ABSTRACT

Synoptic Conditions Producing Cirrus During the FIRE Cirrus IFO

by

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1. Introduction

Although direct observations of cirrus clouds by the FIRE research aircraft were usually confined to the area of the IFO surface network (~100 km in dimension), these cirrus were generally part of a more extensive (≥500 km) zone of upper level cloudiness. It is these large scale patterns of cirriform cloud and their relationship to the corresponding synoptic environment which are the prime focus of this paper. We present three conceptual models and classify each of the individual cases into one these categories. Although the cases manifest significant differences in intensity and small scale structure, we believe they are best viewed in this unified context. The descriptions given below are mostly qualitative, however, quantitative descriptions of the synoptic control and its relationship to cloud structure for all the IFO cases will be summarized during the presentation. A paper giving more detailed and quantitative information on each of the individual cases will be distributed.

The synoptic situations in which extensive cirriform clouds were observed are classified into three basic types: 1) warm front cases, 2) cold front cases, and 3) closed low aloft cases. A simplified summary of each type of situation is presented in the following sections. Our terminology reflects our reliance on the standard upper air and surface analyses provided by the National Weather Service and our cognizance of classical notions of cyclone structure. However, satellite imagery (primarily from GOES) was indispensable in the development and application of our classification scheme. Our categories do have some precedence in the area of satellite image interpretation. The warm front class is always associated with an upper level short wave. Weldon (1976) uses the term "baroclinic leaf" cirrus to describe situations resembling these cases, although, if there is significant development at the surface and middle levels, he uses the term "comma cloud" to describe the whole multilevel system . Our cold front cases correspond to Weldon's "baroclinic zone" cirrus pattern. However, he applies this term to an even larger class of cases whose unifying feature is their correspondence in scale and location with planetary waves (Rossby-Haurwitz waves) .

The three classes of extensive upper level cloud systems described here are not intended to be exclusive, but rather representative of situations encountered during the Fall 1986 field campaign. One obvious class not included is the "mesoscale anvil" cloud associated with mesoscale convective systems in tropical and extratropical regions. In fact, cumulonimbus, which often produce cirrus by injection of moisture and condensate into upper levels, did not occur within the IFO region during the experiment. However, weak cumulonimbus activity was observed in the upstream flow with some of the closed low aloft cases.

2. WARM FRONT CIRRUS

In the classic view, warm front cirrus are the harbingers of an approaching extratropical cyclone with its attendant deep cloud development and precipitation. The presence of cirrus is typically ascribed to gentle broadscale slope convection (upglide) along an elevated warm front as depicted in Figure 1. This is the picture given in numerous meteorological text books. However, it is our opinion that this may be a misleading interpretation of the actual situation as seen in the following description.

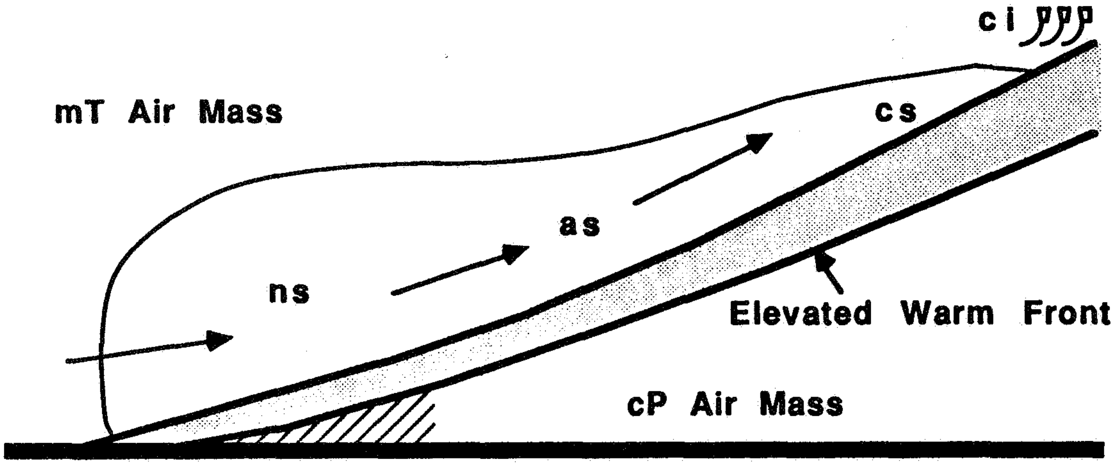

Figure 1: Classic view of clouds along a warm front.

