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GRD RESEARCH NOTES

No. 78

THE ROLE OF ADVECTION IN THE FORMATION OF VORTEX CLOUD PATTERNS

John A. Leese

February 1962

GEOPHYSICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
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THE ROLE OF ADVECTION IN THE FORMATION OF VORTEX CLOUD PATTERNS

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John A. Leese
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Meteorological Research Laboratory
GEOPHYSICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
Bedford, Massachusetts

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Abstract

A case study of the spiral cloud patterns associated with an atmospheric vortex, as seen by the TIROS I meteorological satellite, shows that advection can be a dominant mechanism in the formation of these patterns. This advection is then interpreted in terms of the horizontal and vertical structure of the low pressure system with which the clouds are associated. A comparison of the vortex cloud patterns, at the time of the maximum development of the spiral clear area, with Bergeron's two common types of cold fronts indicates that these patterns should be attributed to upper-air advection relative to the surface front rather than to vertical motion along the front. The similarities displayed by the spiraling vortex cloud patterns seen by TIROS I would suggest that the features found in this detailed case study would also hold for other cases in which this particular cloud pattern exists. The spiraling vortex patterns can be associated with a low pressure area on the surface analysis, but no general statement can be made that the reverse is also true. This case study indicates that the TIROS pictures are particularly well suited for the study of horizontal advection and show promise of yielding quantitative information.

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THE ROLE OF ADVECTION IN THE FORMATION OF VORTEX CLOUD PATTERNS

Introduction

The launching of TIROS I on 1 April 1960 presented the meteorologist with a unique observational tool. The ability to observe the weather on such a large scale has been overwhelming and not without some problems as to the most effective way to utilize these new observations. The easiest way, of course, is to fit these observations to models already constructed. This would mean in the case of cloud patterns associated with a vortex (Fig. 1) fitting the patterns to the frontal model based on the polar-front theory of wave cyclones developed by the Norwegians during World War I. However, evidence that this model does not accurately describe conditions in the upper air was presented long before the advent of TIROS. Critical reviews of the polar-front theory are numerous in the literature and little could be accomplished by a complete review at this time.

A more profitable way of using the TIROS pictures is suggested by the fact that they lend themselves quite readily to the day-to-day surveillance of cloud patterns, such as those associated with extratropical cyclones, as shown by Leese,[8] and with tropical storms, as shown by Sadler.[11] It would thus appear that by studying the day-to-day changes in cloud patterns associated with low pressure systems (here-after referred to as vortex cloud patterns) new information on vortex systems could be obtained. In particular, the type of vortex pattern which has a band of relatively clear air spiraling in toward the center, if studied in this manner, should reveal much about the horizontal and vertical structure of the low pressure system. An analysis of the shape and relative position of the cloud and clear areas around the vortex in various stages of development should make this information available.

The term "clear" used to describe the spiraling air is actually a misnomer, as shown by the examples in Fig. 1. The spiraling region can go through the whole range of cloud cover from completely clear to overcast. The general pattern shown by the TIROS I pictures for the spiral area illustrated in Fig. 1 is mostly clear over the land, as in the pictures taken on orbits 005 and 730, and partially obscured by scattered-to-broken, low cumuliform clouds over the ocean, as shown by the pictures from orbits 422, 605, 619 and 705.

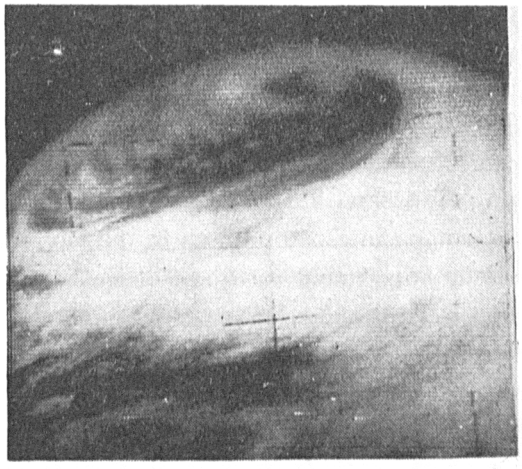
The vortex pattern seen during orbit 705 has previously been related to the large-scale synoptic pattern occurring at that time[9] and to the day-to-day changes in cloud patterns during the life-cycle of the storm.[8] The observations made during orbit 005, including the cloud features associated with the synoptic weather situation, have been described in detail.[5] The spiral area in the vortex pattern observed during orbit 605 is delineated by an abrupt change in cloud reflectivity from nearly white to gray. Conover[6] thinks that this brightness is related to the

depth of the cloud cover but is also influenced by many other factors, the most serious of which is the reflection of the sun glint from the top of the clouds. The spiral in the vortex pattern from orbit 619, which is associated with the same low pressure area seen during orbit 605 but one day later, is defined by the change in cloud cover from overcast to a scattered-to-broken, low cumuliform. An example of a southern hemisphere vortex cloud pattern is shown on orbit 422. The sky-cover patterns seen in orbit 730 provide the subject of the case study presented in this paper.

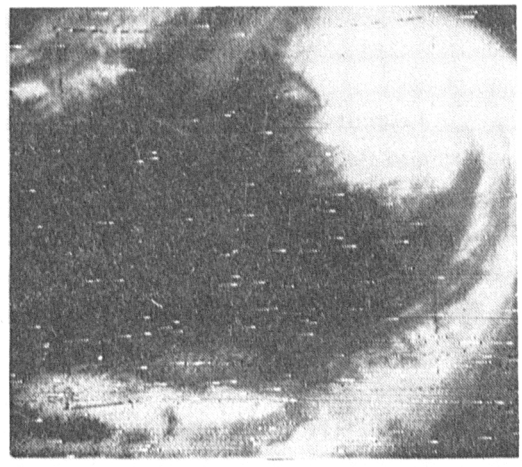
It appears that advection plays an important part in the formation of this type of cloud pattern. Both the size of this spiral area, which can be much greater than 100 mi wide, and its location mainly in strong southerly flow preclude its being a region of actively subsiding air behind the cold front. Sawyer,[12] in a study of humidity data obtained on 23 meteorological research flights through fronts over England, found that a characteristic tongue of relatively dry air was associated with many of the frontal zones. He found the driest air within the frontal transition zone in about half the cases. However, there were also occasions when it was found on either the cold or warm sides of the transition zone. This dry tongue extended down to an average pressure level of 700 mb in cold fronts. He concluded that the presence of this dry air can be adequately explained by large-scale movements of the air which are primarily horizontal; the air has indeed been dried by subsidence, but this may have been 24 hrs or more before it was observed in the frontal region, and is no indication of descending motion in the frontal zone.

According to Reed,[10] a characteristic type of frontal development in the middle troposphere is the formation of a katafront, a sloping stable layer marked by strong vertical wind shear and a rapid upward decrease in humidity. He concluded that the frontal zone does not separate air of polar from air of tropical origin, but rather, after forming within the polar air mass, separates relatively moist air of polar origin from drier air which could be of stratospheric origin.

In a radar study of winter storms, Wexler and Atlas[14] and Boucher[3] found that the passage of an easterly moving cyclone to the south of the radar location is frequently accompanied by a change in the precipitation pattern. The relatively uniform echo previously observed with top at high elevations (temperatures generally below -20°C) changes to a cellular structure with echo tops at lower elevations (temperatures generally -10° to -15°C). During this change there is usually no significant change in the winds or in the temperature and humidity at low levels, but aloft above 700 mb the humidity frequently drops and the temperature may rise. Wexler and Atlas ascribed this change in echo pattern to the advection of dry air aloft over saturated air below. This combination forms a convectively unstable layer.



Orbit M705, 0100Z 20 May 1960
central Pacific



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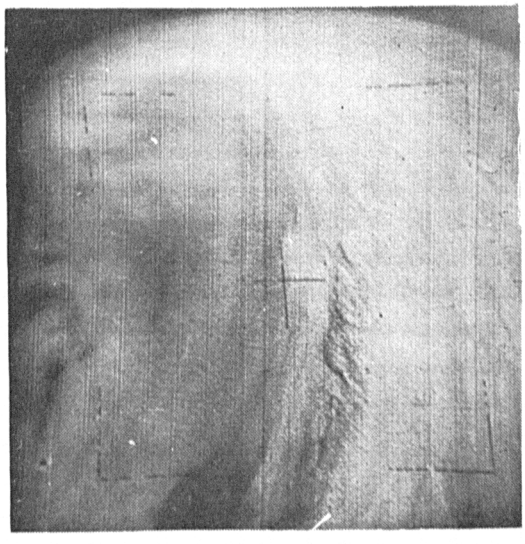

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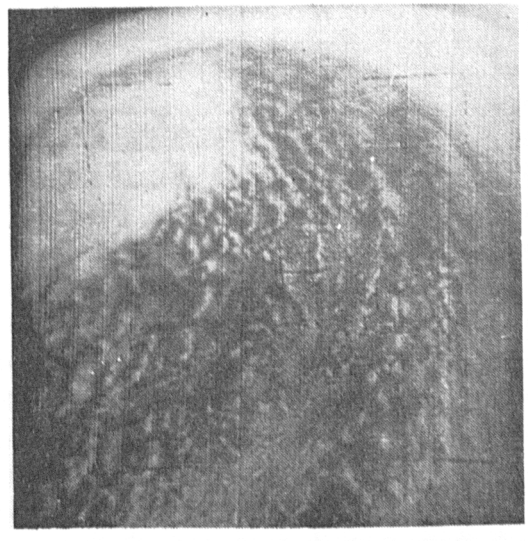
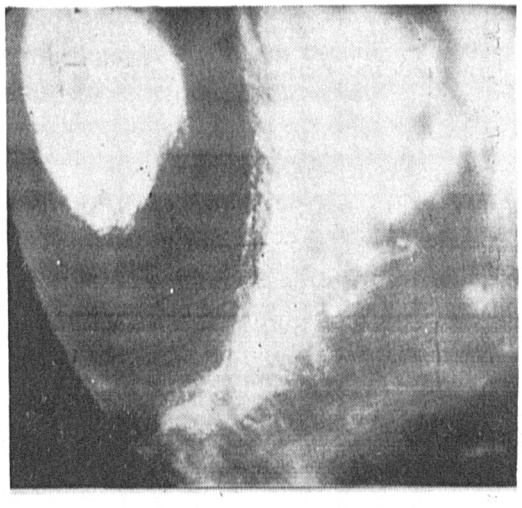
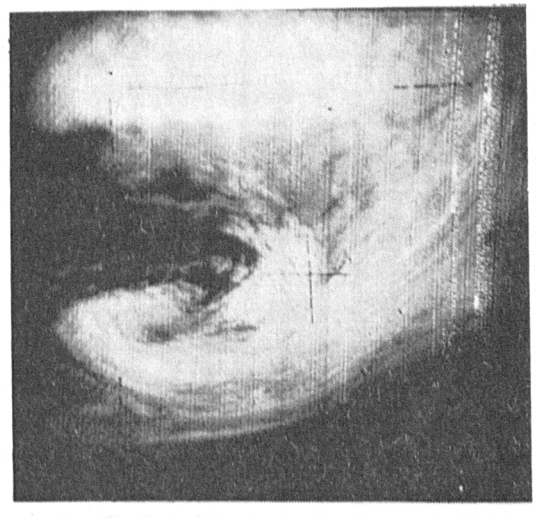
northeastern Pacific



Orbit K619, 0252Z 14 May 1960
northeastern Pacific



Orbit M730, 1816Z 21 May 1960
midwest United States



Orbit K422, 1230Z 30 April 1960
south Atlantic

FIG. 1. Examples of spiral vortex cloud patterns as seen by TIROS I.

According to Boucher,[4] the vortex cloud patterns of TIROS I appear to bear no unique relationship to the location of either the sea-level low or that at the 500-mb level. Instead each vortex occupies a position within a radius of 200 to 300 mi of both. In a study of the day-to-day changes in cloud pattern in the various stages of development of a frontal system, the author[8] found that the "clear" area spiraling in toward the center of the vortex appeared to reach its deepest penetration near the time of the maximum intensity of the storm. A decay in the intensity of the circulation around the vortex appeared to be the beginning of decay of this spiral clear area. If advection is the dominant mechanism in the formation of this type of vortex, then the relative positions of the "clear" and cloudy areas around the vortex should give some indications of its stage of development. Although Boucher[4] did not attribute the formation of this relatively clear spiral to advection directly, he feels this winding spiral conveys meteorological information which specifies, within rather narrow limits, the stage of development and the age and intensity of a cyclone and the placement of its significant features. He has therefore attempted to define a model describing the evolution of cloud patterns attending the development and decay of a middle latitude cyclone. A dominant mechanism of advection would also make it possible to get some indication of the speed of rotation around the vortex relative to its speed of translation, if the speed of rotation is greater than the speed of translation. A requirement for the formation of this type of vortex would then be strong meridional flow ahead of the low.

