SHORE-PARALLEL SNOW BANDS OVER NORTHWEST INDIANA AND SOUTHWEST LOWER MICHIGAN DURING A MAJOR ARCTIC OUTBREAK

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Abstract

The paper investigates three cases of local heavy snow near the southeast part of Lake Michigan during a very strong Arctic outbreak in December, 1989. It in part uses the study by Mecikalski et al. (1989) to help understand the cases in terms of shore-parallel snow bands. It attempts to show how temperature, vertical temperature profiles, pressure, and wind patterns contributed to the development or caused the breakdown of snow bands. It also suggests that the event that yielded the greatest snow accumulation may have been a case of evolution from wind-parallel snow into shore-parallel snow, and it attempts to explain why heavy snow fell during both phases of the event.

1. Introduction

Lake effect snows that form over the Great Lakes occur when cold Arctic air moves over the relatively warm water of the Lakes. These types of snow storms, which occur during the late fall and winter, are often characterized by (1) wind-parallel cloud streets, or (2) shore-parallel snow bands (Mecikalski et al., 1989, hereafter referred to as MEB; McVehil and Peace, 1965). Wind-parallel cloud streets occur when strong north or northwest winds advect cold air across the Great Lakes. The surface pressure gradients are often tight. In contrast, according to MEB, shore-parallel snow bands generally occur under tranquil large-scale settings where surface pressure gradients are relaxed.

During the nine day period from 15–23 December 1989, three apparent shore-parallel lake-effect snow events occurred across the southern part of Lake Michigan and generated varying amounts of snow over extreme southwest lower Michigan and/or extreme northwest Indiana. Figure 1 is a regional map of the area of interest. The first event (Case 1) occurred from 2100 UTC 15 December to 1200 UTC 16 December. Between 25 and 30 inches of snow fell from just west of South Bend (SBN) to just west of Laporte, with the bulk of the snow falling from around 2300 to 1000 UTC. The second event (Case 2) occurred between 1400 and 2000 UTC 19 December. Between eight and 12 inches of snow fell from Laporte to Michigan City (MGC), with the bulk of the snow falling from around 1500 to 1900 UTC. The third event (Case 3) began around 1600 UTC 22 December and ended near 1500 UTC 23 December. Between 12 and 16 inches of snow fell from just east of Laporte to MGC, with most of the snow falling from around 2000 to 0800 UTC.

Synoptic scale waves and their associated dynamics were not responsible for the initiation of at least two of the three events (Cases 2 and 3). Rothrock (1969) noted that many Lake Michigan snow events occur without positive vorticity advection (PVA) or warm air advection to supply mid tropospheric forcing. In each of the three cases in this study there was no detectable PVA at 500 mb. Moreover, the 700-mb trough was east of the site of concern; there were no 850-mb or surface lows south or west of the site; and there was no significant wrap around moisture.

Through the first part of Case 1, there appears to have been a surface trough rotating westward through Lake Michigan from a low pressure system to the east. It also appears that the 850-mb flow, although not optimal, was conducive to the formation of wind-parallel cloud streets at the beginning of Case 1.

Radar data, recorded on 16 mm film at the National Weather Service Office at SBN (WSO SBN) during at least part of each event and viewed via dial-up at the National Weather Service Forecast Office at Indianapolis (WSFO IND), depicted patterns that more closely resembled a shore-parallel snow band rather than wind-parallel cloud streets. Figure 1a shows a sequence of radar reflectivity data from WSO SBN of the 15 December (Case 1) snow band over southwest lower Michigan and extreme north central Indiana. Other radar sequences (not shown) showed little or no movement of the snow band over the course of each case. Forecasters on duty at WSFO IND noted the Case 1 snow band was stationary for "eight hours or more." This study focuses on the conditions under which these three heavy snowfall events developed and were sustained.

2. Review of Previous Studies

A study by Passarelli and Braham (1981) noted the importance of a shallow land breeze to the formation of shore-parallel snow bands when it developed in opposition to a weak synoptic scale flow with an onshore component. An additional study by Schoenburger (1986) showed that strong radiational cooling over interior lower Michigan resulted in the formation of strong temperature gradients. The strong temperature gradients forced a "land breeze front," along with a localized convergence zone, to develop. This resulted in the formation of shore-parallel snow bands along the eastern shore of Lake Michigan.

MEB concluded that shore-parallel snow bands develop when (1) the difference between the lake surface temperature and the land temperature is greater than or equal to 10°C, (2) the difference between the lake surface temperature and the 850-mb temperature is greater than or equal to 13°C, and (3) the flow over Lake Michigan is weak (surface winds usually less than or equal to 10 kt) due to a relaxed synoptic scale