Our view of warm front cirrus is that it is always associated with an upper level short wave as shown schematically in Figure 2a. Its preferred location is capping the short wave ridge with a relatively sharp northern boundary corresponding to the axis of the jet stream and a ragged southern boundary. Streaks or fingers of cirrus generally protrude downstream of the denser ridge-capping region and may reach nearly halfway to the preceding short wave trough. This leading edge of the cloud tends to contain convective cirrus, e.g., uncinus, spissatus and fibratus. Patches of cirrostratus may also be present. A denser cirrostratus overcast is typically found in the ridge-capping region where convective cells are often embedded within the larger cloud mass. Upstream of the ridge axis, patchy cirrostratus are typically found, though cirrostratus overcast is common. The cirrus here usually appear continuous with the ridge-capping cirrostratus. It should be noted that these clouds usually extend upstream of the surface warm front location often to the location of the surface cold front and its associated jet axis. The tops of the highest clouds within this pattern are usually at or not far below the tropopause. In Figure 2a, attention should be given to the correspondence or lack thereof, between the surface features and the corresponding cloud pattern with respect to the classic picture shown in Figure 1.

Ahead of the ridge axis and surface warm front, multilayered development is quite common. Merging of individual upper level cirrostratus layers is often found near the ridge axis where the depth of the entire cloudy layer may reach more than 3 km. A separate lower layer of denser cirrostratus is found in cases when the surface cyclone is of more than minimal intensity. This middle level cloud layer often borders on being an altostratus cloud and typically exhibits moderate convective development originating near cloud base (~6 km). Though dominated by ice

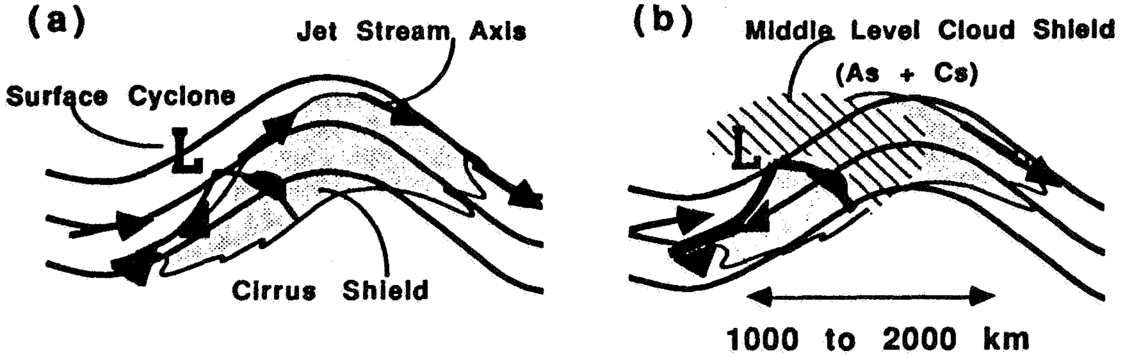

Figure 2: Traveling Short Wave and Warm Front Cirrus Shield:
(a) without middle level clouds ("baroclinic leaf")
(b) with middle level clouds ("comma cloud").

processes, all three phases of water may be found in the vicinity of the cloud base. In weak cyclones, this layer does not develop appreciable vertical extent. However, when the cyclone is of moderate intensity, it may develop vertically through convective processes and actually merge with the high level clouds which grow downward through an ice precipitation process, i.e., a total depth of ~5 km. Development of the lower level cloud layer ceases with the passage of the warm front as illustrated in Figure 2b.