This paper presents a case study of the development and decay of spiral vortex cloud patterns which demonstrates that advection can be a dominant mechanism in the formation of these patterns. This advection is then interpreted in terms of the horizontal and vertical structure of the low-pressure system with which these clouds are associated. The extent to which the cloud patterns, at the time of the maximum development of the spiral clear area, fit the frontal models is also investigated even though the failures of these models have been pointed out previously by numerous authors. The present investigation seems not only justified but needed in view of the attention given Bergeron's[2] two common types of cold fronts, the "anafront" and "katafront," in a recent training manual.[1]

Analysis

The system studied developed over the midwest United States on 20 May 1960 and moved northeastward during the next two days. TIROS pictures of this storm were taken on orbits 716 on 20 May, 730 to 733 on 21 May, and 745 on 22 May.

The location of cloud features on the satellite pictures was determined with methods developed by Allied Research Associates.[7] Attitude data were determined

from landmarks in pictures on orbits 716, 730 and 731. Pictures from orbits 732 and 733 had no visible landmarks to use as a starting point in rectifying the cloud cover.

Clouds are shown on the rectifications (Figs. 2, 11, 12, 13, 14, and 21) in shades of gray which are proportional to the brightness indicated by the TIROS pictures — the brightest clouds are represented by the darkest gray.

On the orbits where visible landmarks appeared the location is thought to be accurate to within 30 mi. The accuracy of locations on orbits without landmarks cannot be estimated, but cloud rectifications on these orbits check out very well with nephanalyses made from conventional surface observations.

To trace the paths of moist and dry regions, the potential temperature and mixing ratio were used. These parameters constitute the most conservative properties of an air mass for dry-adiabatic processes. The potential temperature of 309°K was selected as high enough to be out of the influence of surface conditions at the season in question. The difference between the pressure and saturation pressure of the 309°K potential-temperature surface was assumed to be inversely proportional to the relative moisture content of the air. To verify the analysis of the large-scale moisture patterns on this isentropic surface, several cross sections with different orientations were constructed at 12-hr intervals through the low-pressure area.

Orbit 716 1910Z 20 May 1960

The cloud rectification for orbit 716 in Fig. 2 shows the midwest United States mostly cloud covered. A bright band of clouds extends from eastern Texas northeast to central Indiana. A squall line through this region is shown on the 1800Z Surface analysis in Fig. 3. A second band, slightly less bright than the first, extends north-northwest from eastern Texas to the limit of the rectification in South Dakota. This band is associated with the frontal system, shown in Fig. 3, which passes through the central United States with an incipient wave in Iowa. The cloud rectification shows no organized cloud pattern associated with the warm front through Minnesota and Michigan.

Any requirement for strong meridional flow ahead of the low for the development of the spiral vortex patterns of cloud and clear areas would be well met in this situation as shown by the 500-mb analysis for 0000Z on the 21st in Fig. 4.

The difference between the pressure of the 309°K potential-temperature surface and the saturation pressure of this surface at 0000Z on the 21st is shown in Fig. 5. The dome of cold air on this surface extends to the vicinity of 500 mb. The center of the 500-mb low is shown on the isentropic analysis. The region of dry air circumvents the western and southern periphery of the low and penetrates as far north as southern Illinois. The moist region is mainly to the northeast of

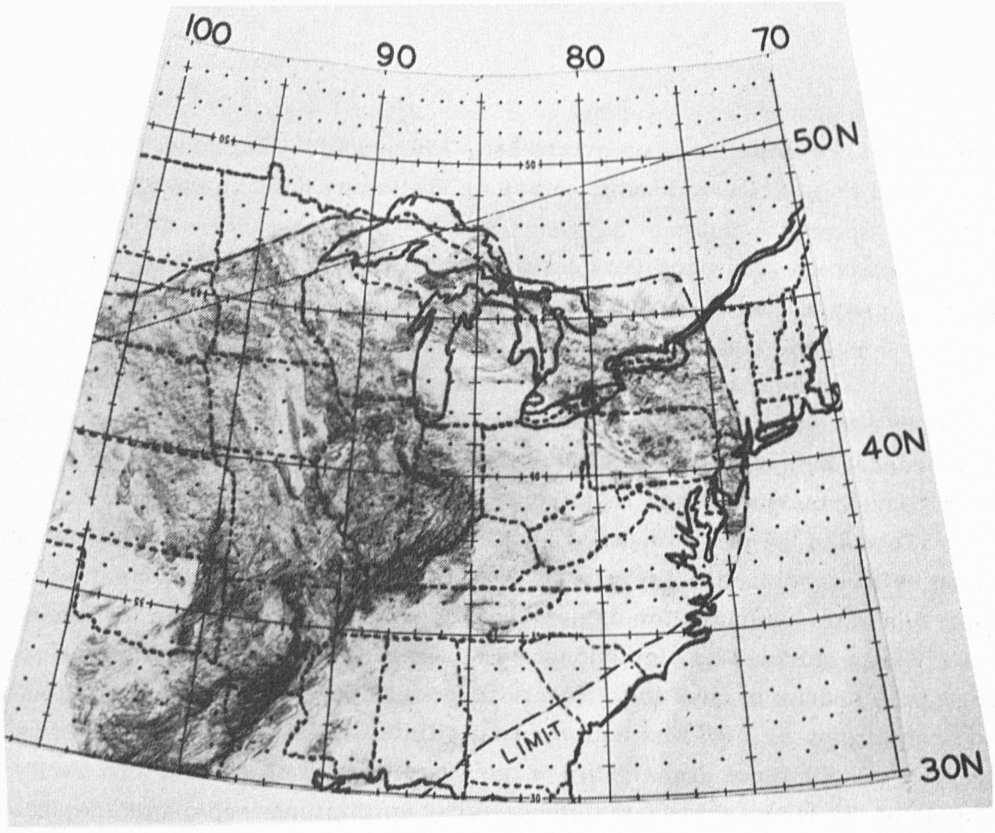


FIG. 2. Cloud rectification for pictures from orbit 716 at 1910Z 20 May 1960.

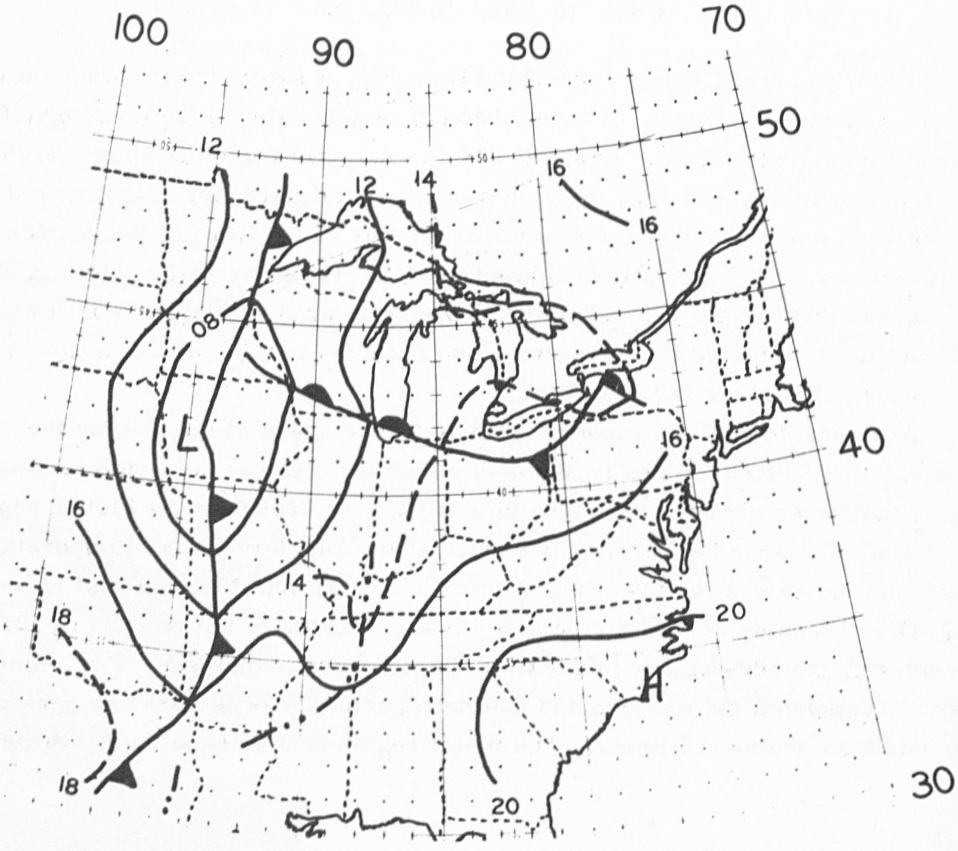


FIG. 3. Surface analysis for 1800Z 20 May 1960.

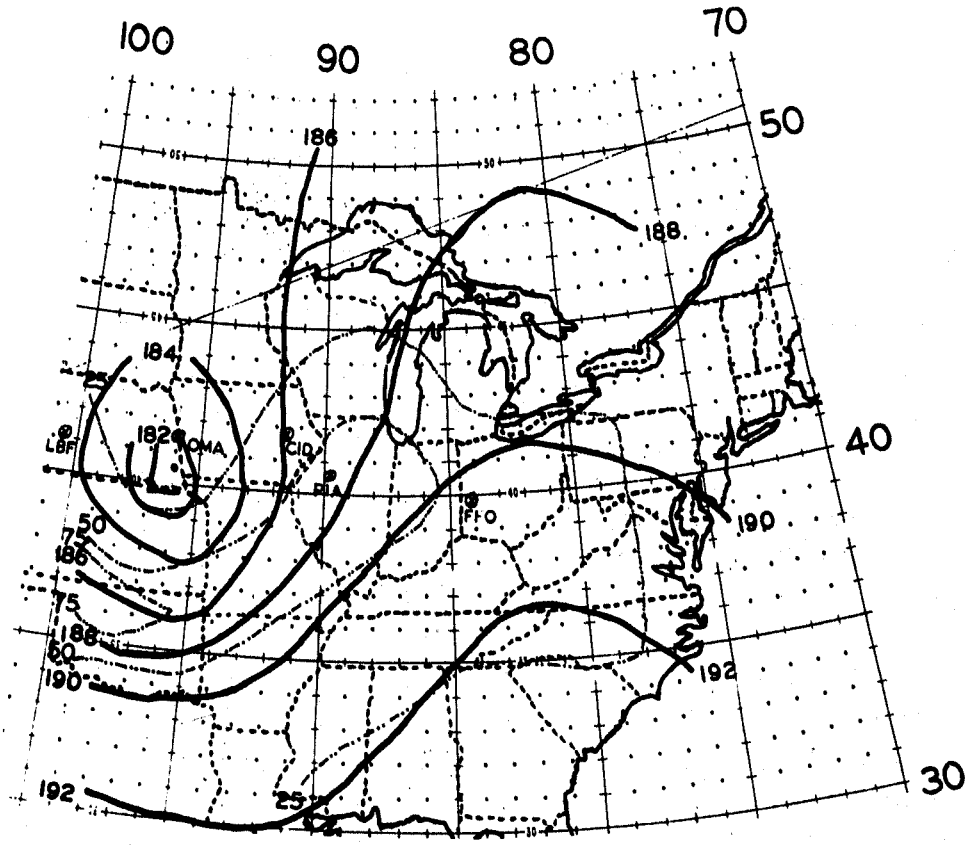


FIG. 4. 500-mb analysis with isotach (kts) for 0000Z 21 May 1960.

