The role of advection in the formation of vortex cloud patterns

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ABSTRACT

A case study of the spiral cloud patterns associated with an atmospheric vortex, as seen by the TIROS 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. 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.

1. Introduction

The advent of TIROS has 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 fitting the cloud patterns associated with low pressure systems (hereafter referred to as vortex cloud patterns), of the type shown in Fig. 1, to the frontal model based on the polar-front theory of wave cyclones, developed by the Norwegians during World War I. Evidence that this model does not accurately describe conditions in the upper air was shown long before TIROS.

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 extra-tropical cyclones, as shown by Leese, (1961), and with tropical storms, as shown by Sadler, (1962). It would thus appear that by studying the day-to-day changes in 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 should reveal much about its horizontal and vertical structure, by the shape and relative position of the cloud and clear areas around the vortex, in various stages of development. The general pattern as seen in TIROS pictures is for this spiral area to be mostly clear over the land, and partially obscured by scattered-to-broken low cumuliform clouds over the ocean.

It would appear that advection plays an important part in the formation of this type of cloud pattern. The size of this spiral area, which can be much greater than 100 mi. wide, as well as being located mostly in strong southerly flow precludes describing this as a region of actively subsiding air behind the cold front. Sawyer (1955), found that a characteristic tongue of relatively dry air was associated with many of the frontal zones over England. This dry tongue extended 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 advection; the air has been dried by subsidence, but this may have been 24 hr or more before it was observed in the frontal region and is no indication of descending motion in the frontal zone. A dominant mechanism of advection in the formation of this type of vortex would make it possible to get some indication of the speed of rotation around the vortex, relative to its speed of translation, i.e. the speed of rotation must be much greater than the speed of translation. A requirement for its formation would then be strong meridional flow ahead of the low.

This paper presents a case study[2] of the development and decay of the spiral vortex

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[2] As this paper was being written, a detailed synoptic analysis of the same storm was published. (Timchalk and Hubert, 1961.)

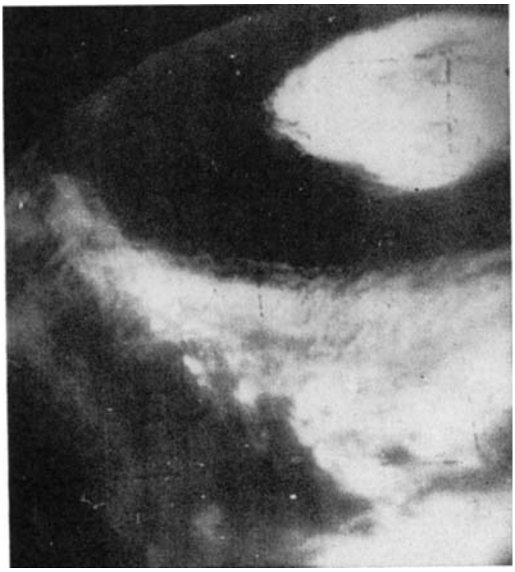


FIG. 1. Spiral-vortex cloud pattern as seen by TIROS I, orbit 730 1816Z May 21, 1960 Midwest United States.

cloud patterns which demonstrates that advection can be a dominant mechanism in the formation of these patterns.

2. Analysis

a. Synoptic

The surface analysis for 1800Z (Greenwich Civil Time) May 20, 1960 (not shown) indicates a frontal system running north-south through the Central United States with an incipient wave on this front. This wave developed to the occluded stage fairly rapidly as the low pressure area moved northeastward at about 20 knots and was centered in Southern Wisconsin at 2100Z on the 21st (Fig. 2*a*). The movement of the low pressure area then slowed down and was nearly stationary over Michigan by 1800Z on the 22nd. The fronts are diffuse and stationary at this time.

The low at 500 mb. was centered in Southeastern Nebraska at 0000Z on the 21st (Fig. 2*b*). 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 satisfied in this situation. The 500 mb. analysis for 1200Z on the 21st (not shown) had the wind speed maximum located in the southeast quadrant of the low with the observed wind velocities as high as 90 knots at this level. By this time the slope of the low was nearly vertical with height and continued to maintain this slope through the remainder of its history. At 0000Z on the 22nd (Fig. 2*c*) the low at 500 mb. was centered over Lake Michigan. The peak wind speeds to the east of the low have decreased by 25 knots from that 12 hr earlier while the wind speeds to the north of the low have increased. During the next 12 hr the low had filled 200 ft with a further decrease in wind speeds to the east of the low.