We believe that this dense middle level cloud layer results from upglide along the warm front. It is found in the proper location and the tendency for convective instability to increase as the layer develops ahead of the surface front, is consistent with the classic notions. However, the high level cirrus appears to develop independently. The spatial pattern of this extended cloud area does not fit the classic notion. Although the cirrus uncinus and spissatus comprising the leading edge of this pattern are the first signs of an approaching disturbance, it does not appear that they are initiated or maintained by a frontal upglide process as is implied in the classic picture. Rather, this upper layer more likely results directly from the effects of the thermodynamic and dynamic structure of the upper level flow, e.g., ascent up the sloping isentropic surfaces of the ridge and possibly differential vertical temperature advection associated with the vertical structure of the jet leading to convective instability near the tropopause (i.e., uncinus). The development of the surface cyclone, which forces the development of the middle level cloud layer, is also dynamically coupled (independently) to the upper level disturbance. This picture is consistent with the notions given by Weldon (1976) where the upper level cloud corresponds to his "baroclinic leaf" cirrus (Fig. 2a) and the middle level clouds form part of the "comma" which is seen when there is significant surface development (Fig. 2b). We acknowledge that the cases we considered in developing the above model had weak to moderate development at the surface. This fact supports our contention since the upper level cirrus were observed with little apparent forcing from below. Furthermore, it is likely that this model also applies to situations of strong surface cyclones, though the separation between the upper layers and the middle layers are probably much less distinct in these cases. In this situation, the convective development of the middle level clouds (and also probably the low level clouds rooted in the boundary layer) leads to a physical connection between the layers and an appreciable vertical transport of water to upper levels, which results in an enhancement of the density (ice contents) and extent of the upper level clouds.

Two of the FIRE Cirrus IFO cases most clearly fit the pattern of warm front cirrus presented above: the 27-28 October and 2 November cases. In each case, a distinct upper level short wave ridge moved from west to east through the IFO region superimposed on a pattern of weak (20 m/s) and generally zonal upper level flow along the US-Canadian border. A surface cyclone with its attendant warm and cold fronts formed in the Montana area and also propagated eastward. Though the surface fronts were well-defined, the cyclone did not intensify appreciably, i.e., no widespread precipitation developed. Upper level cirrus (~9-11 km) were observed below the tropopause in advance of the warm front and also after its passage. The "baroclinic leaf" pattern, which passed directly over the IFO area, was not filled in with a dense cirrostratus overcast. However, the zone where cirrus were present did define a region whose outline was similar to that show in Figure 2a. The high level cirrus were mixture of uncinus, spissatus and patchy cirrostratus. Alto/cirrostratus were intermittently observed between about 4 and 7 km prior to the passage of the warm front at the surface. On the 28th, they were visible in GOES imagery through the high cirrus layer and the trailing edge of this cloud layer clearly paralleled the surface warm front. An underlying layer of very scattered shallow cumulus was also present on each day.

Three other cases also fit the warm front cirrus pattern: the **15, 19 and 30 October** cases. Unlike the previously described cases, the large-scale flow was from the northwest on the 15th. Wisconsin was situated between a ridge over the Canadian Rockies and a trough to the east (axis on a line from eastern Michigan to Louisiana) of a high amplitude long wave pattern. An extensive cirrus shield capped a well-defined short wave ridge that was moving to the southeast. A weak but clearly defined surface cyclone and associated warm front were moving toward Wisconsin from the northwest, i.e., central Canada. No middle level clouds were observed in Wisconsin, though some may have developed to the north in Canada. Stratocumulus were prevalent as cold air behind a recently passed cold front was modified. With respect to the pattern depicted in Figure 2a, the major differences in this case were the orientation of the ridge axis (WSW-ENE) and the breadth of the cirrus shield along the ridge axis relative to its length along the flow, i.e.,greater along the axis than along the flow. It should also be noted that the entire system of relatively dense cirrus moved by mostly to the northeast of the IFO region, i.e., only the ragged southern portion (between the warm and cold fronts of the cyclone that was centered roughly under the ridge axis) of the pattern presented in Figure 2a was actually sampled. Tenuous convective cirrus, often aligned in bands, were observed near the tropopause (~11 km) and extended down to the 9 km level.