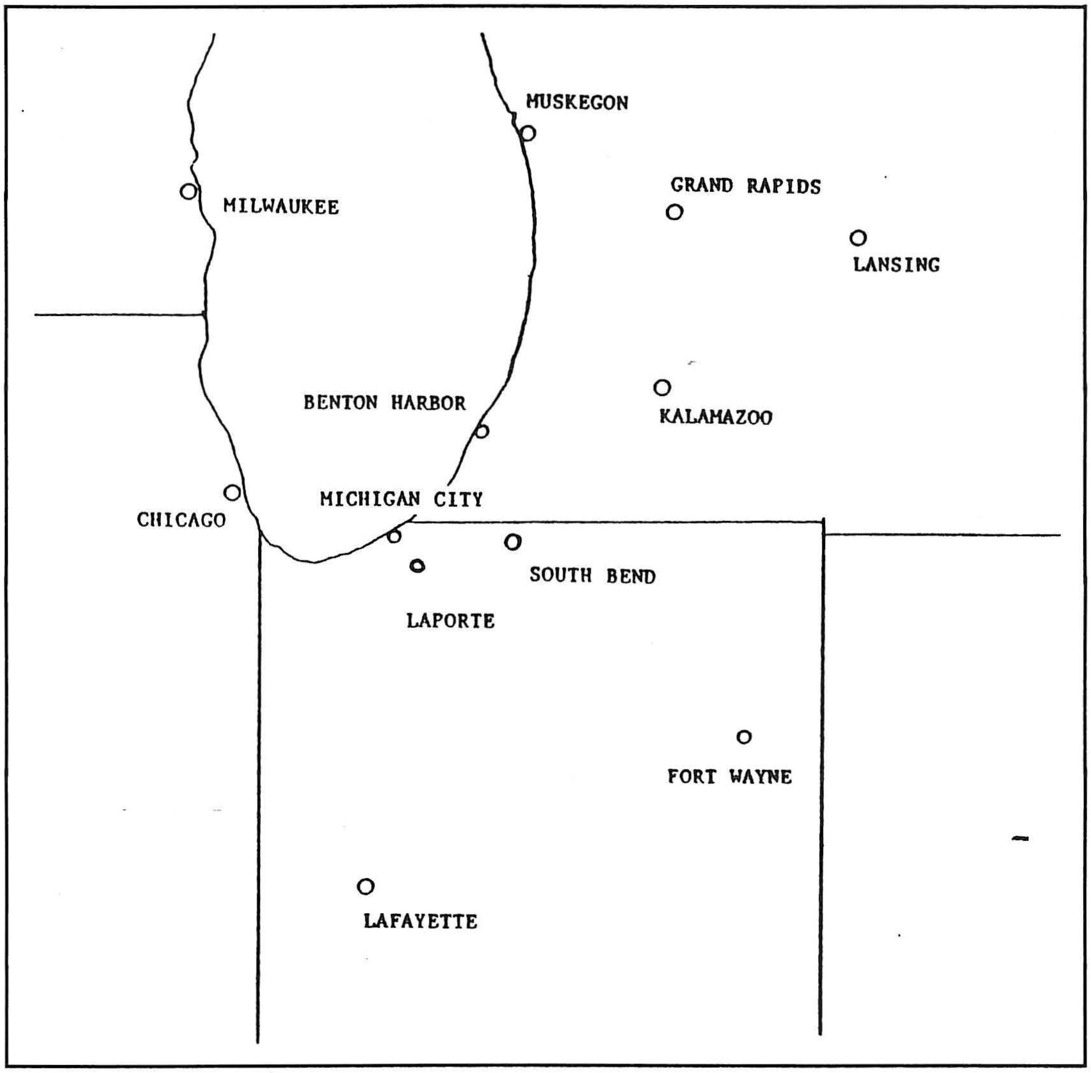

Fig. 1. Regional map of the area of interest.

pressure gradient. Rothrock (1969) first noted the 13°C temperature difference between the lake surface and 850 mb as a criterion for lake snow development.

According to MEB, the three criteria occur when an Arctic high pressure system settles near Lake Superior or when low pressure moves northeast from the Ohio River Valley. They also note an alternate favorable pressure pattern, namely a tighter east/west pressure gradient, as long as the gradient results in a northerly flow over Lake Michigan that is confluent. It may be that resultant snow bands, however, would be wind-parallel bands that were enhanced by the confluent flow.

3. December 1989 Cases

A. Temperature

On 15 December 1989, an outbreak of frigid Arctic air overran the Great Lakes and northern Ohio Valley Regions. From 15 December through 24 December, maximum temperatures reached −8°C at best and nighttime temperatures dropped below −18°C. This outbreak established the MEB temperature conditions necessary for the development of shore-parallel snow bands as far south as the southern tip of Lake Michigan throughout almost the entire period.

As previously stated, there were three apparent shore-parallel snow band events during the period of this study. The first event (Case 1) occurred from 2100 UTC 15 December to 1200 UTC 16 December. Between 25 and 30 inches of snow fell from just west of SBN to just west of Laporte in northwest Indiana, with snow falling at the rate of about two inches per hour between 2300 and 1000 UTC according to estimates from the Indiana State Police.

The second event (Case 2) occurred between 1400 and 2000 UTC 19 December. Between eight and 12 inches of snow fell from Laporte to MGC, with the bulk of the snow falling from around 1500 to 1900 UTC. The Indiana Toll Road Commission reported to WSFO IND that snow fell at the rate of one to two inches per hour along Interstate 80 just east of MGC during the peak period.

The third event (Case 3) began around 1600 UTC 22 December and ended near 1500 UTC 23 December. Between 12 and 16 inches of snow fell from just east of Laporte to MGC, with generally from 10 to 12 inches of snow falling from around 2000 to 0800 UTC according to sources contacted by WSO SBN.

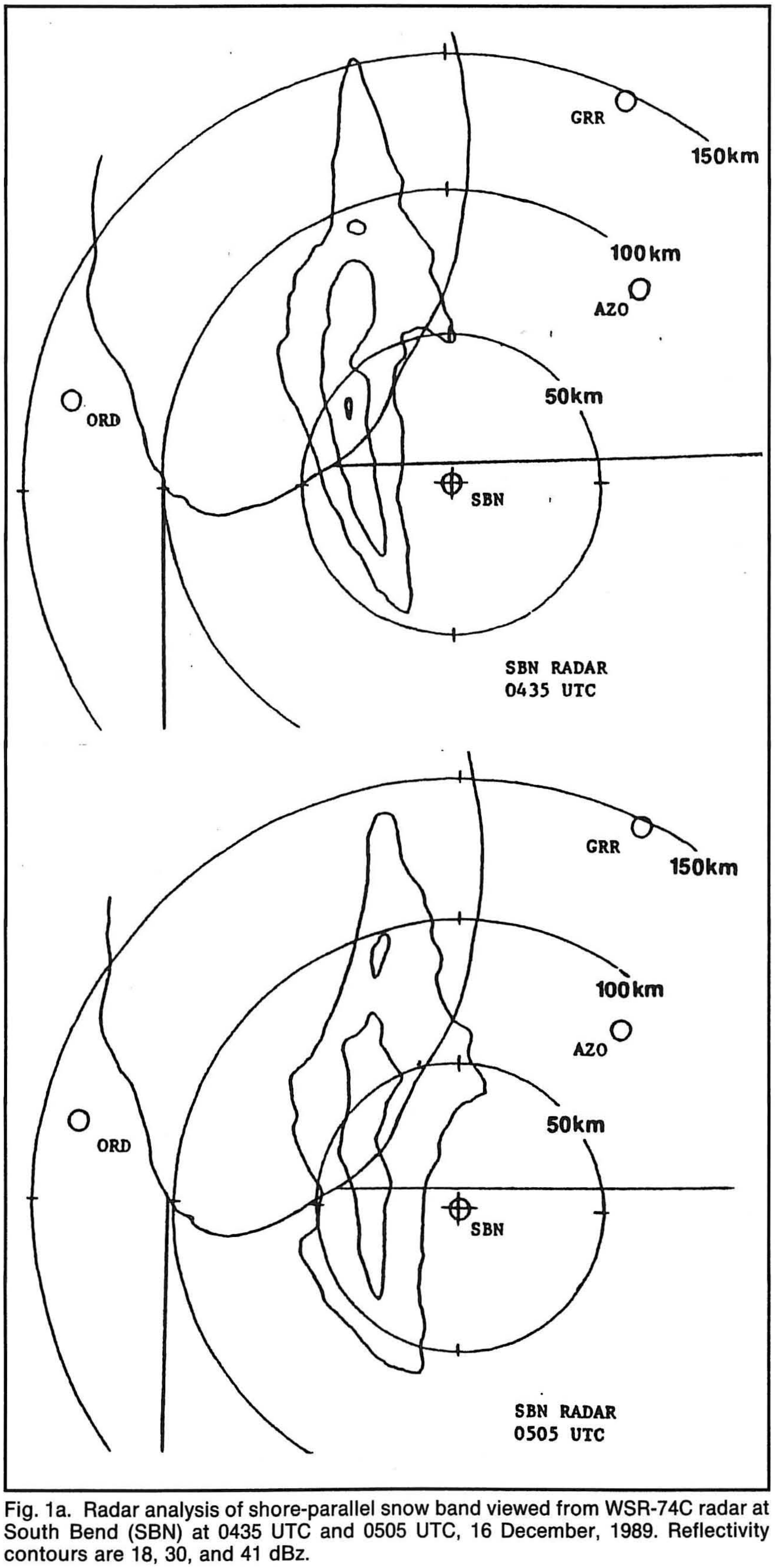

Fig. 1a. Radar analysis of shore-parallel snow band viewed from WSR-74C radar at South Bend (SBN) at 0435 UTC and 0505 UTC, 16 December, 1989. Reflectivity contours are 18, 30, and 41 dBz.