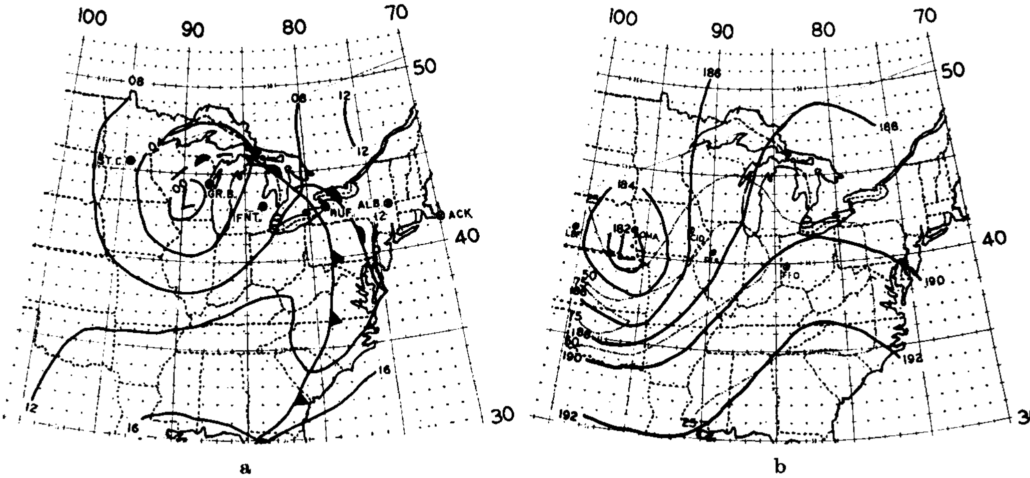
Since the slope of this low pressure area is vertical, the time of occurrence of the lowest central pressure at the surface can be used to give an indication of the time the storm reaches its maximum intensity of circulation. The lowest pressure of 998 mb. occurred near 1500Z on the 21st. This time becomes more meaningful for the occurrence of the lowest central pressure when it is considered that this is also very near the time of the maximum diurnal rise in pressure at this longitude.

b. Cloud Rectification

TIROS pictures of this storm were taken on orbits 716 on May 20, 730–733 on May 21, and 745 on May 22. The locations of cloud features on the satellite pictures were determined using the methods developed by Allied Research Associates (Dean, 1961) and the attitude data determined from landmarks in pictures on orbits 716, 730 and 731. The location should be accurate to within ± 30 mi. on the orbits where visible landmarks appeared. No numerical value can be attached to locations on orbits without visible landmarks on the pictures. However, the cloud rectifications on these orbits checked out very well with nephanalyses made from conventional surface observations.

Clouds are shown on the rectifications (Fig. 3–8) in different shades of gray in qualitative proportion to the brightness of the clouds in the TIROS pictures with the brightest clouds appearing as the darkest gray in the rectification. Conover, (1960) thinks this brightness can be related to the depth of the cloud cover but that it is also influenced by many other factors, among which the most serious is the reflection of the sun glint from the top of the clouds.

The cloud rectification for orbit 716 in Fig. 3 shows the Midwest United States mostly cloud



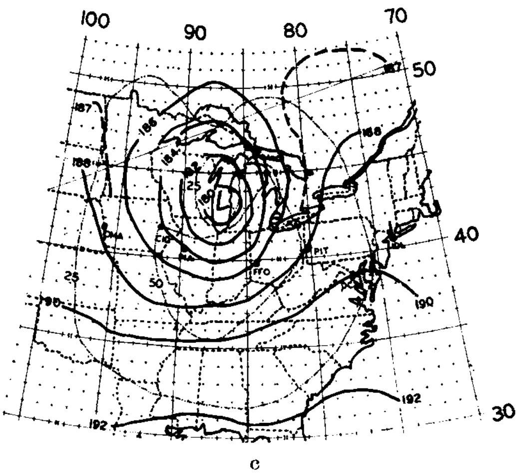


FIG. 2. Surface and 500 mb. analyses nearest the times of TIROS I pictures. a. Surface 2100Z May 21, 1960 b. 500 mb. 0000Z May 21, 1960 c. 500 mb. 0000Z May 22, 1960

covered. A bright band of clouds extends from Eastern Texas (30N, 95W) northeast to Central Indiana (35N, 85W). A squall line is shown through this region on the 1800Z surface analysis. A second band, slightly less bright than the first, extends north-northwest from Eastern Texas to the limit of the rectification in South Dakota (45N, 98W). This band is associated with the frontal system through the central United States.

The cloud patterns around this low were photographed on four different orbits, during the period 1800Z to 2330Z, on May 21. The rectified cloud patterns for these orbits are shown in Fig. 4–7. 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 pictures 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 cloud rectification of pictures from orbit 730 (Fig. 4) shows a line of very bright cellular clouds extending from Southern Ontario (43N, 82W) through Western Pennsylvania, West Virginia and Eastern Tennessee (35N, 84W) associated with a line of thunderstorms through this region. The smaller lines of clouds oriented west-northwest to east-southeast through Eastern Ohio (39–42N, 82W) 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 those levels. Due to the angle of view, the vortex appears almost completely cloud covered on this orbit whereas the rectification of orbit 731 (Fig. 5) shows that the central region of the vortex consisted mainly of broken cloud cover with numerous lines of cumuliform clouds. A band of relatively bright clouds extends around the outer periphery of the vortex. The spiral