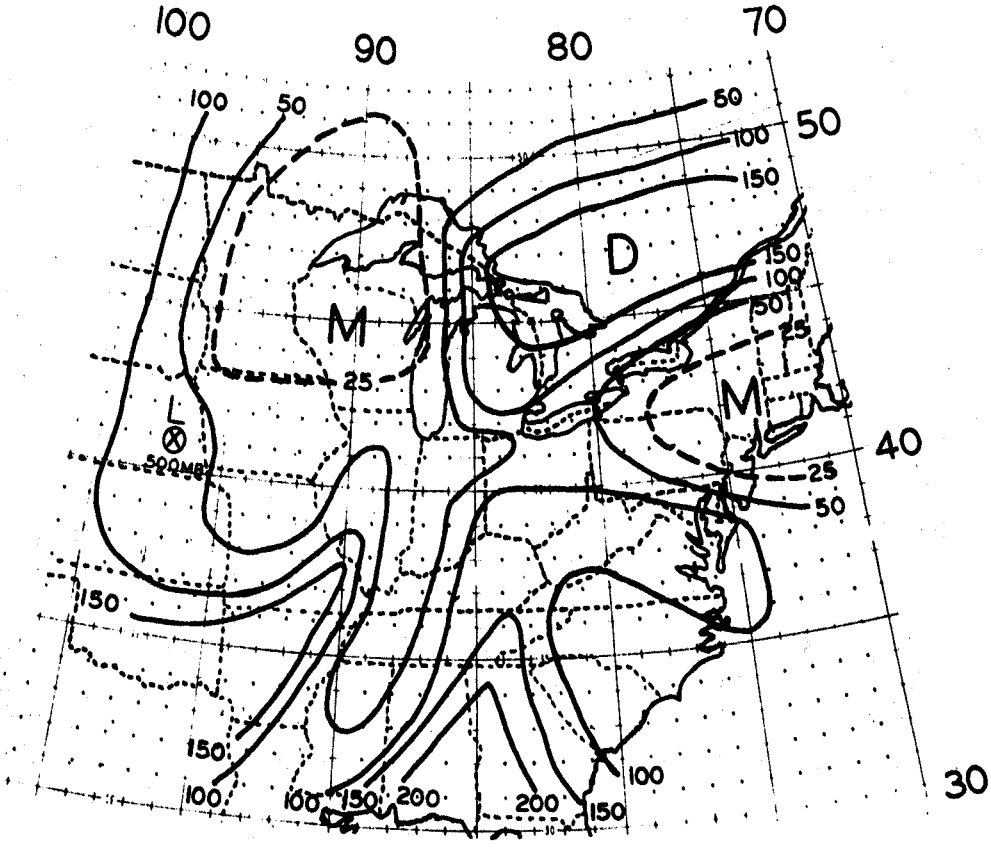


FIG. 5. Difference in pressure (mb) between the pressure and saturation pressure for 309°K potential-temperature surface at 0000Z 21 May 1960.

the low with a narrow tongue extending southward ahead of the dry tongue. The cloud cover on orbit 716 (Fig. 2) is 5 hrs earlier than this analysis and does not show this penetration of dry air at that time. Conventional surface observation at the same time as the isentropic analysis do not yield much information about the dry tongue because of cloud cover below the level of the dry air.

An east-west cross section from Dayton, O. (FFO) to North Platte, Neb. (LBF) is shown in Fig. 6 for 0000Z on the 21st. The location of this line is shown in Fig. 4. The cross section shows the lowest level of the dry tongue at about 680 mb over Peoria, Ill. (PIA), rising to the west over the dome of cold air. Relatively high wind speeds near the level of the base of this inversion are found at the eastern edge of this dry tongue between FFO and PIA. A weak cold front has been placed between Cedar Rapids, Iowa (CID) and Omaha, Neb. (OMA), based primarily on surface observations. The location as well as the actual existence of this front above 700 mb is in doubt.

The isentropic analysis for 1200Z on the 21st (Fig. 7) shows that the dry tongue has advanced to the vicinity of Green Bay, Wisc. (GRB) where it is found at 619 mb. By computing a 12-hr trajectory back from Green Bay along the 309°K potential surface, this air was found to be over southeastern Missouri at 0000Z on the 21st (Fig. 8) at a pressure of 660 mb and a saturation pressure of approximately 460 mb. If we make the reasonable assumption for this very dry air and short time period that the lowering in pressure for the 309°K potential surface from 660 mb to 619 mb was due to vertical motion, we arrive at an average vertical velocity of 1.2 cm sec^{-1} upward for this air during the 12-hr period. The length of this trajectory yields an average advective rate of 47 kts. The translation velocity of the 500-mb low during this period was from the west at 20 kts, which means the advective rate of the dry air around the eastern periphery of the low was more than twice as great as the speed of translation of the low. Two other trajectories over this time period are also shown in Fig. 8, along with the average vertical motions required for isentropic flow along the trajectory. A nephanalysis of conventional surface observations for 1200Z on the 21st shows that this dry tongue is obscured by low-level cloudiness.

A comparison of the isentropic analyses for 0000Z (Fig. 5) and 1200Z (Fig. 7) on the 21st, shows that the moist air is being advected around the north of the cyclone and could also be contributing to the formation of the spiral vortex cloud pattern. The leading edge of the moist tongue is located southwest of the center of the 500-mb low at the end of the period. The average speed of the advancing edge of the cloud shield to the north and rear of the cyclone was found to be 22 kts. In computing this it was assumed that the leading edge of the cloud shield coincided with the leading edge of the 25-mb difference between the pressure and saturation pressure on the isotropic surface.

The cross section in Fig. 9 for 1200Z on the 21st is along the same line as the one 12 hrs earlier (Fig. 6). The inversion at the base of the dry tongue is located between FFO and PIA at approximately the same pressure as 12 hrs earlier, but is now much drier than before. The jet stream is found almost directly over the inversion at both times. This orientation of the dry tongue and the region of maximum wind speeds in the southerly flow continues throughout the history of this storm. The isotach pattern in the vicinity of CID indicates the slope of the low pressure area is nearly vertical.

A comparison of the 500-mb charts for the two time periods (Figs. 4 and 10) shows that the low center has undergone a deepening of 200 ft at this level and the region of wind maximum has advanced around the low to the southeast quadrant.

Orbits 730 — 733 21 May 1960

The cloud patterns around the low were photographed on four different orbits during the period 1800Z to 2330Z on 21 May. The rectified cloud patterns for these orbits are shown in Figs. 11 to 14. The changes in cloud reflectivity shown in different views do not necessarily represent changes in cloud structure over this period; they are one person's interpretation of the brightness of the clouds as viewed by TIROS from different viewing angles and lighting conditions. This approach is taken since the TIROS photographs made over the eastern United States just after noon on orbit 730 may exaggerate brightness, whereas the pictures made of the same area on orbit 733 in near darkness are underexposed. Furthermore the sun should be at least 18 deg above the horizon for taking pictures with TIROS I; in the latter case it was 17 to 20 deg.

The track of the satellite for orbit 730 (Fig. 11), along a path from eastern Texas to Massachusetts, shows the details of the cloud patterns in the eastern United States. Orbit 731 (Fig. 12) had a path across the center of the low from southwest to northeast and shows the details of the cloud patterns around the low as well as the clear area spiraling in toward the center of the vortex. Orbit 732 (Fig. 13) described an east-to-west track across the north side of the low while orbit 733 (Fig. 14) went across the low from northwest to southeast.

The cloud rectification of orbit 730 (Fig. 11) shows a line of very bright cellular clouds extending from southern Ontario through western Pennsylvania, West Virginia and eastern Tennessee associated with a line of thunderstorms through this region. The smaller lines of clouds oriented west-northwest to east-southeast through eastern Ohio are lines of low cumuliform clouds under the inversion of the dry tongue through this region and are oriented perpendicular to a south-southwest flow at the level of the clouds. Because of the angle of view, the vortex appears almost completely cloud covered on this orbit. However the

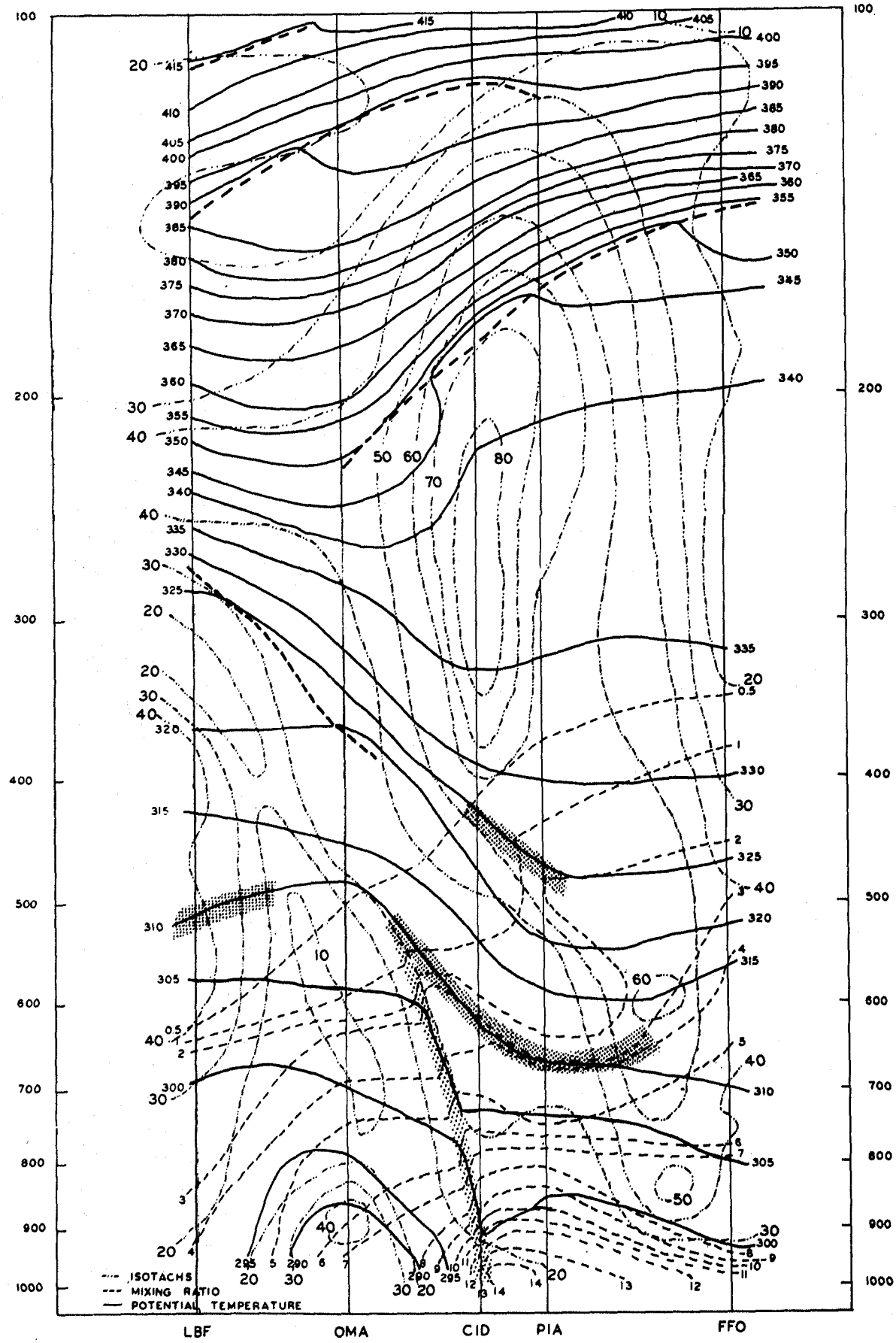


FIG. 6. East-west cross section between Dayton, O. (FFO) and North Platte, Neb. (LBF) at 0000Z 21 May 1960. (Note: Light stipled represents the frontal zone; heavy stipled represents stable zones other than frontal.)