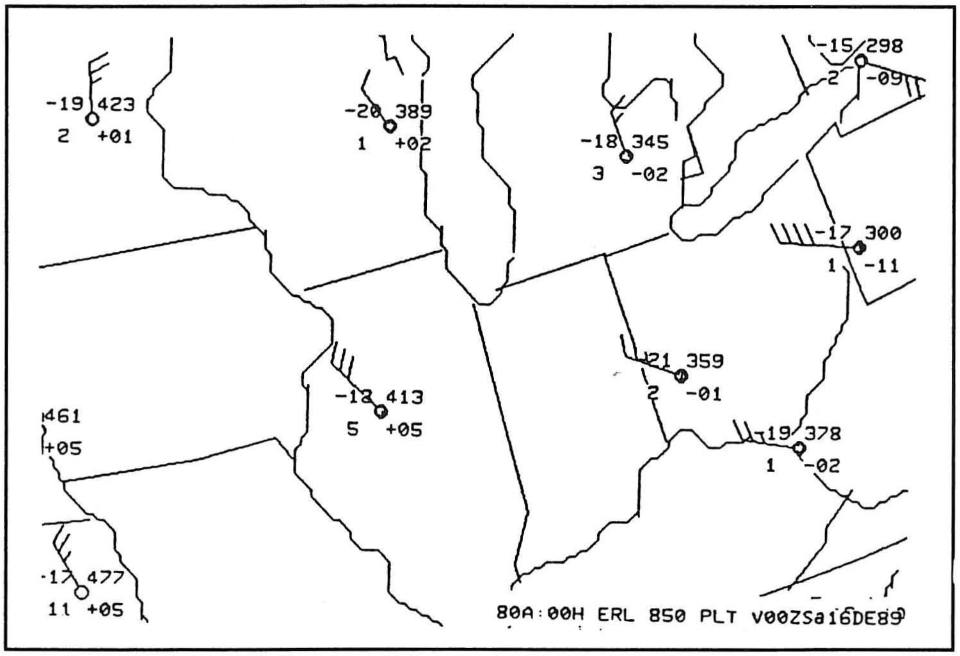

Fig. 2. NMC 850-mb plot, 0000 UTC 16 December, 1989.

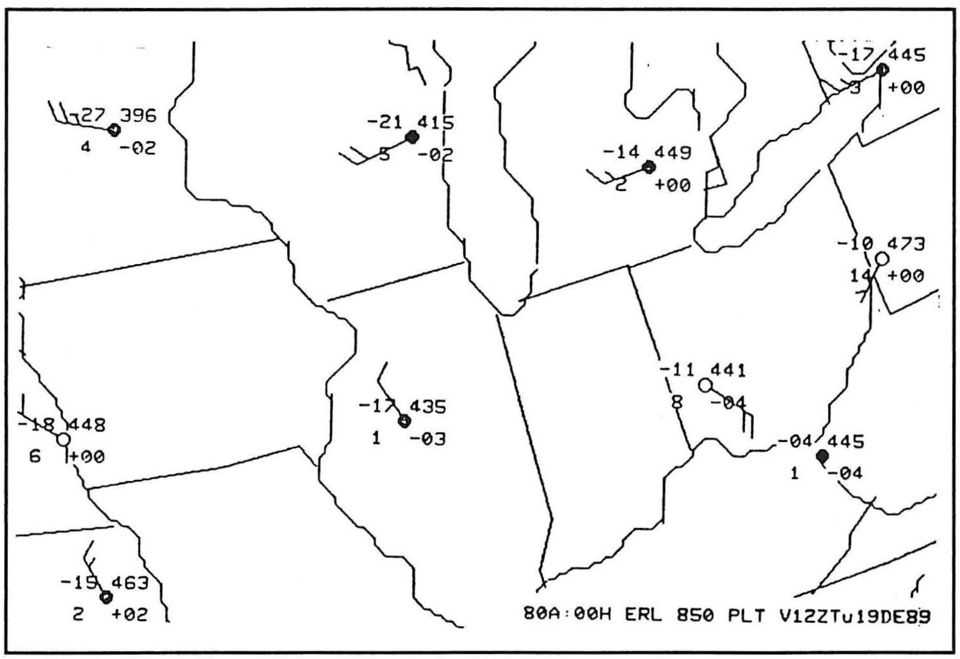

Fig. 3. Same as Figure 2 except at 1200 UTC 19 December, 1989.

Figure 2 shows temperatures at 850 mb near the beginning of the period of maximum snowfall during Case 1. Figure 3 shows 850-mb temperatures two hours prior to the beginning of Case 2. It is chosen because it was the most representative 850 mb plot obtainable. Figure 4 shows 850-mb temperatures during the period of maximum snowfall in Case 3. Given the Lake Michigan surface water temperature was no lower than between 0° and 1°C, an 850-mb temperature less than or equal to −13°C would satisfy one of MEB's temperature conditions. 850-mb temperatures for all three events were below −13°C.

Figures 5 and 6 are surface plots from the period of maximum snowfall during Case 1. Figure 5 is valid around the beginning of that period; Figure 6 is valid six hours later and about five hours prior to the end of that period. Figure 7 is a surface plot from the period of maximum snowfall during Case 2. It is valid about one hour into that period. Figures 8 through 10 are surface plots from the period of maximum snowfall during Case 3. Figure 8 coincides with the time that period began; Figure 9 coincides with a time just past the halfway point; Figure 10 coincides with the time that period ended.