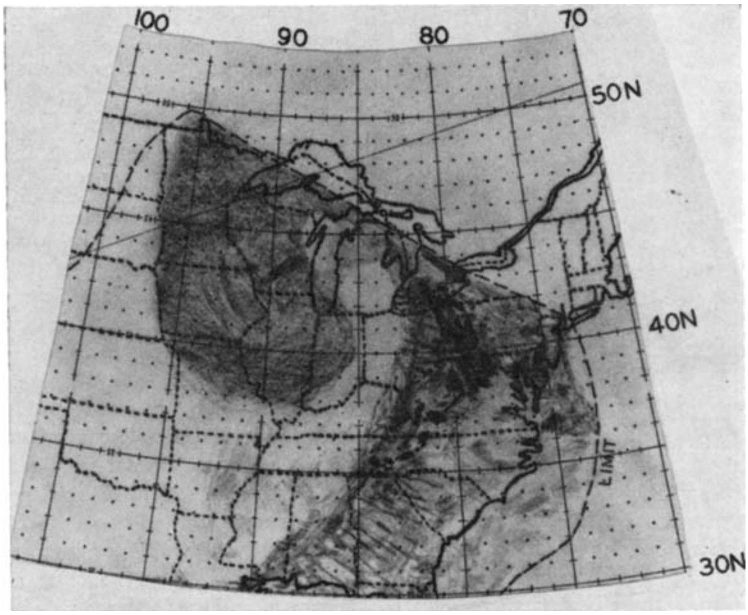


FIG. 3. Cloud rectification for pictures from orbit 716 at 1910Z May 20, 1960.

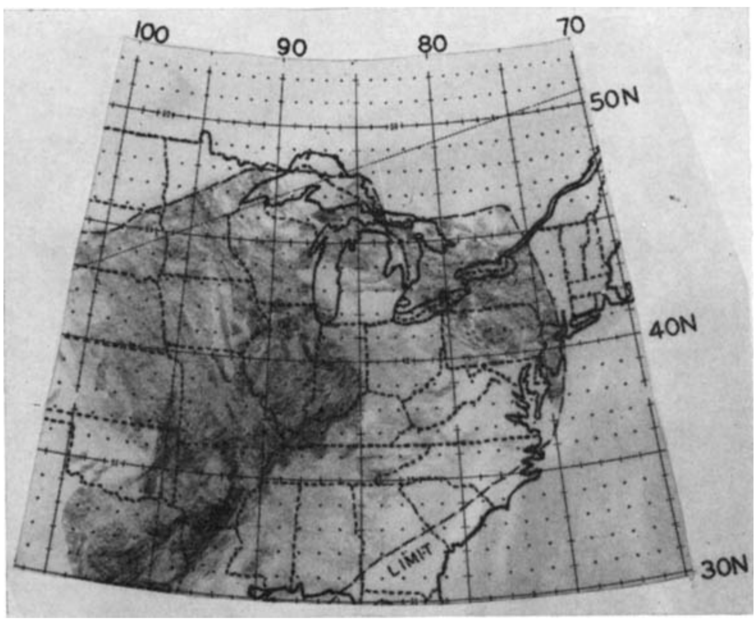


FIG. 4. Cloud rectification for pictures from orbit 730 at 1815Z May 21, 1960.

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. The scattered cirrus was transparent to the TIROS cameras as it normally is, and the cumulus cloud coverage was not large enough in any one area for the resolution of the wide-angle cameras. Pictures from orbits 732 (Fig. 6) and 733 (Fig. 7) had

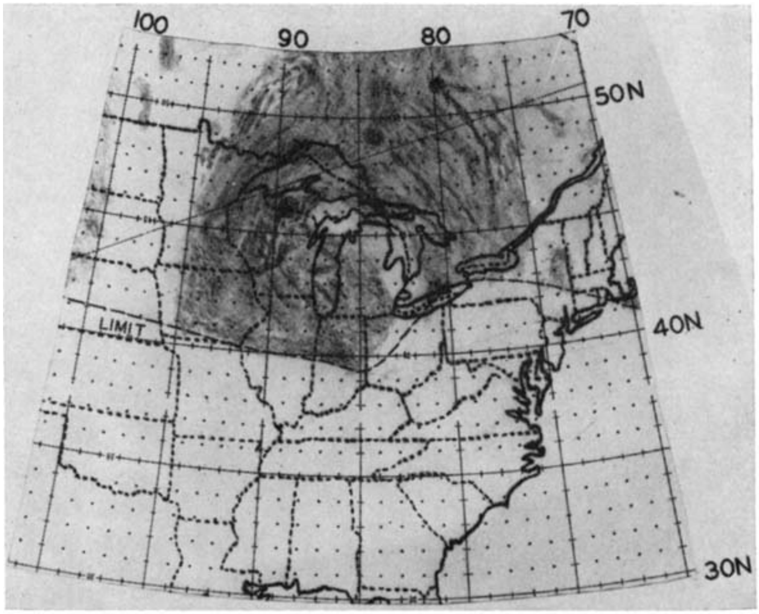


FIG. 5. Cloud rectification for pictures from orbit 731 at 2000Z May 21, 1960.