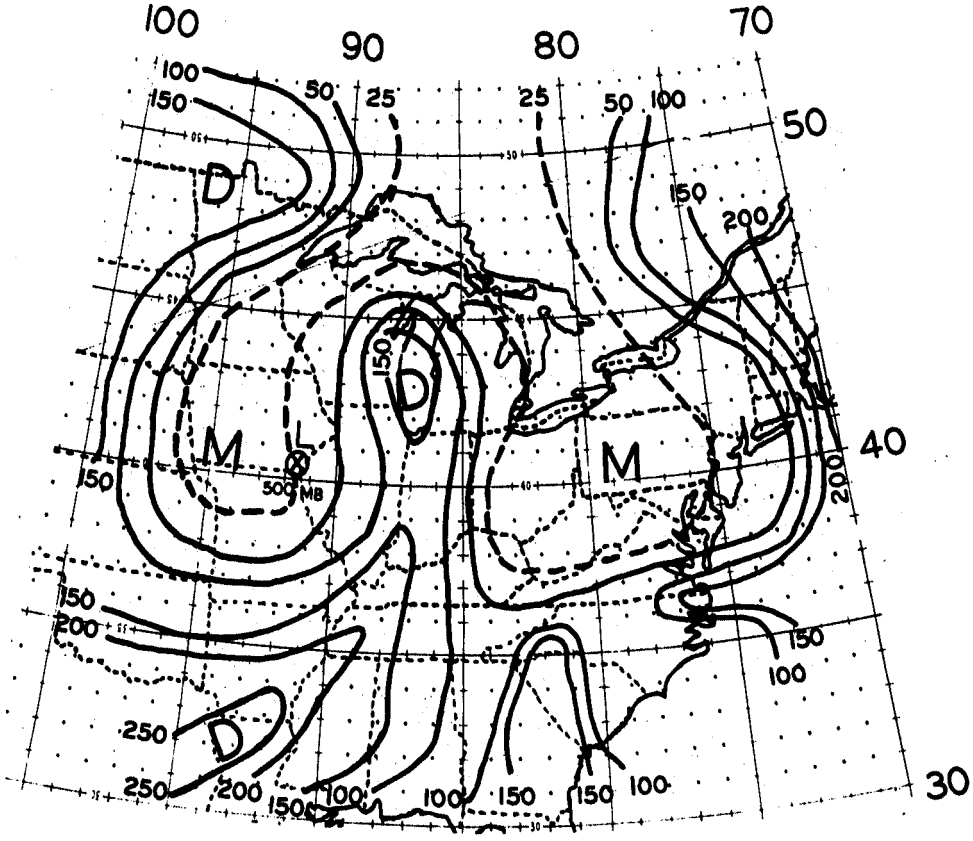


FIG. 7. Difference in pressure (mb) between the pressure and saturation pressure for 309°K potential-temperature surface at 1200Z 21 May 1960.

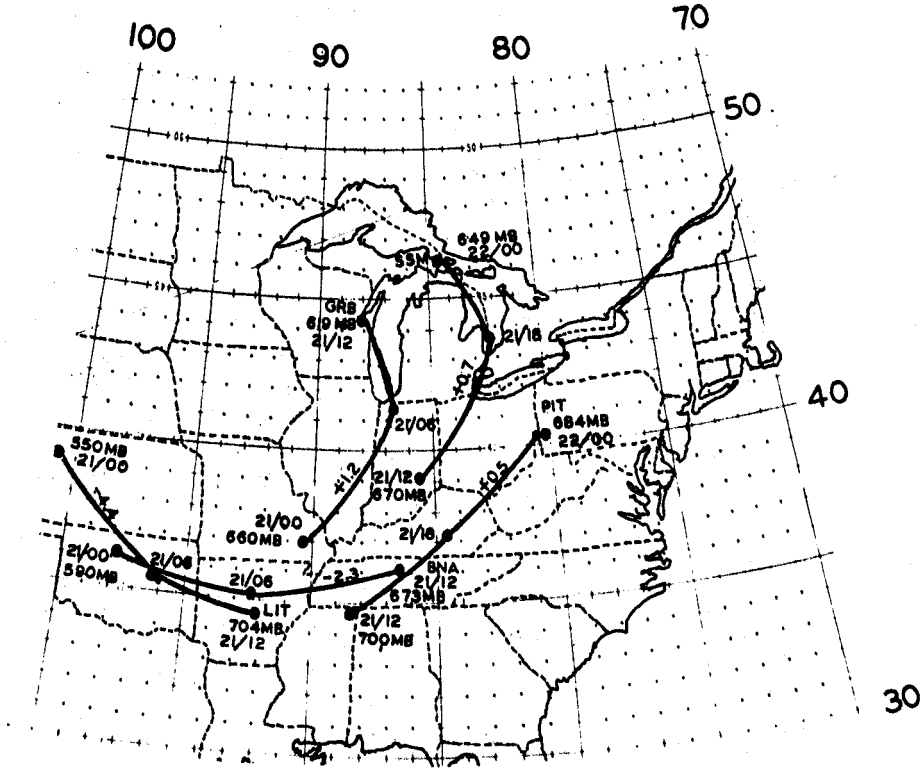


FIG. 8. Trajectories along 309°K potential-temperature surface. (Date, time and pressure are labeled at beginning and end of trajectories. Resultant vertical motion labeled along the trajectory.)

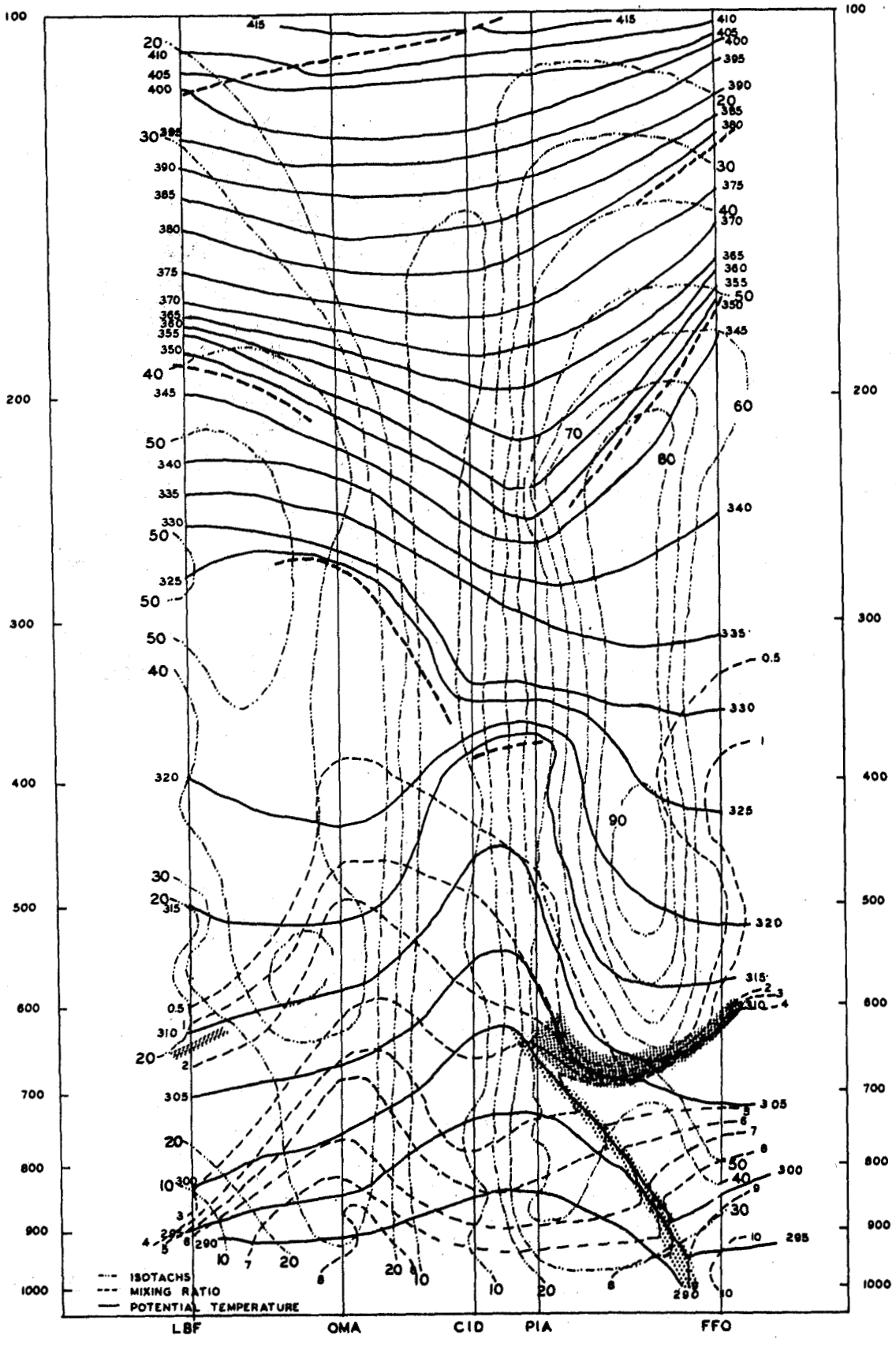


FIG. 9. Cross section along the same line as Fig. 6 at 1200Z 21 May 1960.

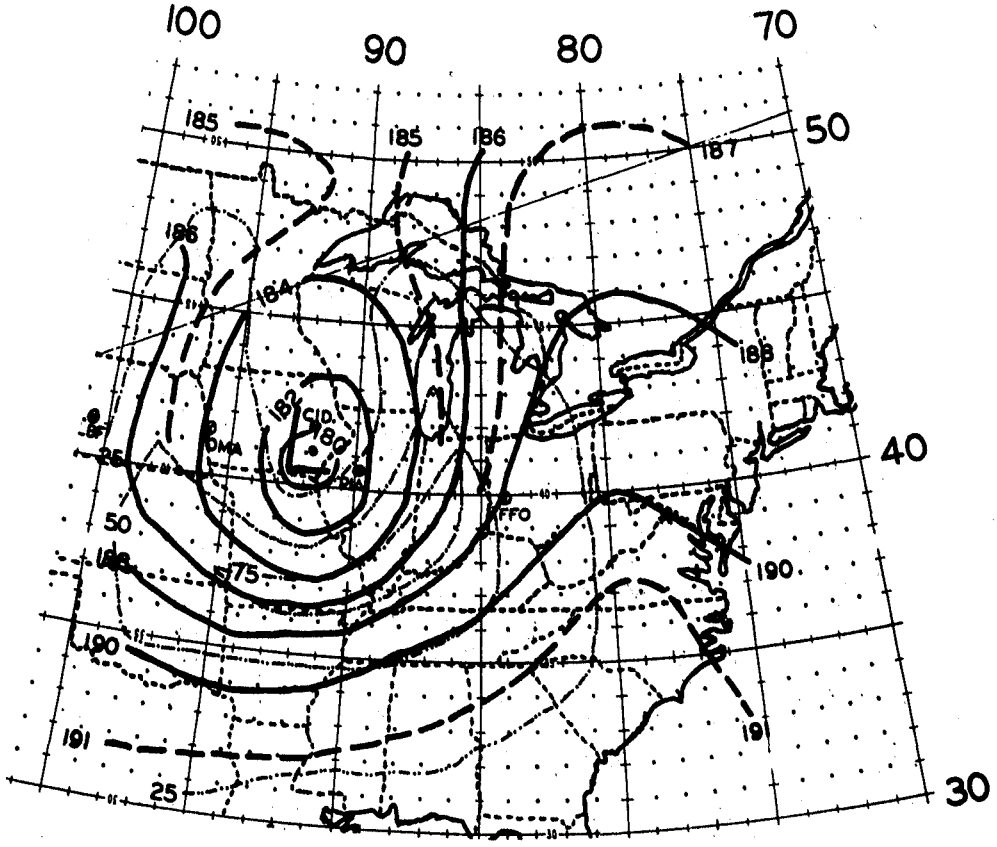


FIG. 10. 500-mb analysis with isotachs (kts) for 1200Z 21 May 1960.

rectification of orbit 731 (Fig. 12) shows that the central region of the vortex consisted mainly of broken cloud cover with numerous lines of cumuliform clouds. Of particular interest is the line of bright clouds extending from northeast Iowa through central Wisconsin. A funnel cloud was observed near 44N 91W approximately 45 min before these pictures were taken and probably originated in this particular band. A band of relatively bright clouds extends around the outer periphery of the vortex. There are cells and lines of brighter reflectivity embedded in this band, suggesting the presence of deep cumulus within this otherwise fairly uniform band. The spiral clear area through Ohio and eastern Michigan appears completely cloud-free on TIROS pictures, but surface reports at this time show this region had scattered cirrus and widely scattered low cumulus clouds. This discrepancy occurred because scattered cirrus clouds are transparent to the TIROS cameras, and the cumulus cloud coverage in this case was not large enough in any one area to be resolved by the wide-angle camera.