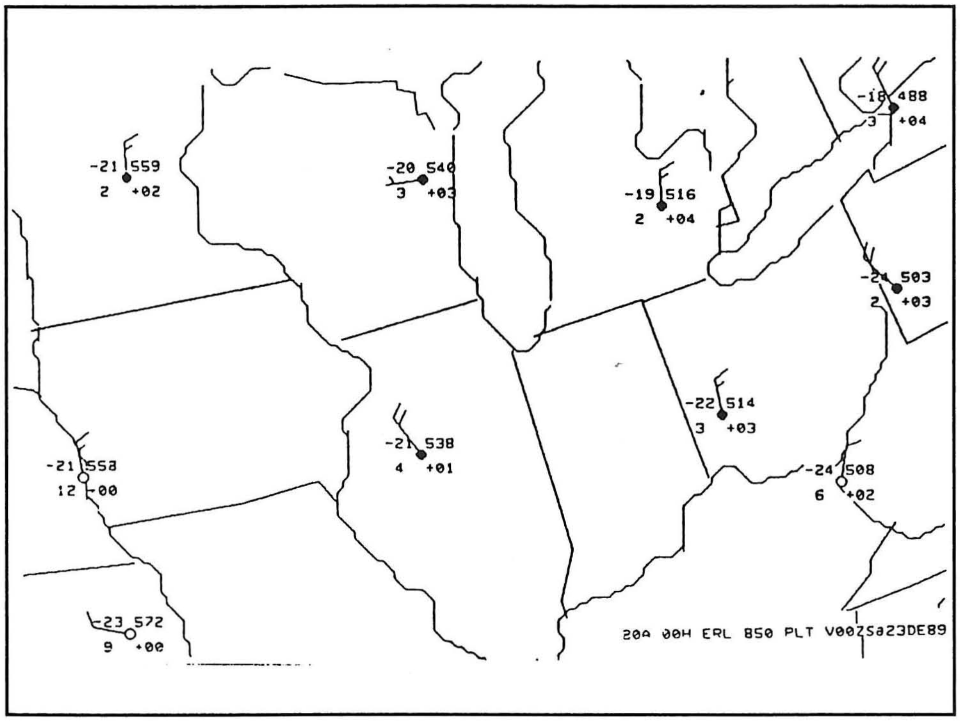

Fig. 4. Same as Figure 2 except at 0000 UTC 23 December, 1989.

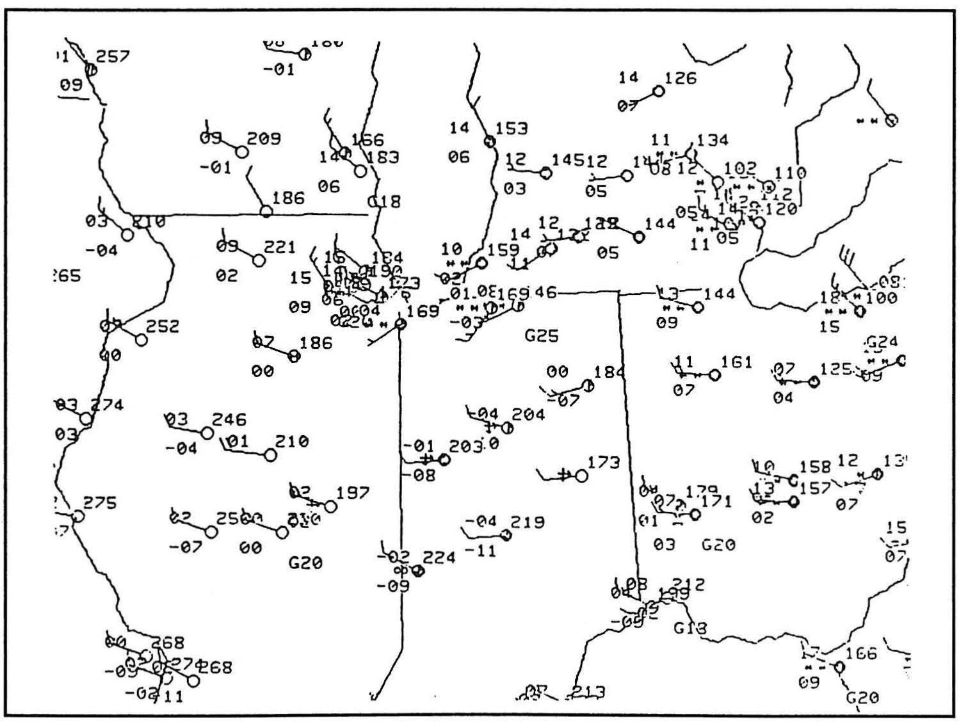

Fig. 5. Surface plot, 2300 UTC 15 December, 1989.

Given the Lake Michigan surface water temperature was no lower than between 0° and 1°C, surface temperatures of 15°F or below would satisfy MEBs surface temperature criterion. Figures 5 and 6 indicate the surface temperatures during Case 1 met the criterion essentially everywhere around southern and central Lake Michigan when the heaviest snow was beginning to fall, and everywhere around the Lake at 0500 UTC 16 December, about five hours before the heaviest snow ended. Figure 7 indicates the surface temperatures during Case 2 met the criterion mainly west of Lake Michigan during the fairly brief period of heavier snowfall. Figures 8 through 10 indicate the surface temperatures during

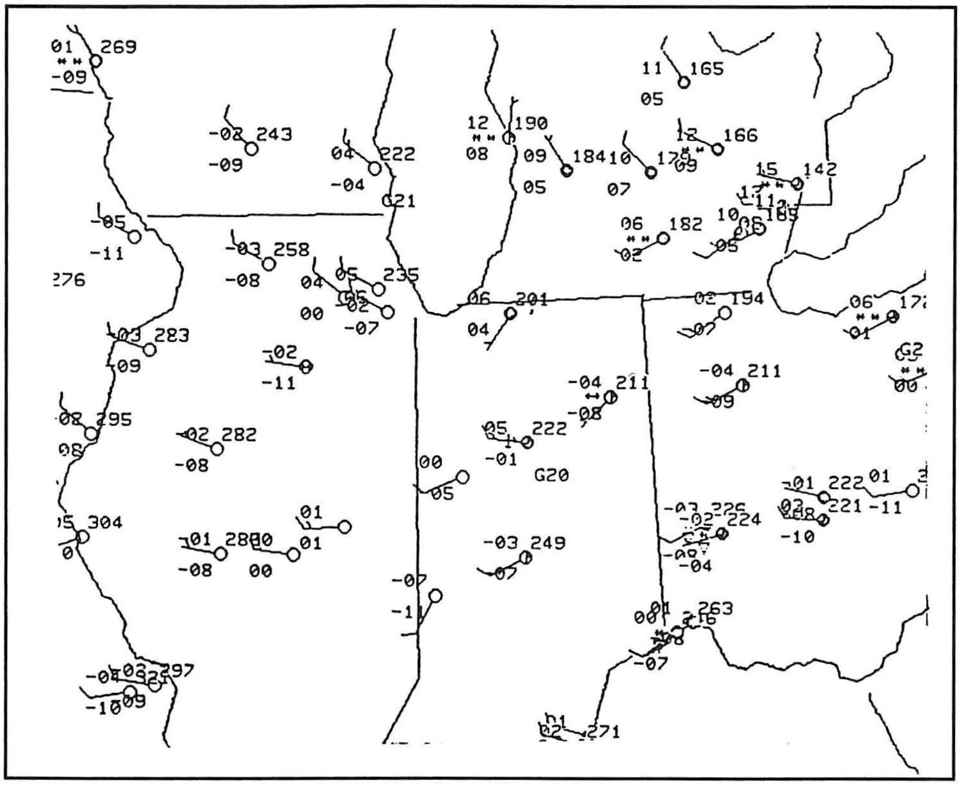

Fig. 6. Surface plot, 0500 UTC 16 December, 1989.