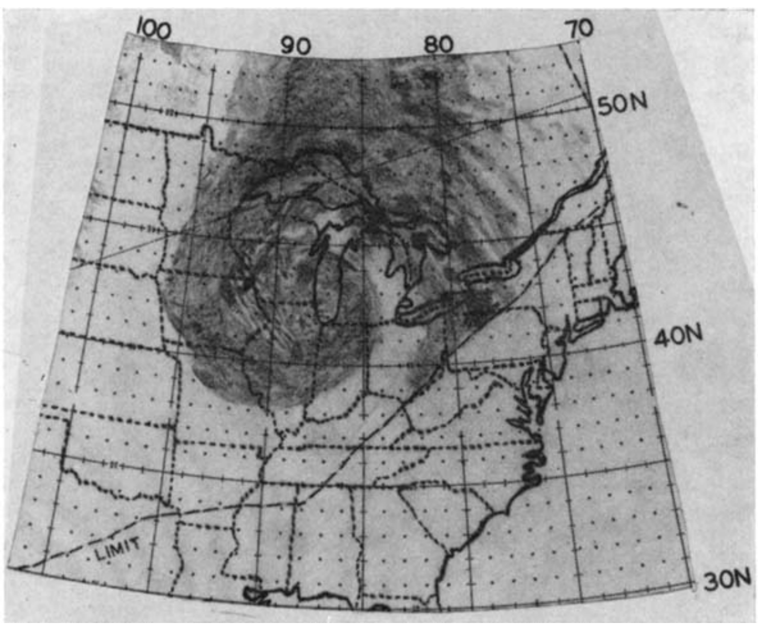


FIG. 6. Cloud rectification for pictures from orbit 732 at 2145Z May 21, 1960.

no visible landmarks to use as a starting point in rectifying the cloud cover. Confidence of the accuracy in the location of cloud patterns for orbits 732 and 733 is not good enough to determine 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 area can be made between orbits.

The spiral clear area in this case has been

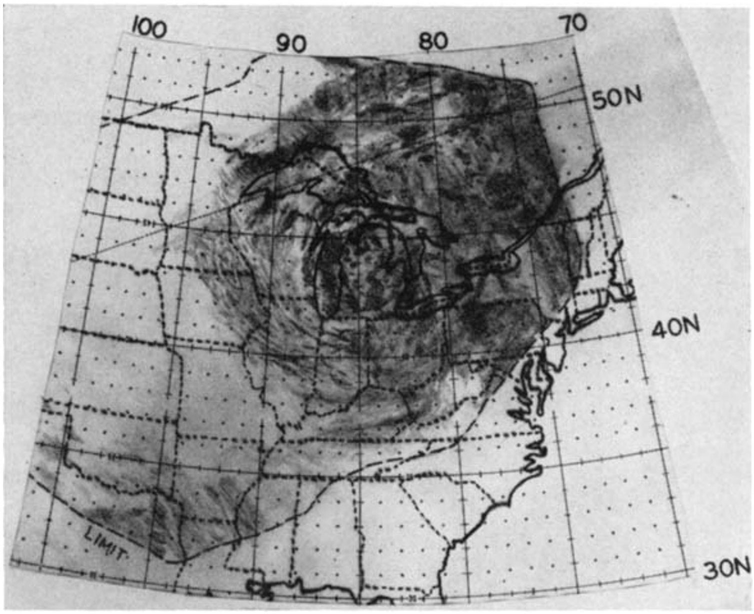


FIG. 7. Cloud rectification for pictures from orbit 733 at 2325Z May 21, 1960.

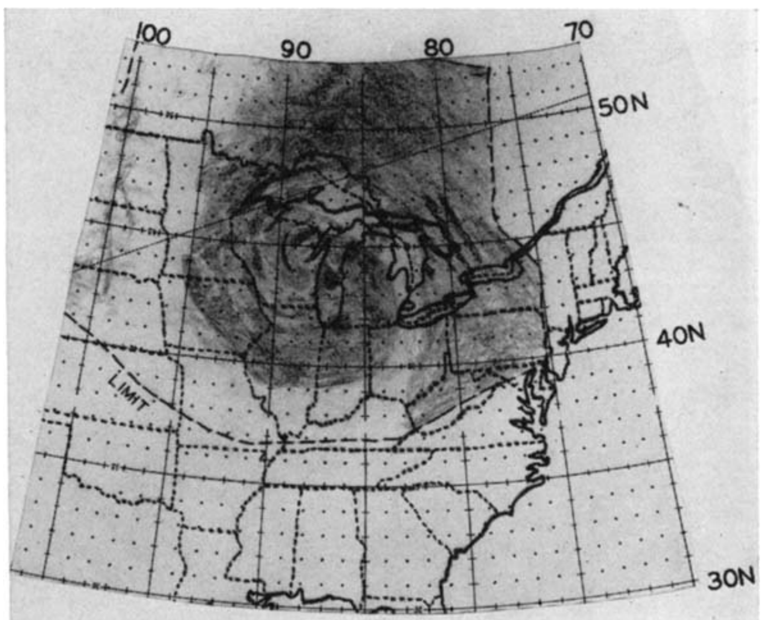


FIG. 8. Cloud rectification for pictures from orbit 745 at 1905Z May 22, 1960.

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. This would result in a decrease in the width of this spiral clear area in the southeast quadrant. The width of this clear area in the region of 40N to 45N was approximately 120 n.