On 19 October, a region of cirrus developed rapidly near the Minnesota-North Dakota border. It did not clearly have the shape of the "baroclinic leaf" nor was a short wave ridge clearly evident. However, this may have been a result of distortions imposed by a strong closed low system centered over eastern Nevada. The cloud development was rapid and did seem to correspond with the passage of a weak and poorly defined short wave ridge that emanated from the closed low system - actually, when this feature was superimposed on the relatively stationary exit region ridge feature of the closed low circulation (see Section 4). At the surface, a weak front was advancing from the west. Though analyzed as a cold front extending from a low pressure center in central Canada to a developing cyclone in southeast Utah, it is evident only as a distinct line of changing wind direction at the surface (SE to NW) with little or no temperature or moisture contrast. The cirrus developed rapidly in both areal and vertical extent in advance of this front. Multiple layers, chaotically arranged, were observed from ~11 -7 km. However, two distinct generating levels were evident at ~10 and ~8 km, respectively. The entire system propagated rapidly to the ESE and passed over the IFO area during the evening.

Initially, the 30 October case closely resembled the 27-28 October and 2 November cases, i.e., an extensive zone of cirrus capping an eastward moving short wave ridge. However, the major portion of the cloud shield was west of the IFO region. Only the "protruding fingers" region of the leading edge was actually sampled. These cirrus bands were composed of convective cirrus cells as shown by Sassen at al. (1988). Cloud tops were just below the tropopause (~11.5 km) and each band showed progressively greater vertical development, i.e., base heights lowering from ~10.5 to below 8 km. On the 30th, two low pressure centers moved toward Wisconsin from Montana, each with a cold front trailing to the southwest. During the evening, these systems merged and intensified in northeast North Dakota. A warm front formed and the entire system rapidly swept to the ENE through Wisconsin producing widespread light precipitation at the surface during the night. By morning, the upper level short wave had moved well to the northeast of the IFO region and the capping cloud shield had evolved from the "leaf" shape to the "comma" shape. The trailing cold fronts joined and stretched from the intensifying system in the southwest US to southeast Canada.

3. COLD FRONT CIRRUS

Cold front cirrus were one of the most extensive cirrus cloud patterns observed during FIRE. Though only observed in the IFO region during the two-day period of **31 October and 1 November**, this pattern could be found somewhere in the northern hemispheric region viewed by GOES on most days during the IFO. Typically, a channel of nearly contiguous cirrus extends from a long wave trough axis northeastward to the preceding ridge (Fig. 3), which is also capped by cirrus much as seen for the traveling short waves (described above) though of much greater horizontal extent. The length of this cloud system is more than 3000 km while the width is ~500 km. The northern edge of the cloud mass is quite distinct while the southern edge is diffuse in appearance. The northern edge corresponds to the axis of the polar (or midlatitude) jet stream which overlies a similarly extensive air mass boundary. The large scale cirrus system is most developed when the long wave is of moderate or greater amplitude. Typically, this occurs when the contrast between the underlying air masses is high and the jet stream is correspondingly strong, which has led to the use of the term "baroclinic zone" cirrus for these situations. Viewed from a large scale perspective, the air mass boundary is a cold front since it tends to progressively sink to the southeast as the long wave slowly propagates eastward. Thus, our choice of the terminology "cold front" cirrus. Distinct banded structures are often evident in the upper level clouds where the bands are aligned roughly parallel to the jet axis as described by Conover (1960) who termed these clouds "jet stream" cirrus. Cirrus formation occurs at multiple levels within the system where a strong tendency for development of a convective layer near the tropopause appears prevalent. Traveling short waves with their associated warm front cirrus ("baroclinic leaf") patterns may move rapidly through the large scale baroclinic channel with the respective upper level cloud patterns being superimposed. These traveling disturbances may trigger development at lower levels and evolve to the "comma cloud" pattern associated with a mature extratropical cyclone by the time they near the long wave ridge axis.