Pictures from orbits 732 and 733 had no visible landmarks to use as a starting point in rectifying the cloud cover. Confidence in the accuracy of the location of cloud patterns for orbits 732 and 733 is not good enough for determining the movement of specific cloud patterns from one orbit to the next. However, the consistency within an orbit has been maintained so that comparisons such as the width of the spiral clear area can be made between orbits.

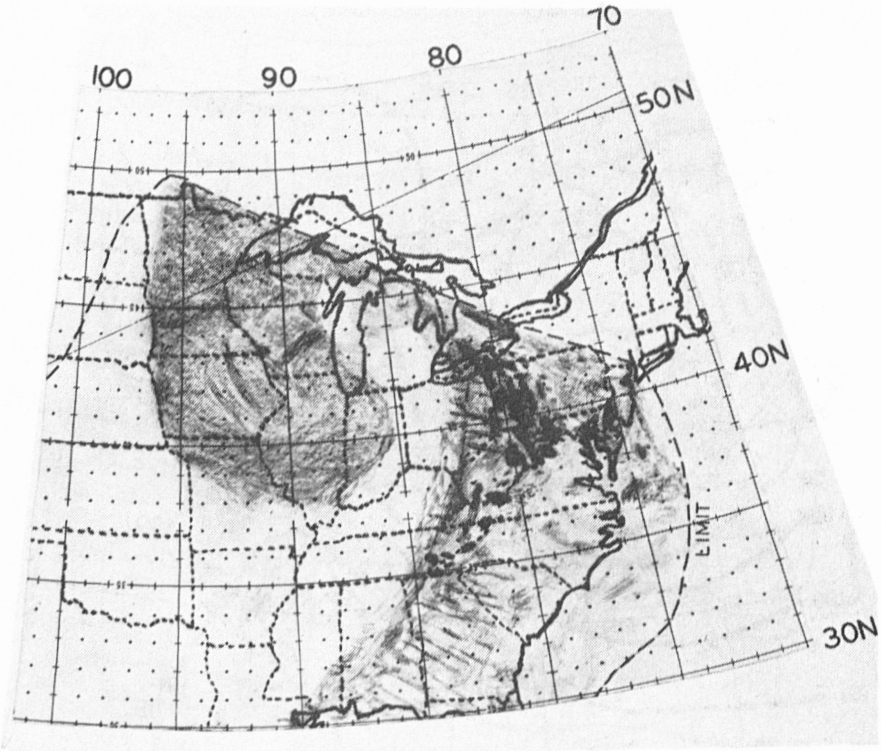


FIG. 11. Cloud rectification for pictures from orbit 730 at 1815Z 21 May 1960.

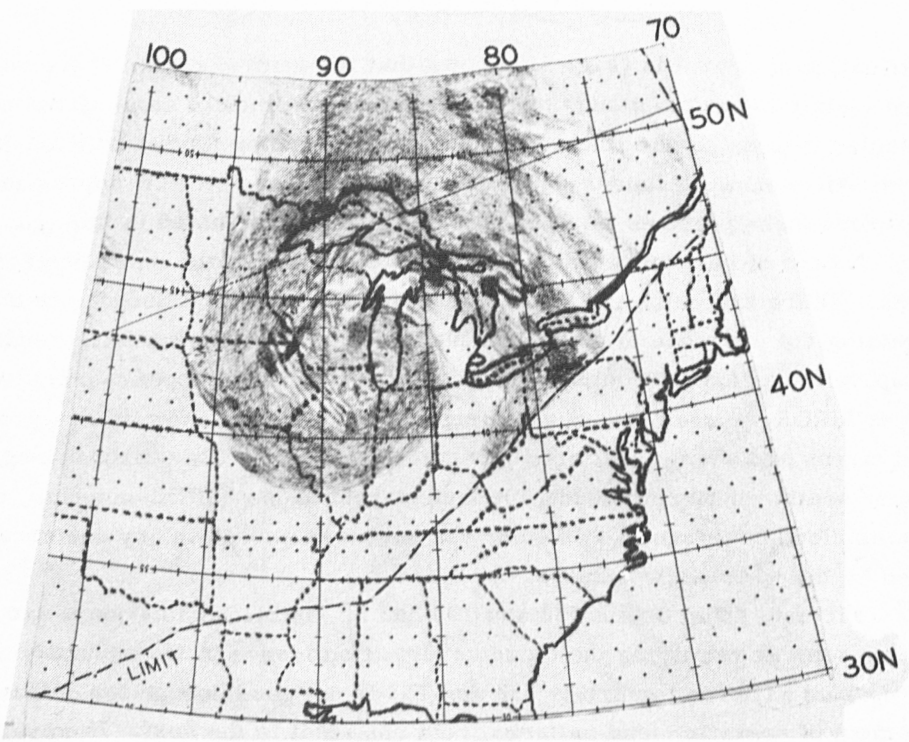


FIG. 12. Cloud rectification for pictures from orbit 731 at 2145Z 21 May 1960.

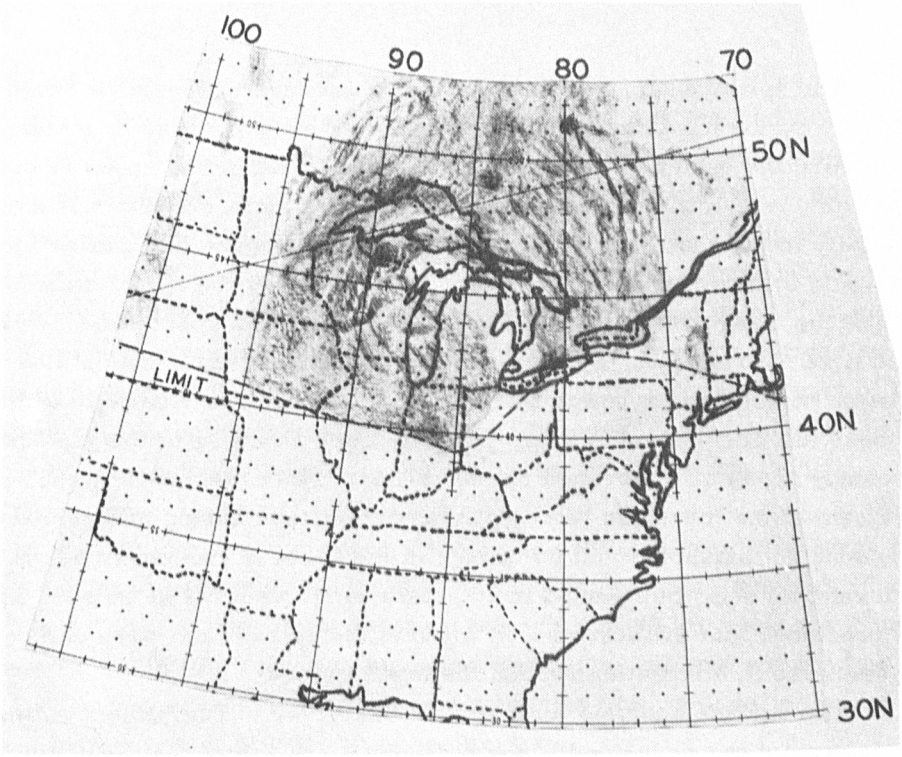


FIG. 13. Cloud rectification for pictures from orbit 732 at 2145Z 21 May 1960.

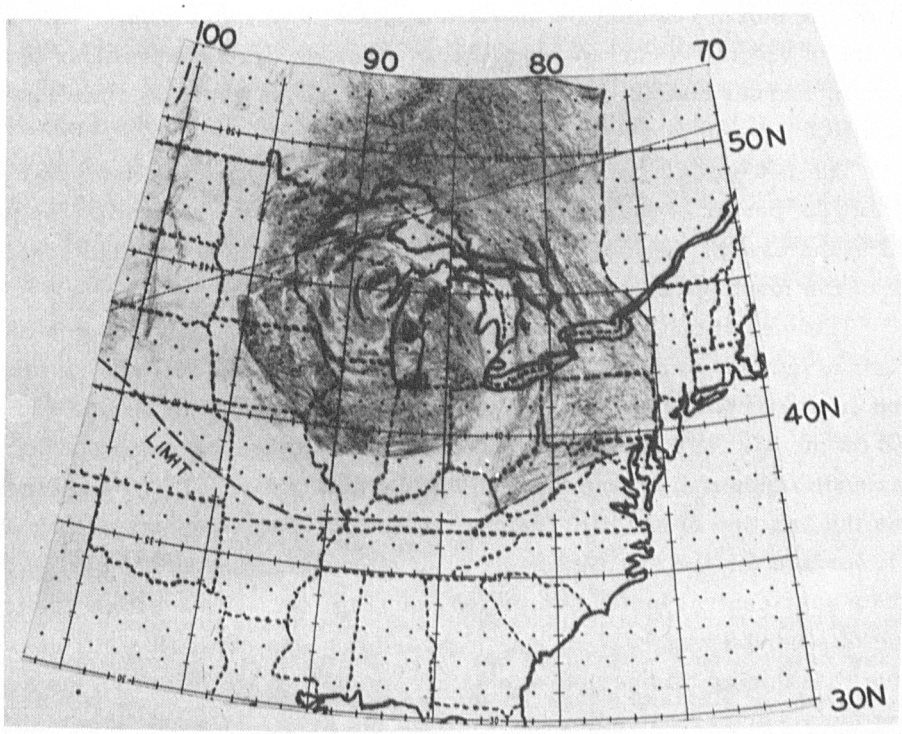


FIG. 14. Cloud rectification for pictures from orbit 733 at 2325Z 21 May 1960.

The spiral clear area in this case is the result of an advective pattern made up in part by the movement of the low-pressure area and also by a component of flow toward the center of the low. A decrease in either the speed of movement of the low or the inflow component would result in a more circular advective pattern, especially in the southeast quadrant of this low. A more circular advective pattern would in turn result in a decrease in the width of the spiral clear area. The width of the clear area in the region of 40N to 45N was approximately 120 naut. mi. at the time of orbit 730. By the time of orbit 733 the width of this clear area in the same region had narrowed to 70 to 75 naut. mi. The change in width of 50 naut. mi. over the time period in these orbits led to a "closing of the gap" between the two cloudy areas at an average rate of 10 kts. Since no change in the speed of movement of the low could be detected at the surface during this period and since it is reasonable to assume that no change in the speed of movement has occurred at any level over this time period in a system with a vertical slope such as this one, it is concluded that the decrease in width of the spiral clear area can be attributed to a decrease in circulation around the low.

The surface analysis for 2100Z, 21 May 1960 in Fig. 15 shows that the frontal system has developed to the occluded stage fairly rapidly during the previous 27-hr period. Since the slope of this low-pressure area is vertical, the time the lowest central pressure occurred at the surface can be used to indicate the time the storm reached its maximum intensity of circulation. The lowest pressure of 998 mb occurred near 1500Z. As this time is very near that of the maximum diurnal rise in pressure at the longitude in question, this low-pressure observation is even more significant.

The 500-mb analysis for 0000Z on the 22nd (Fig. 16) shows no change in height at the center of the low from that 12 hrs earlier. However, the peak wind speed to the east of the low has decreased by 25 kts while the wind speeds to the north of the low have increased.

The isentropic analysis for 0000Z on the 22nd (Fig. 17) indicates that the dry tongue has not continued its rapid advance around the low during the 12-hr period ending at 0000Z on the 22nd as it did during the 12-hr period ending at 1200Z on the 21st. The rectification of orbit 733 (Fig. 14) suggests that this dry air extends farther to the northwest, but the absence of horizon and landmarks leaves the location of specific features in doubt. The 12-hr trajectory along the 309°K surface for the air over Sault Saint Marie (SSM) at 0000Z places the same air over east-central Indiana 12 hr earlier (Fig. 8). The average vertical motion during this period was +0.7 cm sec^{-1} upward for isentropic flow. The average advective rate during this period was 41 kts, which is 6 kts less than the average during the 12-hr period ending at 1200Z on the 21st. An even larger difference in the advective rates is obtained if the 12-hr period ending at 0000Z on the 22nd is split into two 6-hr periods. The trajectory for the period 1200Z to 1800Z yields

an average advective rate of 50 kts while the following 6-hr period has an average of only 31 kts. This provides further evidence that the low reached its maximum intensity near 1500Z as shown by the central pressure of the low at the surface. A comparison of the speed of movement of the moist and dry tongues at 40° latitude shows the moist tongue "closing the gap" at the rate of 6 kts during the 12-hr period ending at 0000Z on the 22nd. This discrepancy of 4 kts between the isentropic analysis and the rate revealed by the cloud pattern can be attributed to the longer time period covered by the isentropic analysis. The spiral clear area was still being advected toward the center of the vortex during the early part of the period between the isentropic analyses. Also, the moist tongue was still being advected around the southwest quadrant during the early part of the period.