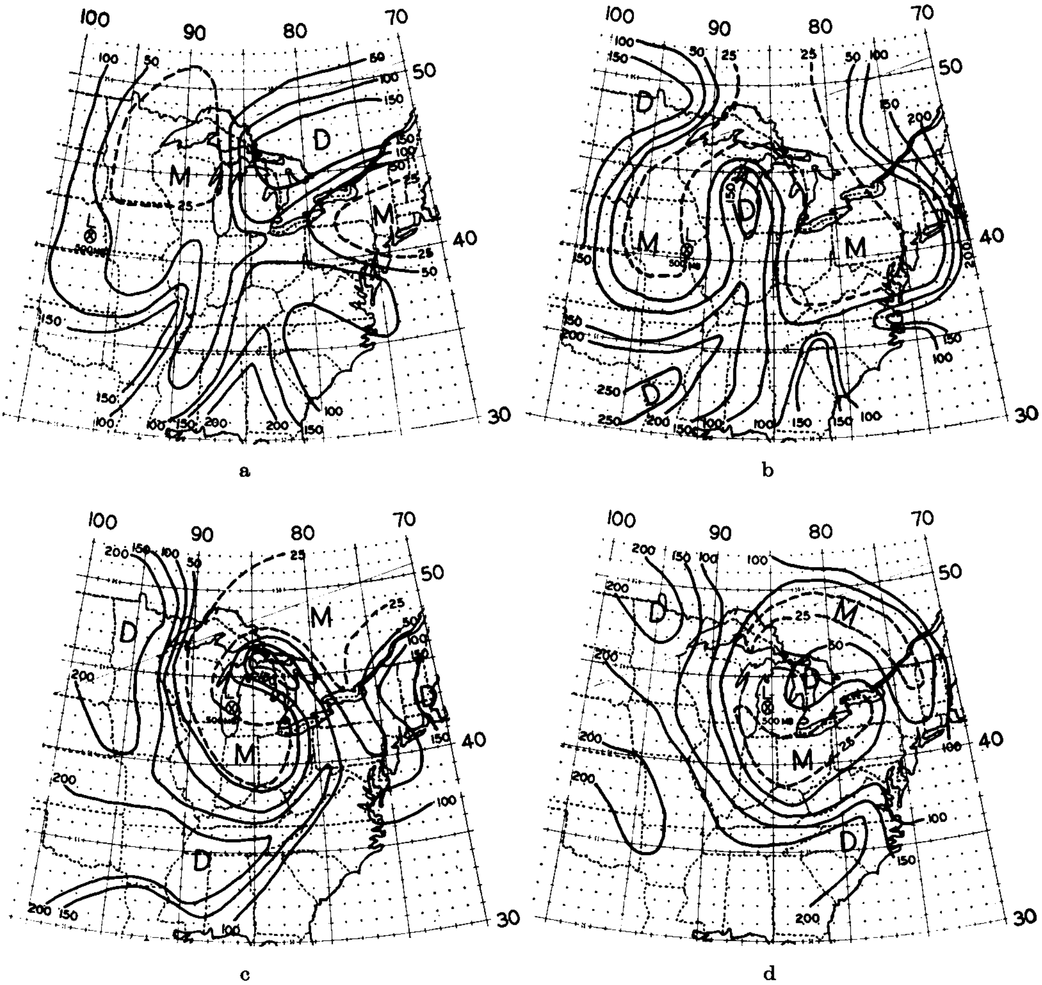


FIG. 9. Difference in pressure (mb.) between the pressure and saturation pressure for 309K potential temperature surface.
a. 0000Z May 21, 1960 b. 1200Z May 21, 1960 c. 0000Z May 22, 1960 d. 1200Z May 22, 1960

ni. 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 70–75 n. mi. The change in width of 50 n. mi. over the time period of these orbits leads to a "closing of the gap" between the two cloudy areas at an average rate of 10 knots. Since no change in speed of movement of the low could be detected at the surface during this period and 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 cloud rectification for orbit 745 (Fig. 8) shows cloud cover completely surrounding the vortex with only a narrow ring of less bright clouds 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.