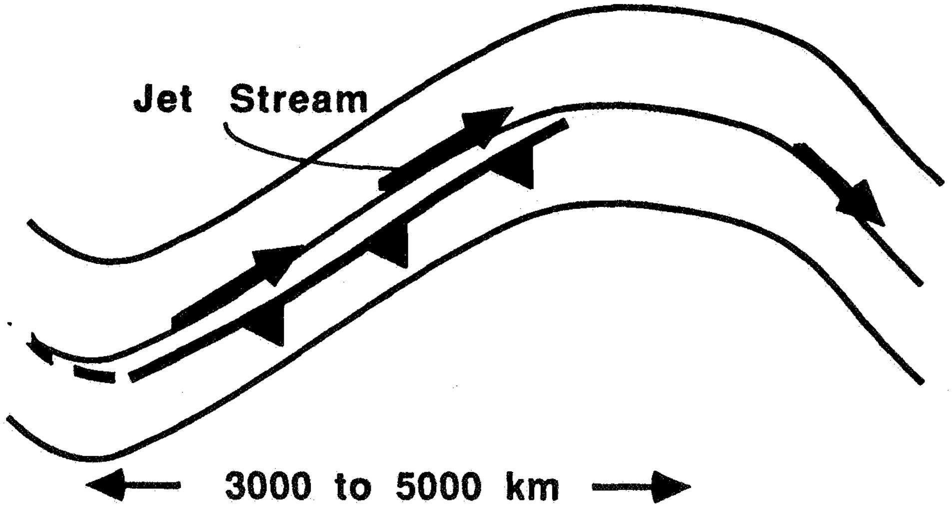

Figure 3: Planetary Wave and Cold Front Cirrus.

On the 31st, the cold front and jet axis were initially to the north of the IFO region. Cirrus, comprising the diffuse southern half of the channel, were observed at the tropopause (~13 km) and at other levels extending down to nearly 7 km. Altostratus were observed between 4 and 7 km with a stratocumulus undercast below. Cloud conditions were broken to patchy at middle and upper levels with banded structure often evident in the high level cirrus. Wind speeds exceeding 50 m/s were encountered in the upper troposphere. The entire system drifted slowly to the east (front moving to the southeast). [Showers along the front restricted aircraft operations on the 1st, however, the surface lidar at Wausau did sample very thin and high cirrus overhanging the distinct northern boundary. On the 2nd, the system had passed to the south and east. However, the ER-2 overflew some of this system early in the day over Illinois.] A remarkable upper level dry zone (parallel and north of the jet axis) - dramatically seen on the GOES water vapor channel imagery - separated this system from the warm front cirrus system which evolved on the 2nd. An important factor in this case which apparently led to appreciable enhancement of cirrus within the large scale baroclinic channel was the disturbance which developed to the east of the intense closed low at the base of the long wave trough in the southwest US. This feature appeared to "pump" moisture into upper levels. In should also be noted that a "baroclinic leaf" rapidly propagated through the channel on the 1st. There was no associated surface cyclone development though showers along the cold front may have been enhanced. The associated short wave was not well-defined in the height pattern, which is often the case when superimposed on such an intense large scale feature.

4. Closed Low Cirrus:

Upper level closed lows generated the most areally extensive cirrus shields observed during the Cirrus IFO. Though lacking the length scale of the linear cold front cirrus systems described above, these systems are equally or more extensive by virtue of their oval shape as depicted schematically in Figure 4. The actual shape assumed by the cirrus cloud shield does appear sensitive to the specific relationship between the closed low flow pattern and the larger scale flow environment, i.e., the whole pattern - clouds and/or flow - may be rotated and/or distorted. Closed lows represent disturbed conditions and tend to be rather stationary for an extended period of time. However, when the pattern does eventually open up, it generally moves rapidly and is quickly absorbed into the larger scale flow. As shown in Figure 4, the cloud mass is located on the eastern (downstream) side of the closed low but may also extend back into the central and southern regions. This was particularly evident when very short waves, evident primarily in the GOES water vapor channel imagery, propagated through the system. High level cirrus (near the tropopause) are typically found capping the stationary exit region ridge and extending downstream from there. These clouds appear to result directly from the upper level structure of the flow much as described for the warm front cirrus. There may not be clouds underlying the northernmost portion of these high cirrus. However, there may be extensive middle level (cirrostratus and altostratus) and low level clouds. East of the center of the closed low circulation aloft, extensive lower level cirrostratus and altostratus cloud decks, low level clouds and precipitation are prevalent over a wide region. In addition to the nimbostratus, there may also be embedded deep convection, i.e., cumulonimbus. Precipitation is generally widespread and of light to moderate intensity.