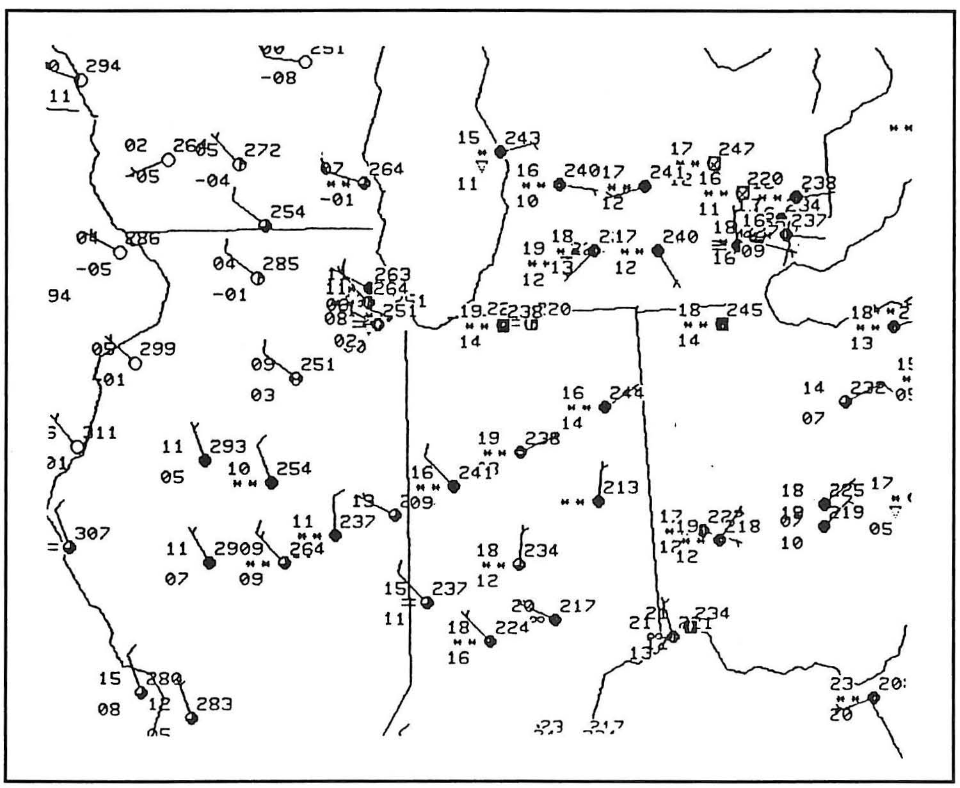

Fig. 7. Surface plot, 1600 UTC 19 December, 1989.

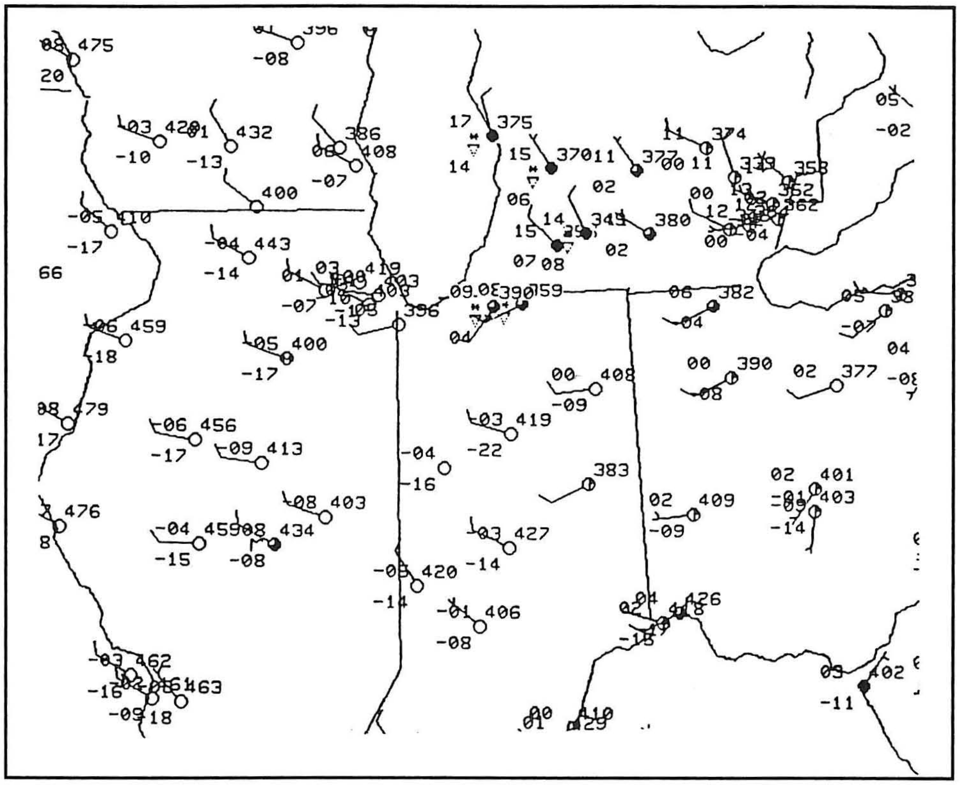

Fig. 8. Surface plot, 2000 UTC 22 December, 1989.

