices that do complete this cycle. It has been shown that both vertical motion and horizontal advective processes play a significant role in the determination of the life history of such a vortex.

4. CONCLUSIONS

Let us appraise the foregoing results in the light of the stated aims of this paper.

We find that both horizontal and vertical motions are important factors in determining the configuration of large-scale cloud systems. Leese [9] has stressed the importance of the former in a case of vortex formation. Indeed, as in the work of Nagle et al. [10], when these factors are both considered the evolution of cloud structure is quite successfully accounted for. There is some suggestion that the coincidence between ascent and cloud is best in the earliest phase of storm evolution, before extensive rotary circulation has developed. After closed cyclonic circulation has developed, dry clear air streaming into the eastern quadrants of a storm encroaches upon ascent, while moist cloud-bearing air circulates around the top of the storm and intrudes upon descent in the western quadrants. Thus in middle latitudes the large-scale vertical motion cannot generally be directly inferred with confidence from the cloud pictures without reference to the horizontal motions.

The cloud vortex per se is seen under two rather different motion environments. The situation which favors a long-lived vortex is one in which an extensive cut-off cyclone remains relatively isolated from the rest of the general circulation for a period of days. The diagnostic significance of the TIROS vortex per se is thus somewhat ambiguous. Other large-scale aspects of cloud structure seem at least equally important.

On the positive side, we have gained some understanding of the dynamics of large-scale cloud systems. It does not seem necessary to invoke the release of latent heat of condensation in the calculation of vertical motions which are adequate to explain the clouds.

Finally, we are left with a feeling of confidence in the application of quasi-geostrophic theory, at least qualitatively, to scales smaller than those which can be defended as suitable a priori.

ACKNOWLEDGMENT

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