Often the surface feature associated with the closed low aloft system are not well defined. Typically, there is a relatively stationary surface trough under the axis of the upper level trough feature. In addition, one or more slow moving or stationary fronts may often be found extending to the east under the main mass of vertically developed clouds and precipitation. However, these features are generally indistinct with respect to thermal gradient and wind shift and their analysis often relies more on persistence of previous features than present surface conditions. This is probably a consequence of their stationarity and the cumulative effects of widespread precipitation around the frontal boundary in the absence of any strong frontogenetic forcing from above, i.e., the upper level flow is usually weak. The disturbed region typically exhibits southerly flow over a rather deep layer. North of the stationary weak surface front(s), precipitation is stratiform in character though mesoscale regions of embedded convection may be present. The middle level altostratus and cirrostratus in this region appear to be associated with a frontal upglide process, i.e., the fronts may be better defined aloft than at the surface. To the south, deep convection is more prevalent and apparently injects moisture into middle and upper levels.

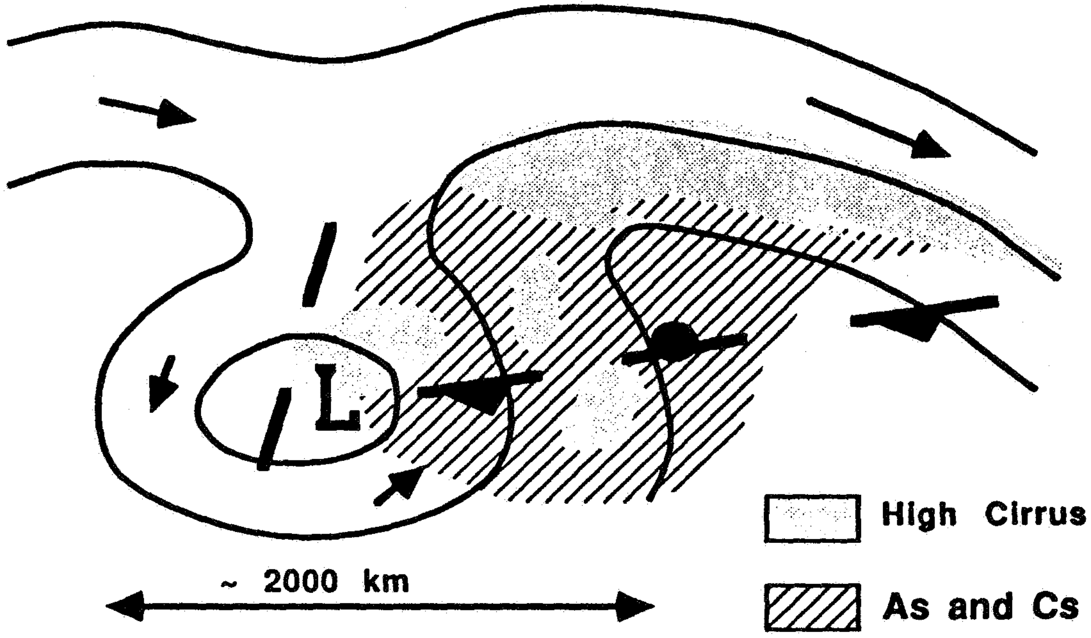

Figure 4: Cloud Pattern for Closed Low Aloft

Two closed low systems were observed during the IFO: the first was the **13 October** case. The second system dominated the synoptic situation over the most of the central US from the Rockies to the Ohio Valley from **21-26 October**. On the 13th, the center of the closed low contours were located in western Iowa. The IFO region was in the center of the disturbed region on the backside of a cyclone centered just north of Lake Huron. A cirrus shield was present to the north with tops generally at about 9 km and bases extending down to about 7 km. As the disturbance drifted toward the northeast, cirrus tops lowered to about 8 km and the layer became more broken. An extensive broken to overcast altostratus deck was present between 3 and 4 km over a low level stratocumulus layer (~1 km). There were scattered showers over the region. This system was short lived as the pattern, which had formed the previous evening, opened up and moved off on the morning of the 14th.

The second system was very extensive and long-lived. Missions were flown on each day except the 23rd when rain precluded aircraft operations. Closed height contours at the level of the jet stream were first observed over Nevada on the 18th. By the 0000 GMT on the 20th, the closed circulation had become largely cutoff from the planetary scale pattern and was centered over Utah. The system drifted slowly to the ENE over northern Colorado into southwest Nebraska over the next 72 hours. Over the next 48 hours, it continued to drift eastward but during this time the pattern opened up and appeared ready to move more rapidly and rejoin the large scale westerly flow to the north. However, during the night of the 24th, the closed circulation was again established and was centered over southwest Iowa and northeast Kansas. The system then slowly drifted eastward toward and into Illinois before the wave pattern finally opened up and moved rapidly off during the night of the 26th.