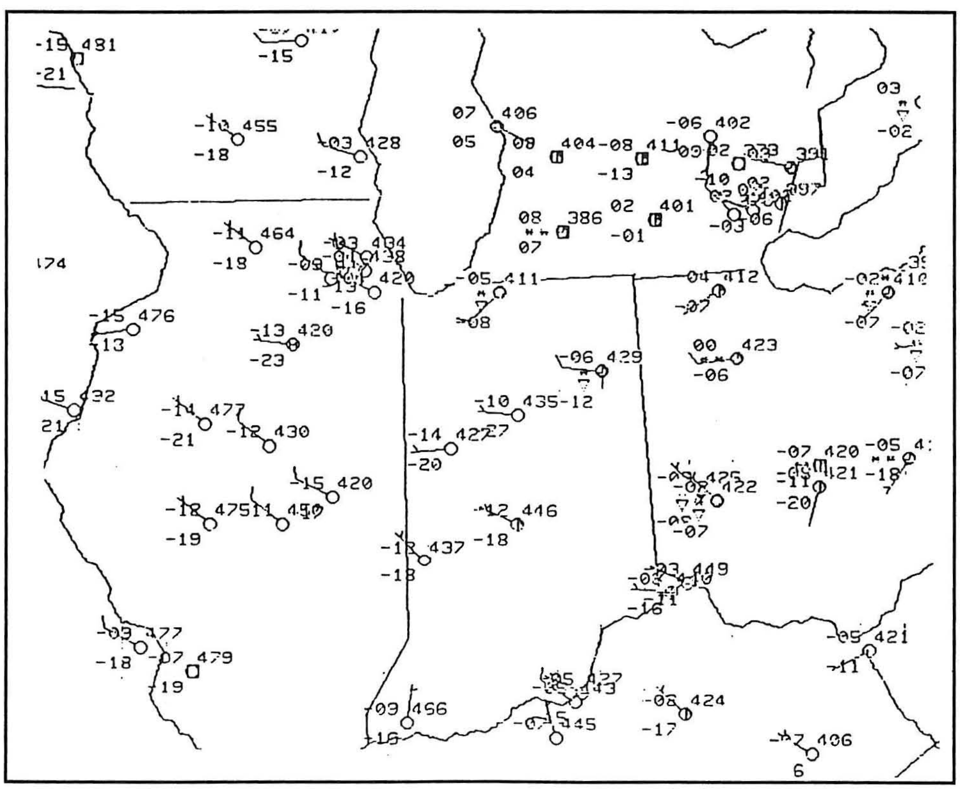

Fig. 9. Surface plot, 0300 UTC 23 December, 1989.

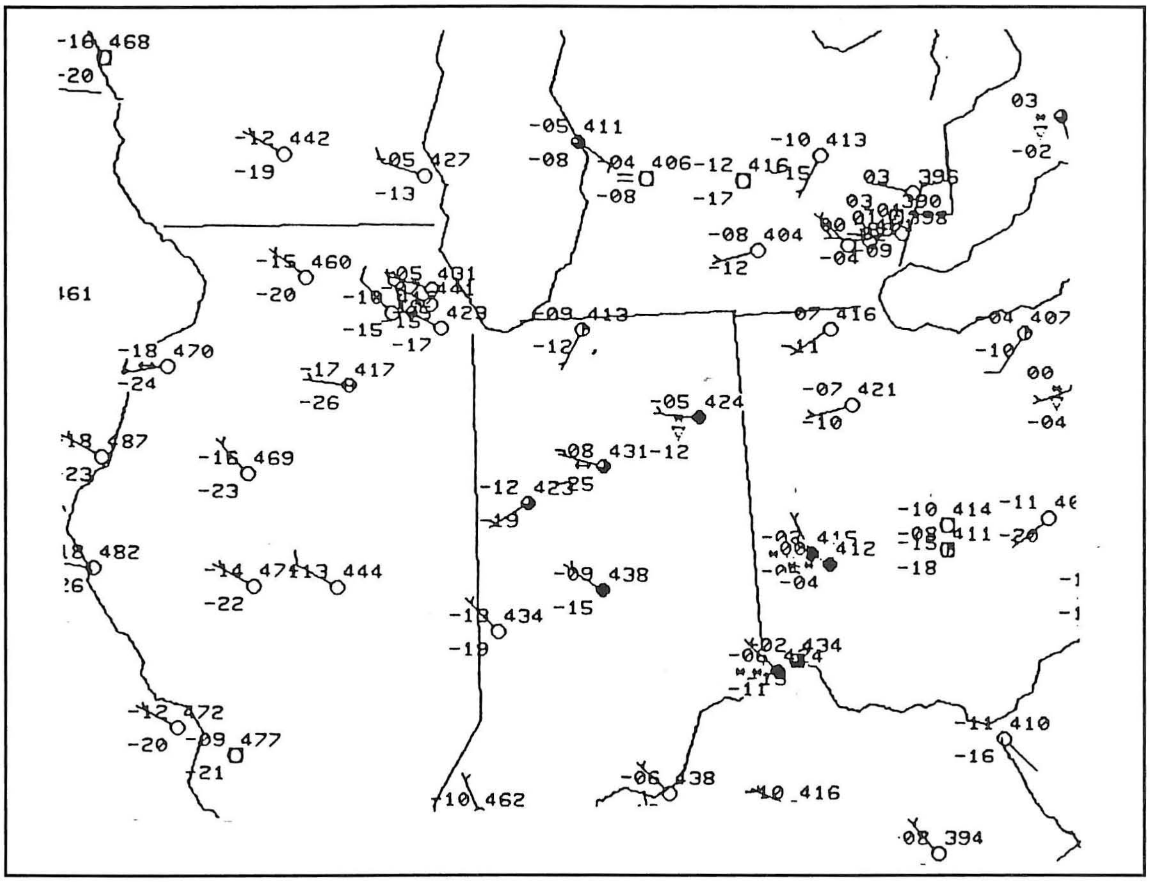

Fig. 10. Surface plot, 0800 UTC 23 December, 1989.

Case 3 met the criterion essentially everywhere around the Lake when the heaviest snow was beginning to fall and everywhere around the Lake during that period.

B. Winds and Pressure Pattern

MEB stated that shore-parallel snow bands develop under relaxed pressure gradients resulting in winds usually less than 10 kt. Figures 5 and 6 show that the winds from Case 1 only marginally met the conditions from MEB. Surface winds west of Lake Michigan generally were from 10 to 15 kt throughout much of the period, and winds south of Lake Michigan were above 10 kt at the beginning of the period. Winds at Milwaukee (MKE) and Muskegon (MKG) show that confluence over southern Lake Michigan increased between 2300 UTC 15 December and 0500 UTC 16 December. At 2300 UTC, winds at both locations were from the northwest or north northwest at between 10 and 15 kt; at 0500 UTC winds at MKE were from the northwest at 15 kt while winds at MKG had gone around to the north northeast at five kt. Also, the 850-mb wind direction (Fig. 2) was more suggestive of wind-parallel snow bands than shore-parallel bands, although the speed (approximately 15 to 20 kt over Lake Michigan) was somewhat lower than typical during wind-parallel snow band events.

Figure 7 shows that winds from Case 2 met the prerequisite conditions well, as they were light and confluent. Winds at MKE at 1600 UTC 19 December were from the west northwest at 10 kt, while winds at MKG were from the east northeast at five kt. Figures 8 through 10 show that winds from Case 3 also met the prerequisite conditions well, as they were light throughout the event. Figures 8 and 9 indicate that confluence developed over the Lake between 2000 UTC 22 December and 0300 UTC 23 December. Winds at MKG shifted from north northwest at around 10 kt to east southeast at around five kt while winds at MKE remained from the northwest at around 10 kt.