The cross section from Idlewild, N. Y. (IDL) to Omaha, Neb. at 0000Z on the 22nd in Fig. 18 verifies that the dry tongue is centered over Pittsburgh (PIT). The 12-hr decrease in wind speeds within this dry tongue is as much as 30 kts at this latitude. The fact that wind speeds on the order of 90 kts were not found at any of the stations in this region is evidence that during the preceding 12 hr there was a decrease in the intensity of the circulation and not simply a motion of the wind speed maximum out of this cross-section line.

Difficulties in rectifying the cloud patterns on orbit 733, occasioned by the uncertain locations, do not allow any comparison between the cloud patterns and the front as shown on the cross section. A comparison of the cloud patterns seen on orbit 730 (Fig. 11) and the location of the cold front on the surface analysis at 1800Z on the 21st (not shown) reveals that the line of thunderstorms is located just above the front at the surface. This would place the line of thunderstorms just ahead of the leading edge of the tongue of dry air shown on the cross sections for 1200Z on the 21st (Fig. 9) and 0000Z on the 22nd (Fig. 18). The clouds to the west of this line of thunderstorms are predominately low cumuliform aligned perpendicular to the flow. The relatively narrow weather band located near the leading edge of the surface front is one of the characteristics of Bergeron's[2] "katafront." However, a "katafront" by definition is associated with downslope motion in the warm air over the higher reaches of the frontal surface. Although dry air found above this frontal surface implies active subsidence, it was found that isentropic flow requires upward motion in this air.

Orbit 745 1905Z 22 May 1960

The movement of the low-pressure area had slowed down and was nearly stationary over Michigan by the time orbit 745 occurred. The low was weak at the surface and the fronts diffuse and stationary on the analysis for 1800Z on the 22nd (Fig. 19). The low at 500 mb had filled 200 ft during the 12-hr period prior to 1200Z on the 22nd. Wind speeds to the east of the low had further decreased, as shown by the analysis for this time in Fig. 20.

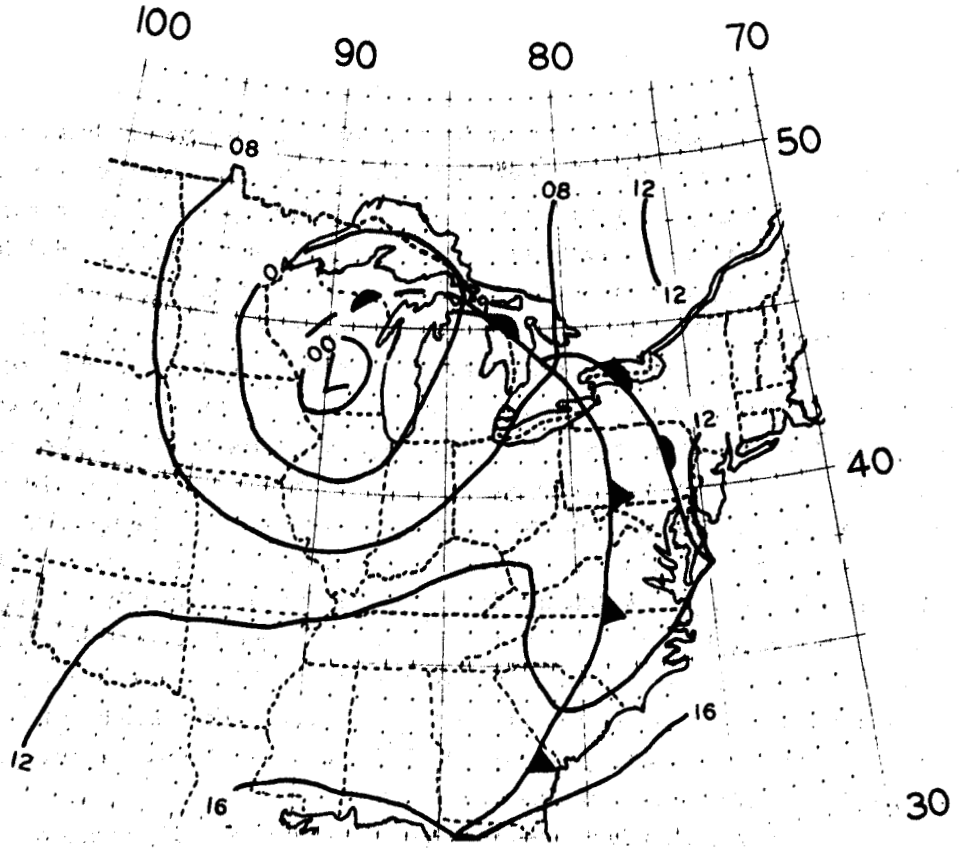


FIG. 15. Surface analysis for 2100Z 21 May 1960.

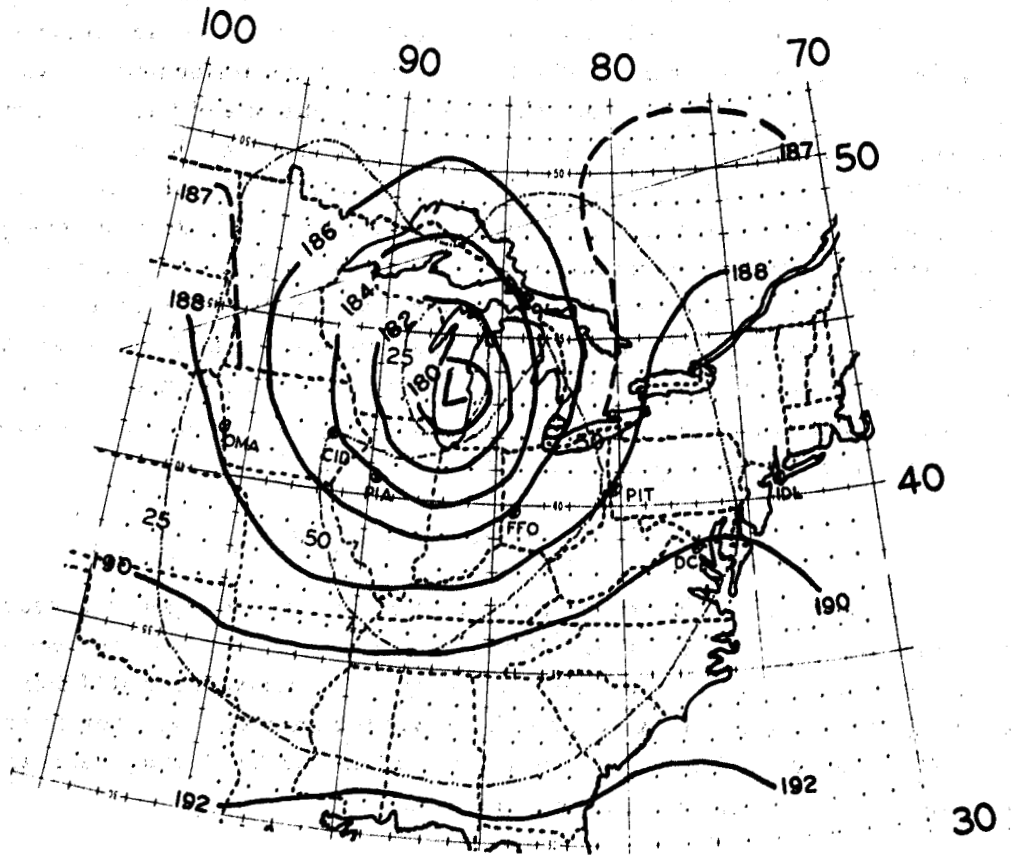


FIG. 16. 500-mb analysis with isotachs (kts) for 0000Z 22 May 1960.

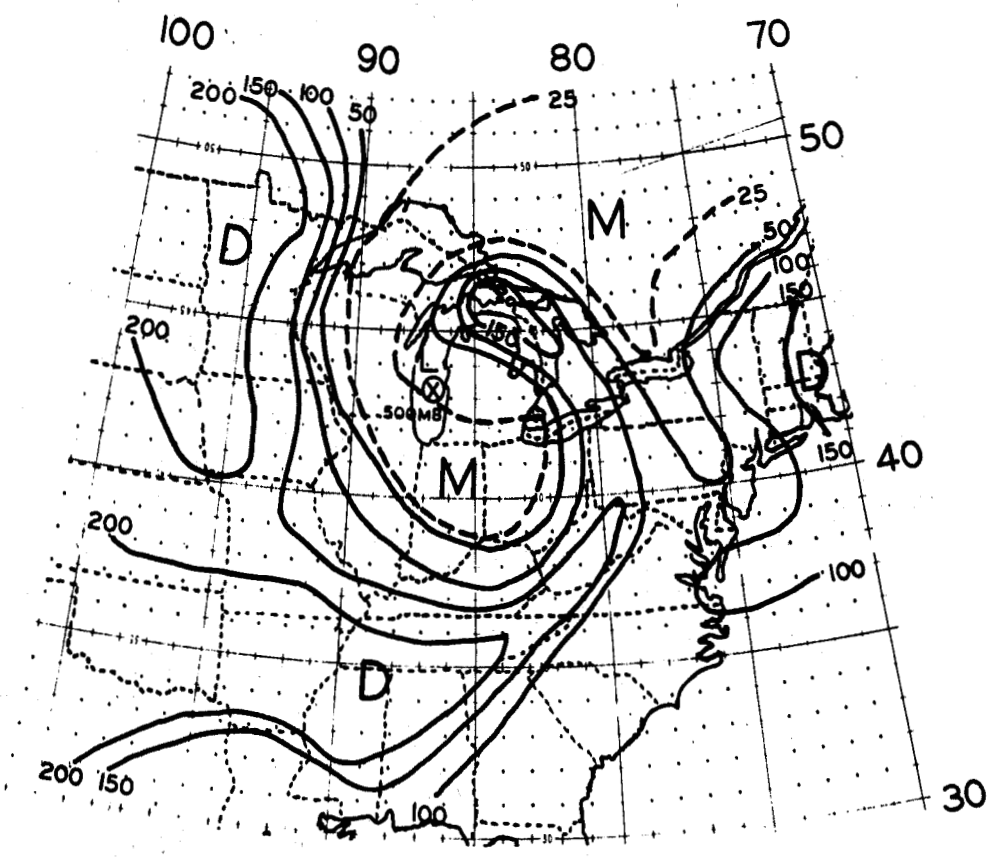


FIG. 17. Difference in pressure (mb) between the pressure and saturation pressure for 309°K potential – temperature surface at 0000Z 22 May 1960.

The cloud rectification for orbit 745 (Fig. 21) shows cloud cover completely surrounding the vortex with only a narrow ring of less bright clouds (oriented north-south through central New York around the northern periphery of the low and extending through eastern Wisconsin to northern Indiana) remaining as any indication of the spiral clear area of the previous day. Numerous brighter clouds are found in all but the southwest quadrant. In this quadrant, low cumuliform clouds have formed into lines approximately parallel with the wind under a weak inversion.

The dry air has been almost completely cut off on the 309°K isentropic surface for 1200Z on the 22nd (Fig. 22). Lateral mixing and vertical motion have reduced the maximum difference between the pressure and saturation pressure of this surface to approximately 50 mb.