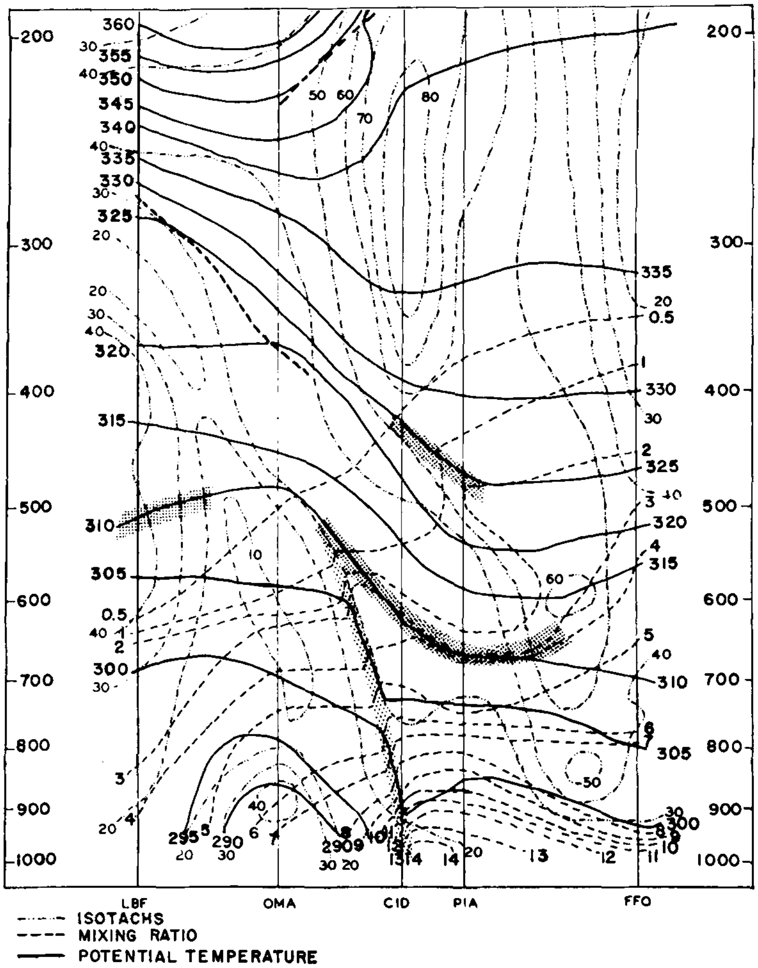


Fig. 10 a

Fig. 10. East-west cross sections through the low pressure area. (Note: light stippled represents the frontal zone; heavy stippled represents stable zones other than frontal.)
a. 0000Z May 21, 1960 b. 1200 May 21, 1960 c. 0000Z May 22, 1960 d. 1200Z May 22, 1960

c. Moisture

As a means of tracing the paths of the moist and dry regions, the potential temperature and mixing ratio were used. The potential temperature of 309K was selected as high enough to be uninfluenced by surface conditions at this season of the year. The difference between the pressure and saturation pressure of the 309K 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 each time through the low pressure area.

The difference between the pressure of the 309K potential temperature surface and the saturation pressure of this surface at 0000Z on the 21st is shown in Fig. 9*a*. 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 has penetrated as far north as Southern Illinois (40N, 90W). The moist region is mainly to the northeast of the

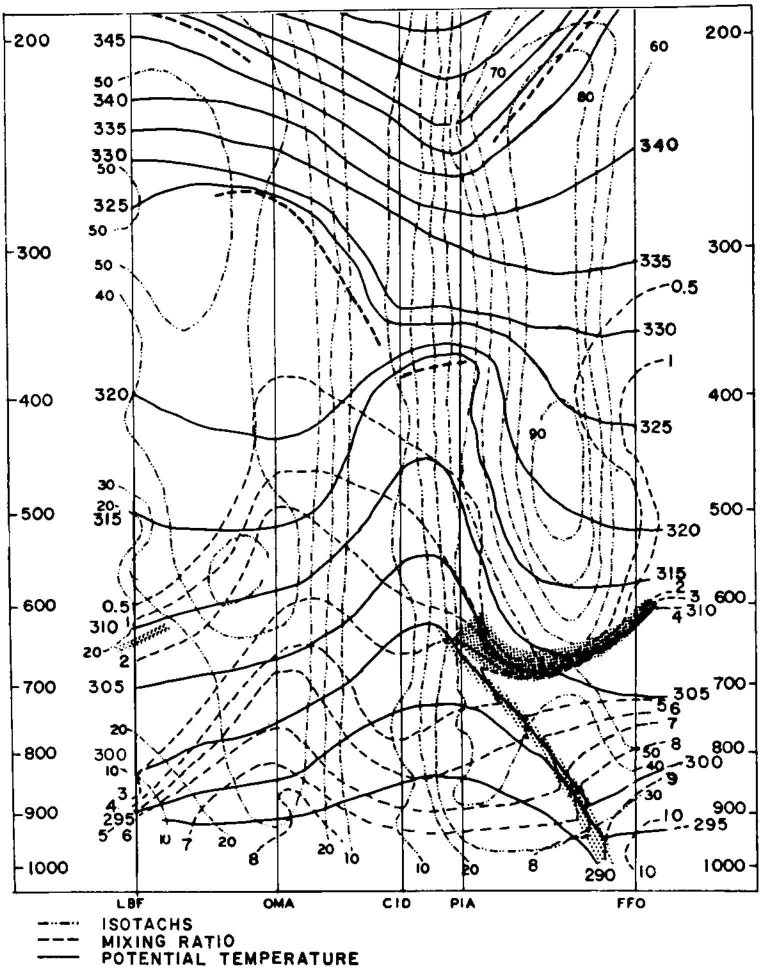


Fig. 10 b

low with a narrow tongue extending southward ahead of the dry tongue. The cloud cover on orbit 716 (Fig. 3) is five hours earlier than this analysis and does not show this penetration of dry air at that time. Conventional surface observations at the same time as the isentropic analysis do not yield much information about the dry tongue due to cloud cover below the level of the dry air.