On the 21st, a long (~1000 km), narrow (~50-100 km) band of high cirrus forming the leading edge of this system was observed by aircraft over central Iowa. We are calling this the "hydrodynamic band" case. This feature was evident in satellite imagery from the 20th to the 22nd and, since our attention was drawn to it, we have observed that it is a common feature of situations like this. We hope to present results of a detailed analysis of this case in the near future. The band was composed of cirrostratus with embedded convection. Cloud top was at about 12 km and the base generally was above 10.5 km. Distinct waves were observed at cloud top (~0.5 km amplitude) in the ER-2 lidar images for one of the overpasses. Distinct thin cirrostratus layers were often found near cloud top.

On the 22nd, a high cirrostratus deck was observed in the vicinity of the exit region ridge. Cirrus were present in a layer from near the tropopause at about 12.5 km (thin layers) down to below 7 km. Generation was apparent at a number of levels with embedded uncinus cells whose tops were variously at ~12 km, 10.5 km and 8.5-10 km. A layer of convective clouds with bases at about 6 km (altostratus/altocumulus/cirrostratus) was below. This middle level cloud deck developed with some convective cells apparently reaching to the 10 km level. It is our feeling that the middle level cloud layer resulted from a frontal upglide process, i.e., southerly flow over an elevated frontal surface sloping up from the south - an east-west stationary front was analyzed through northern Illinois the previous evening but had been dropped from the analysis by the 22nd. However, we believe that the upper level cirrus resulted independently from the upper level flow features. In particular, there is qualitative evidence that differential (in the vertical) horizontal temperature advection maintained the instability reflected in the convective character of the high cirrus in this case (We hope to be able to quantify this). On the 23rd, the situation in Wisconsin became quite disturbed with widespread precipitation which precluded flight operations. On the 24th, a very similar situation (to the 22nd) occurred. However, the cirrus were generally less dense and less convective. Low level clouds generated light showers over the region. Middle level clouds were mostly absent, except for a scattered layer at about 4 km.

On the 25th and 26th, widespread precipitation over the region greatly restricted operations. However, missions were flown to the northern part of the IFO area where conditions were less severe. These cases were characterized by a high level cirrostratus layer between ~10 and 11 km, a secondary patchy layer between ~8.5 and 9.5 km, and a well-developed middle level cloud layer between about 5.5 km and 8 km. By the 26th, the IFO region was under the entrance ridge region of the closed low. This area and the center of the closed low had each become cloud filled as was the entire area to the east.