Figure 11 is the NGM initial sea level pressure field with 1000 to 500-mb thickness superimposed for 0000 UTC on 16 December (Case 1). Heavy snow had been falling for about one hour at that time over northwest Indiana. It is apparent from Figure 11 that a significant pressure gradient was present. The low pressure system in central Pennsylvania was moving northeast, and high pressure had dropped well into the central Great Plains to produce the significant pressure gradient. As noted previously, the surface trough over the southern tip of Lake Michigan was rotating around the low toward the south (Fig. 11). Both numerical and graphical initial analyses (not shown), however, depicted negative vertical velocities (at 700 mb) and a pattern consistent with large scale drying.

Figure 5, the surface plot from 2300 UTC 15 December, only one hour before the time of Figure 11 and about the time heavy snow began, shows little or no confluence along the southern part of the Lake. Specifically, Figure 5 shows little or no confluence between MKG and MKE, as the MKG wind

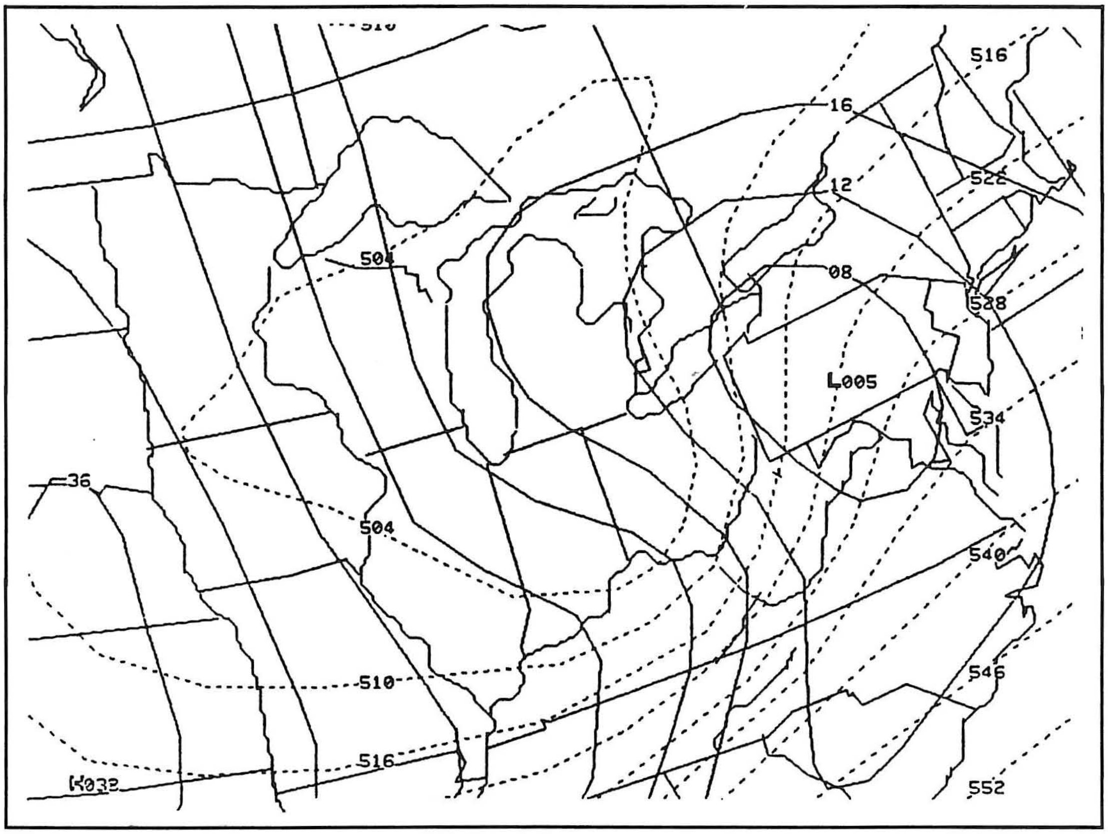

Fig. 11. NGM 00 h MSL pressure/1000–500-mb thickness valid 0000 UTC 16 December, 1989.

has only a little less of a westerly component than the MKE wind.

Figure 5 also indicates a trough at the southern tip of Lake Michigan. Winds along the western bank were from the northwest, while winds along the southeastern bank were from the southwest. A streamline drawn through the wind field near the southern tip of Lake Michigan clearly would depict a trough pattern. This likely was a "thermal trough" induced by the temperature contrast between the lake and the unusually cold ambient air. Because it was so cold throughout the period of this study, such a phenomenon would have been relatively persistent. Indeed, the trough in the wind field at the southern tip of the Lake can be found in each of the surface plots (Figs. 5 through 10) from each of the events.

Figure 12 is an NGM six hour prognosis of the sea level pressure field with a 1000 to 500-mb thickness prognosis superimposed. It was chosen since its valid time, 1800 UTC 19 December, falls within the period of maximum snowfall of Case 2. It shows a pressure gradient that is more relaxed than that of Case 1, and as mentioned previously, wind speeds from Case 2 were light. A weak low was north of Lake Michigan, while another weak low was along a cold front in southern Ohio. High pressure was dropping into the eastern Great Plains, and surface flow was anticyclonic over Lake Michigan in contrast to Case 1.

Figure 13 is the NGM initial sea level pressure field with 1000 to 500-mb thickness superimposed. It is valid for 0000 UTC 23 December (during the period of maximum snowfall of Case 3). One can see that the pressure gradient over Lake Michigan is about the same as it was in Case 2 (Fig. 12); low pressure had moved into the Canadian Maritimes, and high pressure had dropped into the central Great Plains. This pressure pattern is most similar to those described by MEB as a prerequisite to the development of shore-parallel snow bands. Figures 8 and 9 show that confluence increased between opposite shores of southern Lake Michigan between 2000 and 0300 UTC; Figures 9 and 10 show that confluence maintained itself until at least 0800 UTC.