The cross section for 1200Z on the 22nd in Fig. 23 lies along a line from Nantucket, Mass. (ACK) to Saint Cloud, Minn. (STC). The base of the dry tongue appears as a stable layer at approximately 600 mb over Buffalo (BUF) and Albany (ALB) with a decrease in moisture through this stable layer and much less moisture than was seen at previous times. The base of this stable layer is 80 to 90 mb lower in pressure than the inversion over PIT 12 hrs earlier. The air below the base of this stable layer is fairly homogeneous in the horizontal down to

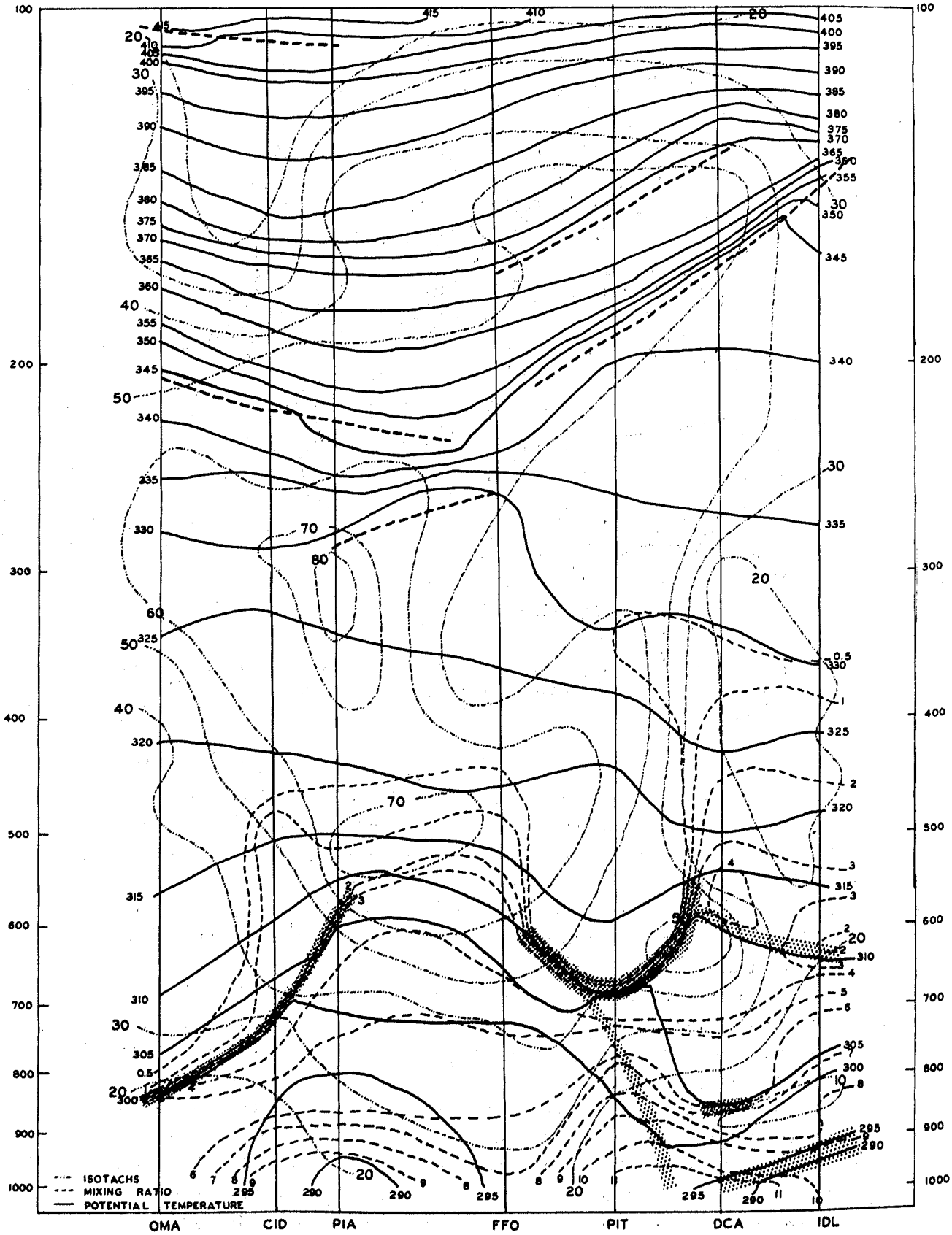


FIG. 18. East-west cross section between Idlewild, New York (IDL) and Omaha, Neb. (OMA) at 0000Z 22 May 1960.

about the 700-mb level, indicating that the front does not extend above this level. It has been suggested by Sansom[12] that when a "katafront" weakens, it becomes a weak "anafront." In this case such an impression was created more by a change in advective pattern rather than any change in sign of the vertical motion.

Discussion of Results

The foregoing analysis has shown that advection was the dominant mechanism in the formation of the spiral vortex cloud patterns in the studied case. The advection was found to be more than twice as large as the rate of translation in the developing stage. In the development stage of this vortex pattern, the component of the flow toward the center set up a spiral pattern for the moist and dry regions. After the low had developed to its maximum intensity, the circulation began to lose intensity, causing a decrease of the wind component toward the center. With continued advection of the moist air, but in a more circular pattern, the tongue of dry air began to decrease in width. Finally, as a result of vertical motion and lateral mixing, the vortex pattern disappeared.

The presence of the relatively clear spiral to the east of the low does not necessarily indicate active subsidence is taking place. In this case the vertical motion was upward within the clear dry air. This air had been dried by subsidence but, as Sawyer[13] has pointed out, this may have been 24 hrs or more before it was observed in the region.

The upper winds and weather found in this system near the time of its maximum intensity are typical of a "katafront" as characterized by Sansom.[12] However, there was little evidence of a front above about 700 mb. The front gave the appearance of being sheared off at this level and capped by a "dry" inversion separating the warm dry air above from the cool moist air below. The extreme dryness of the air above this inversion implies active subsidence. However, as it has previously been pointed out, isentropic flow requires upward motion in this air. Furthermore, if active subsidence were taking place, there would be a strengthening of the discontinuity between the two air masses, rather than a weakening as was found in the case studied.

The formula generally used for determining vertical velocity at a front is:

$$w = (c - u) \tan \theta$$

where w is the vertical velocity, c is the speed of the front, u is horizontal component of the wind normal to the front, and $\tan \theta$ is the slope of the front. If the cross sections in this study had been analyzed in the usual manner to show a

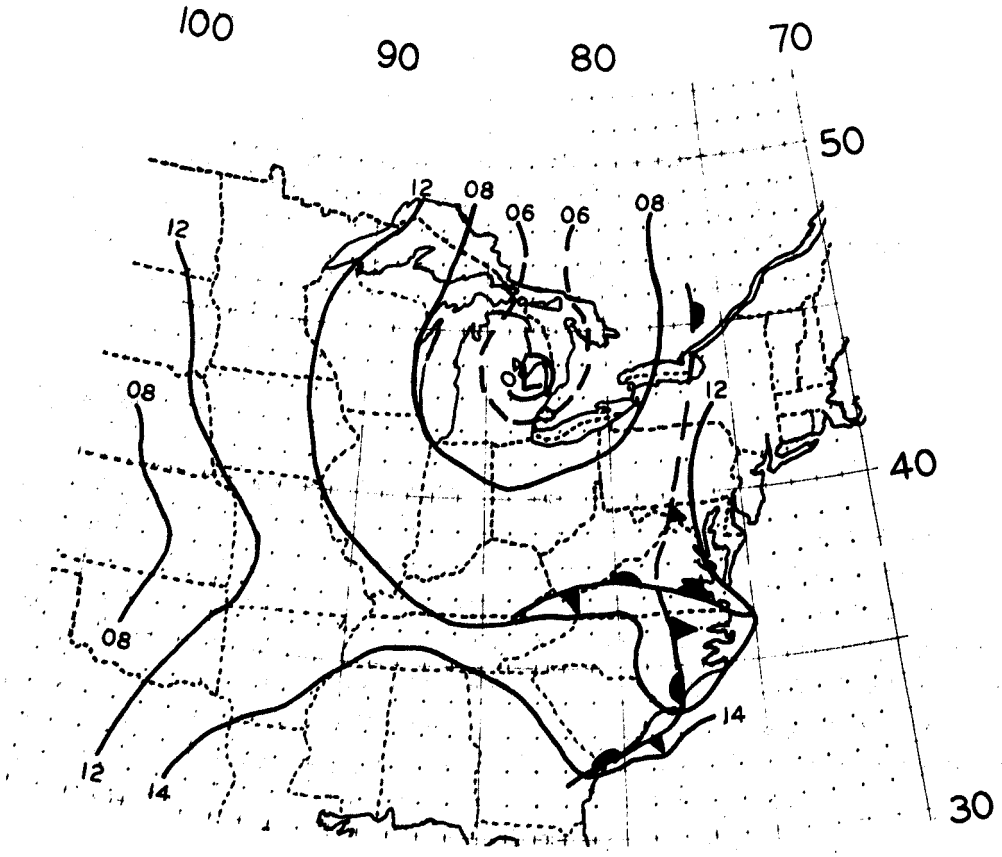


FIG. 19. Surface analysis for 1800Z 22 May 1960.

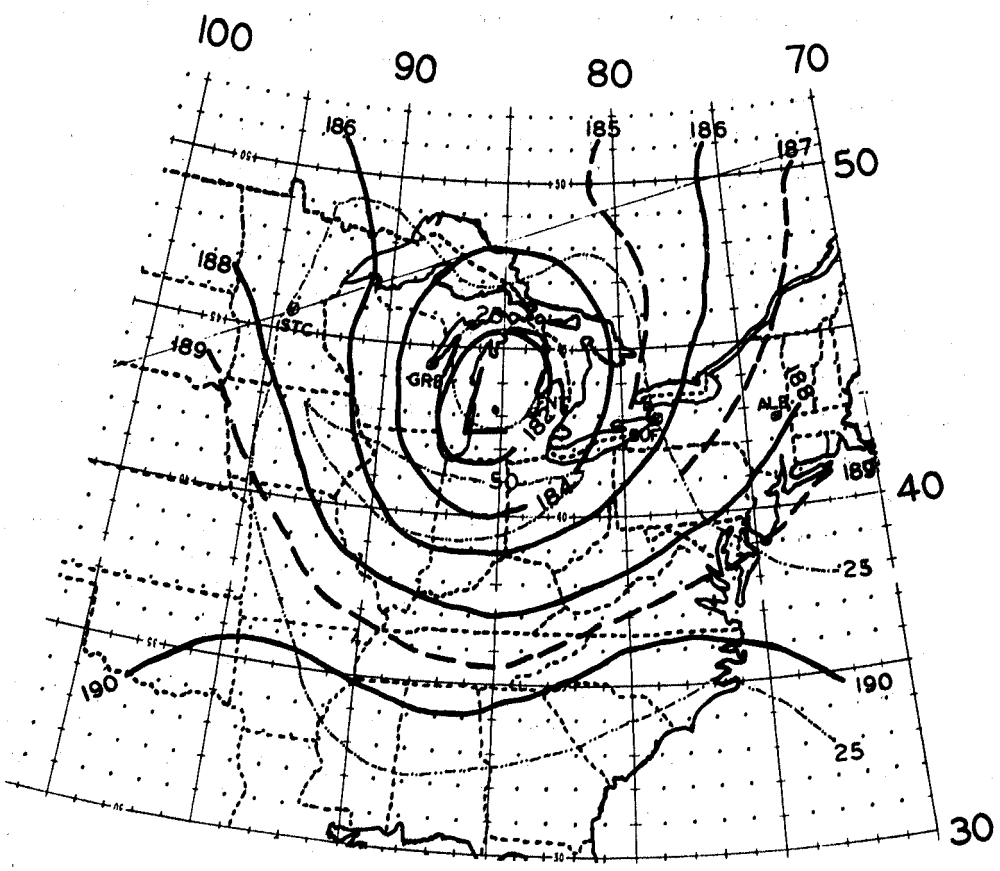


FIG. 20. 500-mb analysis with isotach (kts) at 1200Z 22 May 1960.