An east-west cross section from Dayton, Ohio (FFO) to North Platte, Nebraska (LBF) is shown in Fig. 10*a* for 0000Z on the 21st. The location of this line is displayed in Fig. 2*b*. The cross section indicates the lowest level of this dry tongue at about 680 mb. over Peoria, Illinois (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.

The isentropic analysis for 1200Z on the 21st (Fig. 9*b*) shows that the dry tongue has advanced to the vicinity of Green Bay, Wisconsin (GRB) where it is found at 619 mb. By computing a 12 hr trajectory back from Green Bay along the 309K potential temperature surface, this air was over Southeastern Missouri (37N, 90W) at 0000Z on the 21st (Fig. 11) 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 309K potential surface from 660 mb. to 619 mb. was due to vertical motion, we

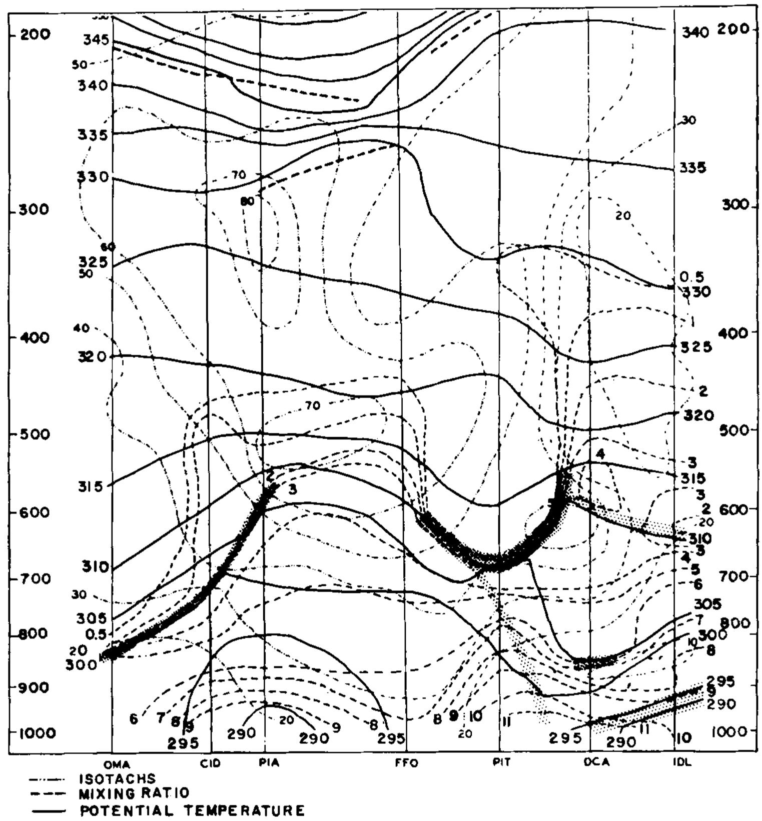


Fig. 10 c

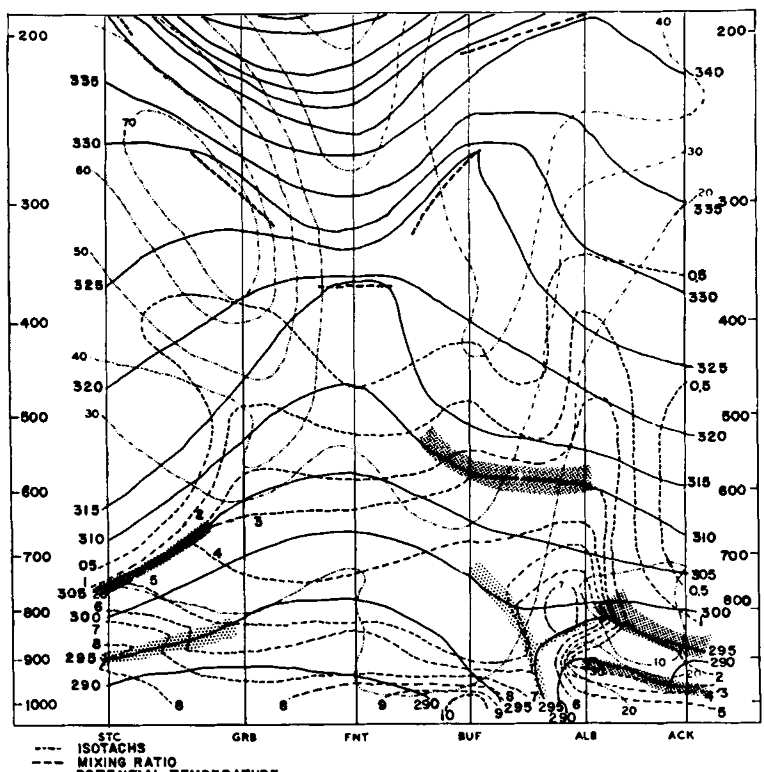


Fig. 10 d

compute 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 knots. The translation velocity of the 500 mb. low during this period was from the west at 20 knots 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 on Fig. 11 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. 9*a*) and 1200Z (Fig. 9*b*) 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 500 mb low center by 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 knots. This was computed by measuring the movement of the leading edge of the 25 mb. difference between the pressure and saturation pressure as the leading edge of saturated air on this surface.