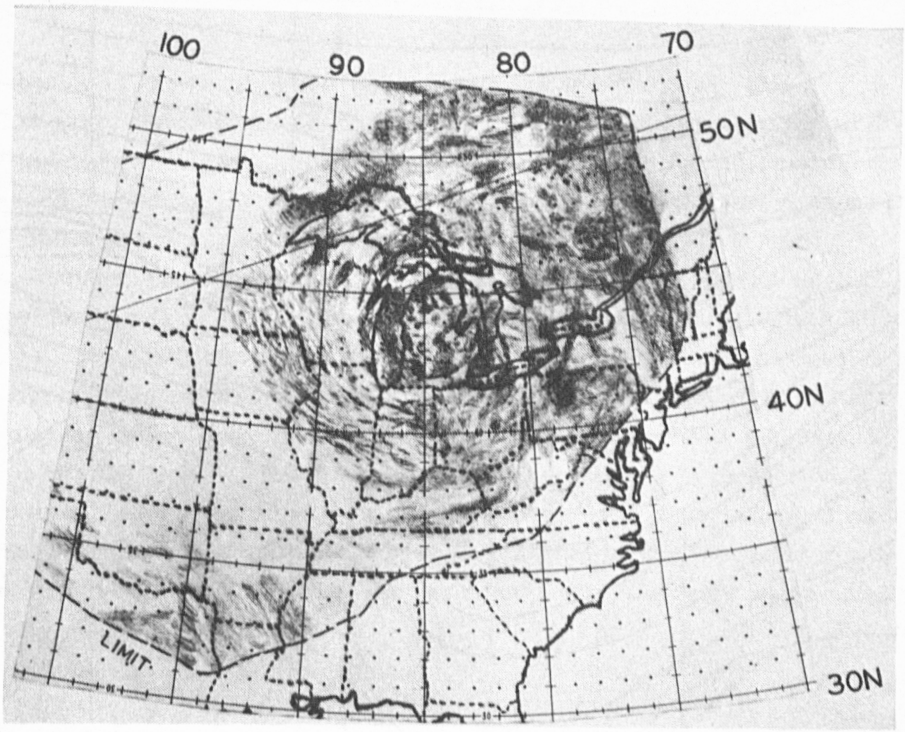


FIG. 21. Cloud rectification for pictures from orbit 745 1905Z 22 May 1960.

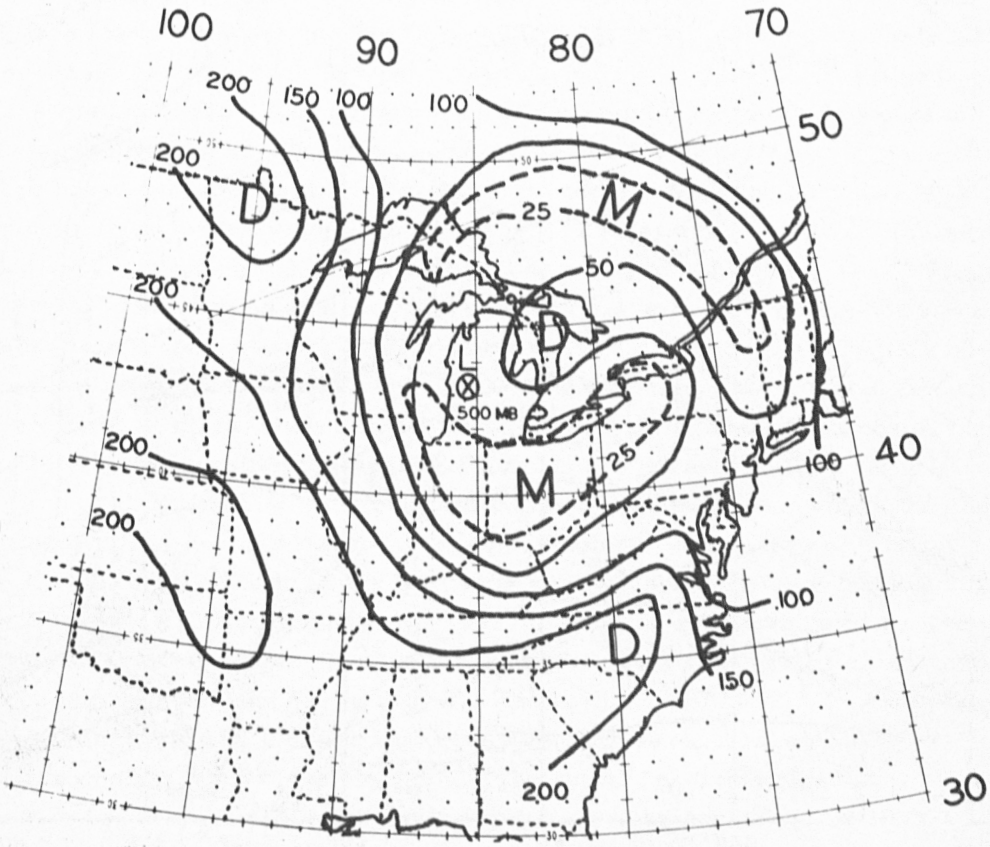


FIG. 22. Difference in pressure (mb) between the pressure and saturation pressure for 309°K potential-temperature surface at 1200Z 22 May 1960.

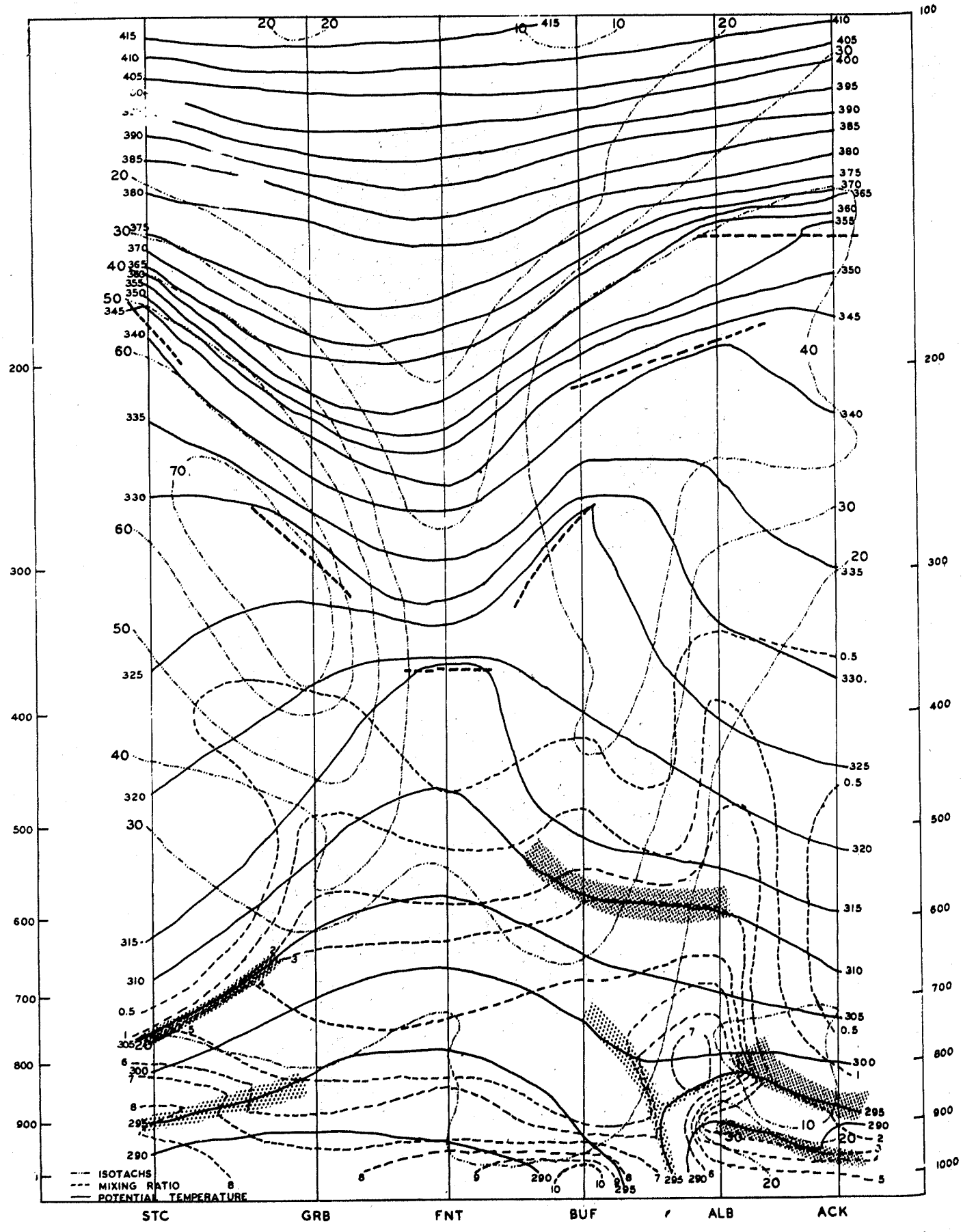


FIG. 23. East-west cross section between Nantucket, Mass. (ACK) and Saint Cloud, Minn. (STC) at 1200Z 22 May 1960.

continuation of the front above 700 mb with the warm dry air ahead of it, the above formula presumably could be used to determine the vertical motion in this dry air. If the axis are chosen so that the slope is positive, the formula necessarily shows downward motion in this dry air because the horizontal wind component normal to this front is greater than the speed of the front.

Sansom[12] observed that as the "katafront" weakens with age, the amount of subsidence will decrease until finally, in the ultimate quasi-stationary stage, the front may again be a weak "anafront." In the case studied, the weather pattern displayed characteristics of such a change from a "katafront," but this can be explained by a change in the advective pattern rather than a change in the amount of subsidence. The change in advective pattern in the decaying stage resulted in cutting off the supply of dry air. The "dry" inversion was raised by vertical motion. This vertical motion and lateral mixing resulted in a weakening of the "dry" inversion creating the impression that the front was a weak "anafront."

Indications and Conclusions

The similarities displayed by the spiral vortex cloud patterns seen by TIROS I would suggest that the features found in this detailed case study also hold for other cases in which this particular cloud pattern exists. It is also possible that this particular cloud pattern may be partially obscured in some cases. In the case studied, the air which had subsided and was being advected in the southerly flow ahead of the low was dry enough to permit a fairly long period of upward motion which did not bring it to saturation. If very dry air such as this were not present, saturation and clouds could occur which would destroy the clear spiral pattern. The case studied was that of a cold low with a vertical slope at the time of its maximum intensity. It is possible these spiral cloud patterns are obscured in a low where the slope is very small. The absence of any vertical motion on the convective scale precludes cloud formation in this region and thereby prevents the pattern from revealing the western boundary of the advecting dry air.

Indications that the storm had begun to weaken were given by the change in width of the spiral clear area in the case studied. No pictures of this vortex were available from the time it was beginning to develop until after it had reached its maximum intensity. An indication that the stage of development of a vortex can be ascertained from the cloud patterns is given by a comparison of the vortices seen in orbits 605 and 619 in Fig. 1. The vortex cloud pattern shown in the picture from orbit 619 is associated with the same low-pressure area as the one shown in orbit 605 but one day later. The spiral relatively clear area advanced around to the north of the low during the intervening period.

The motion of the spiral clear area appears to give some indication of the maximum intensity reached. A comparison of the surface analysis prior to the time of the picture of the vortex cloud pattern shown on orbit 705 (Fig. 1) and the vortex cloud pattern shown in pictures from orbit 730 (Fig. 1) and (Fig. 12) reveals two differences other than the fact that one occurred over water and the other over land. The low took nearly two days to develop the spiral pattern shown on orbit 705, whereas the cloud pattern shown on orbit 730 developed to this stage in less than one day. Furthermore the minimum central pressure at the surface was approximately 20 mb less in the low associated with the cloud patterns shown on orbit 705. The spiral relatively clear area penetrated nearly one complete revolution farther into the center of the cloud patterns shown on orbit 705. The longer development period allows more time for advection.

The spiral cloud patterns can be associated with a low-pressure area at the surface, but no general statement can be made that the reverse is also true. The TIROS pictures of a system which developed in the midwest United States on 16 May 1960 and moved northeast during the next two days showed no spiral cloud patterns at any time. Although the development of the low and associated frontal system at the surface was nearly identical to that of the system discussed in this case study, the upper-air low showed a closed circulation at 700 mb and 500 mb only briefly during the middle of the period. A comparison of Boucher's[4] model describing the evolution of cloud patterns attending the development and decay of a middle latitude cyclone with the cloud patterns seen throughout the history of the 16 May storm would suggest that these cloud patterns had not developed beyond the stage he has called "The Open Wave." An example of the lack of any vortex cloud pattern was seen by TIROS on 6 April 1960. An occlusion on the surface analysis over the north-central United States was associated with a shallow trough in the upper-air pattern. The TIROS pictures showed only a band of clouds ahead of this occlusion.

The observations in this case study indicate that the "katafront" could be described better in terms of upper-air advection with reference to the surface front than by the vertical motion occurring within a frontal zone.

A general conclusion resulting from a limited study such as this is that the TIROS pictures are particularly well suited for the study of horizontal advection and show promise of yielding quantitative information.

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