The cross section in Fig. 10*b* for 1200Z on the 21st is along the same line as the one 12 hr earlier (Fig. 10*a*). The inversion at the base of the dry tongue is located between FFO and PIA at approximately the same pressure as 12 hr 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.

The isentropic analysis for 0000Z on the 22nd (Fig. 9*c*) 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. 7) suggests that this dry air extends farther to the northwest but the lack of horizon and landmarks leaves the location of specific features in doubt. The 12 hr trajectory along the 309K surface for the air over Sault Saint

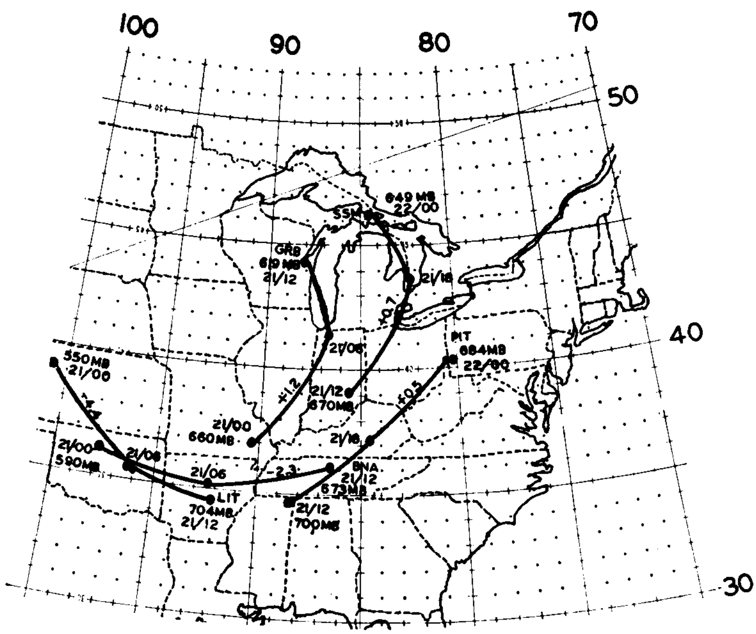


FIG. 11. Trajectories along 309K potential temperature surface. (Date, Time and Pressure (mb.) are labeled at beginning and end of trajectories. Resultant vertical motion (cm sec^{-1}) labeled along the trajectory.)

Marie (SSM) at 0000Z places the same air over East-central Indiana (39N, 86W) 12 hr earlier (Fig. 11). 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 knots which is six knots less than the average during the 12 hr period ending at 1200Z on the 21st. There is a larger difference in the advective rates if the 12 hr period ending at 0000Z on the 22nd is split into two six-hour periods. The trajectory for the period 1200Z to 1800Z yields an average advective rate of 50 knots while the following six hours has an average of only 31 knots. 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 deg latitude shows the moist tongue "closing the gap" at the rate of six knots during the 12 hr period. This discrepancy of four knots 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, New York (IDL) to Omaha, Nebraska at 0000Z on the 22nd in Fig. 10*c* verifies the dry tongue over Pittsburgh (PIT). The location of this line is shown in Fig. 2*c*. The 12 hr decrease in wind speeds within this dry tongue is as much as 30 knots at this latitude. The fact that wind speeds on the order of 90 knots were not found at any of the stations in this region at 0000Z on the 22nd is evidence that during the preceding 12 hr there was a decrease in the intensity of the circulation rather than simply motion of the wind speed maximum out of this cross section line.

The dry air has been almost completely cut off on the 309K isentropic surface for 1200Z on the 22nd (Fig. 9*d*). 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. 10*d* is along a line from Nantucket, Massachusetts (ACK) to Saint Cloud, Minnesota (STC). The location of this line is shown in Fig. 2*a*. The base of the dry tongue appears as stable layer at approximately 600 mb. over Buffalo, New York (BUF) and Albany, New York (ALB) with a decrease in moisture through this stable layer but much less than was seen at previous times. The base of this stable layer is 80–90 mb. lower in pressure than the inversion over PIT 12 hr earlier (Fig. 10*c*).

3. Discussion of Results

The analysis has shown that advection was the dominant mechanism in the formation of the spiral vortex cloud patterns in this 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 which resulted in 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 (1955) has pointed out, this may have been 24 hr or more before it was observed in the region. Aside from the fact that isentropic flow requires upward motion in this air, 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.

4. Indications and conclusions

The similarities displayed by the spiral vortex cloud patterns seen by TIROS would suggest that the features found in this detailed case study also hold for other cases in which this particular cloud pattern exists.

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. However, the motion of the spiral clear area appears to give some indication of the stage of development and the maximum intensity reached. A comparison of the surface analyses prior to the time of the picture of the vortex cloud pattern seen over the Central Pacific on orbit 705 (Leese, 1961) and the vortex cloud pattern shown in pictures from orbit 730 (Fig. 1) and (Fig. 4) 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. Also 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 May 16, 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, (1961) 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 May 16th 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 I on April 6, 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.

A general conclusion resulting from a limited study such as this is that the TIROS pictures show promise of yielding quantitative information in an area for which they are particularly well suited, i.e. horizontal advection.

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