C. Sounding Data

One factor MEB did not consider was the effect of the ambient vertical temperature profile above 850 mb on convection. Recall MEB's condition of a 13°C minimum temperature difference between Lake Michigan's surface and the 850-mb level. Given that condition, a parcel raised to 850 mb, especially a parcel ascending moist adiabatically for part of that distance, will remain positively buoyant. However, if the ambient temperature profile was such that a parcel did not remain positively buoyant above 850 mb, then convection above 850 mb would be inhibited. Unfortunately, soundings were available only for the days of Cases 1 and 2; no soundings were available for Case 3. Figure 13a depicts the soundings from Green Bay, Wisconsin (GRB, about five miles west of the western shore of Lake Michigan) and from Flint, Michigan (FNT, about 125 miles east of the eastern shore of Lake Michigan) at 0000 UTC 16 December. This is three hours after the beginning of Case 1. Figure 13b depicts the

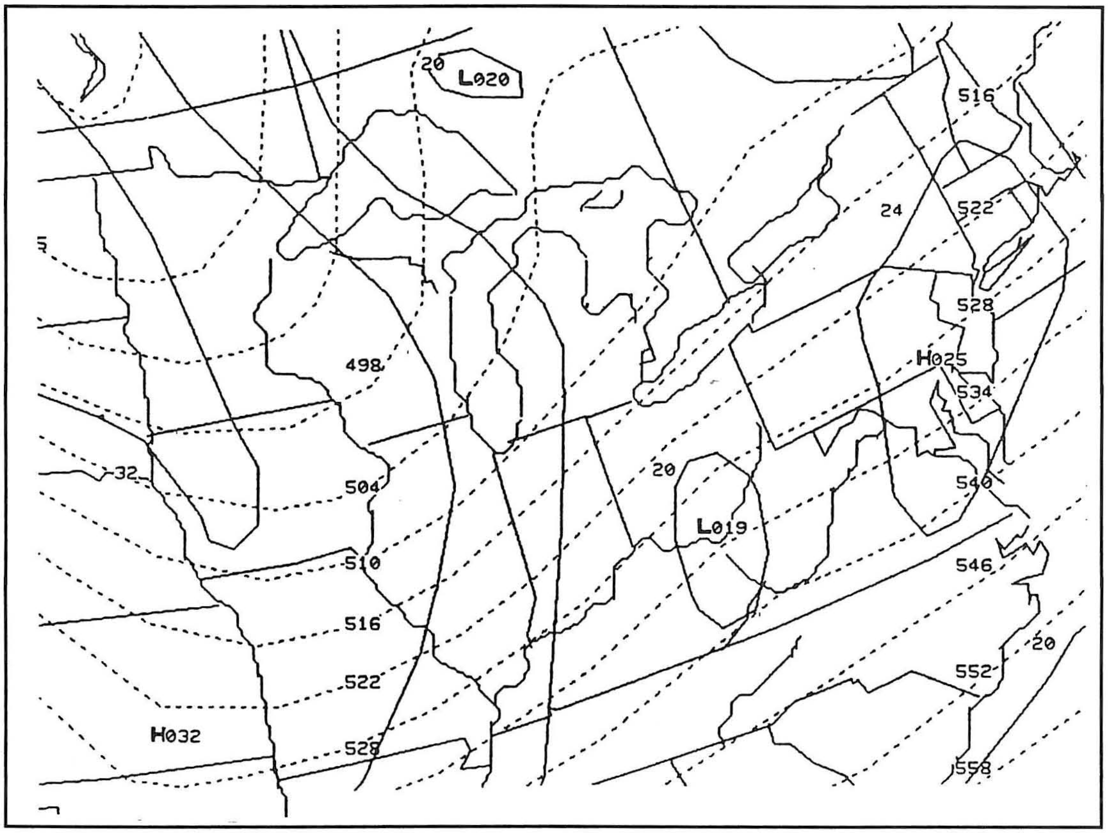

Fig. 12. NGM 06 h MSL pressure/1000–500-mb thickness prog valid 1800 UTC 19 December, 1989.

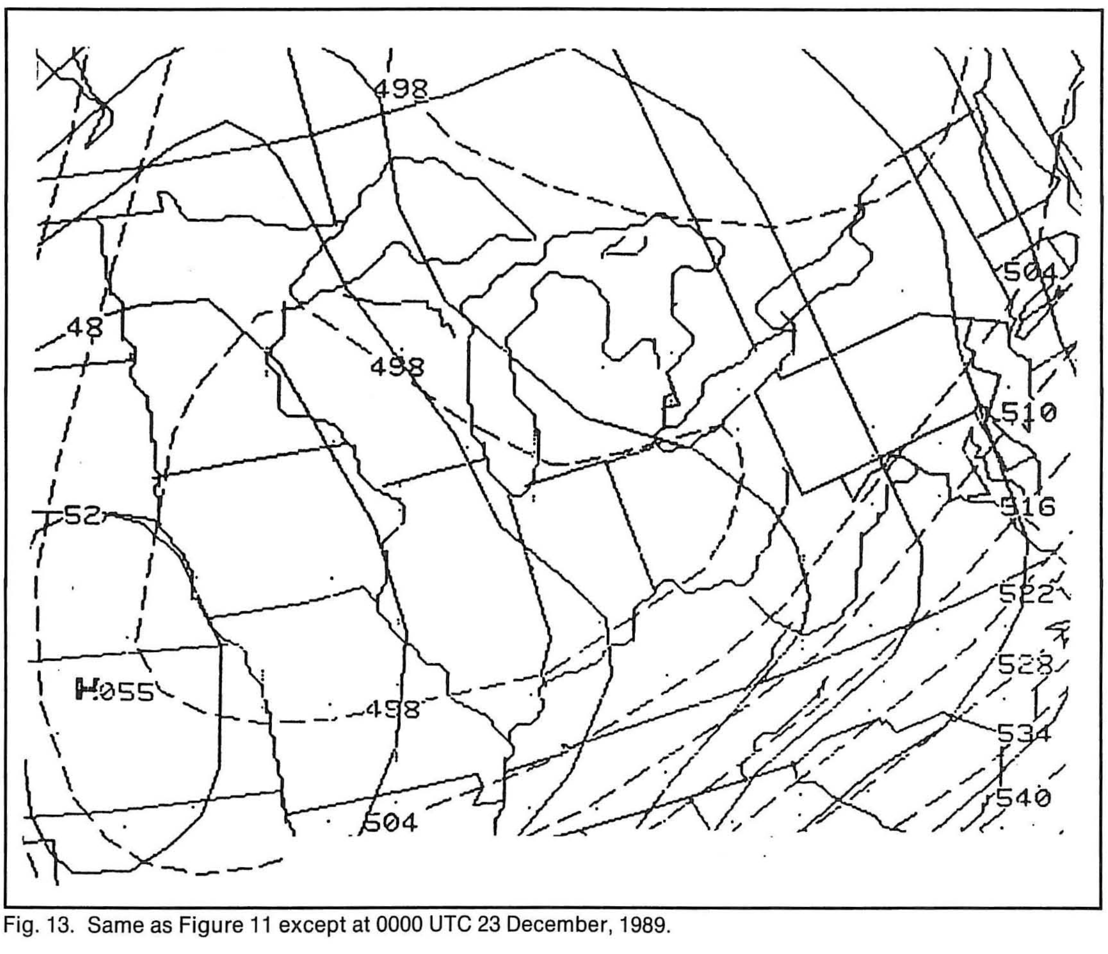

Fig. 13. Same as Figure 11 except at 0000 UTC 23 December, 1989.

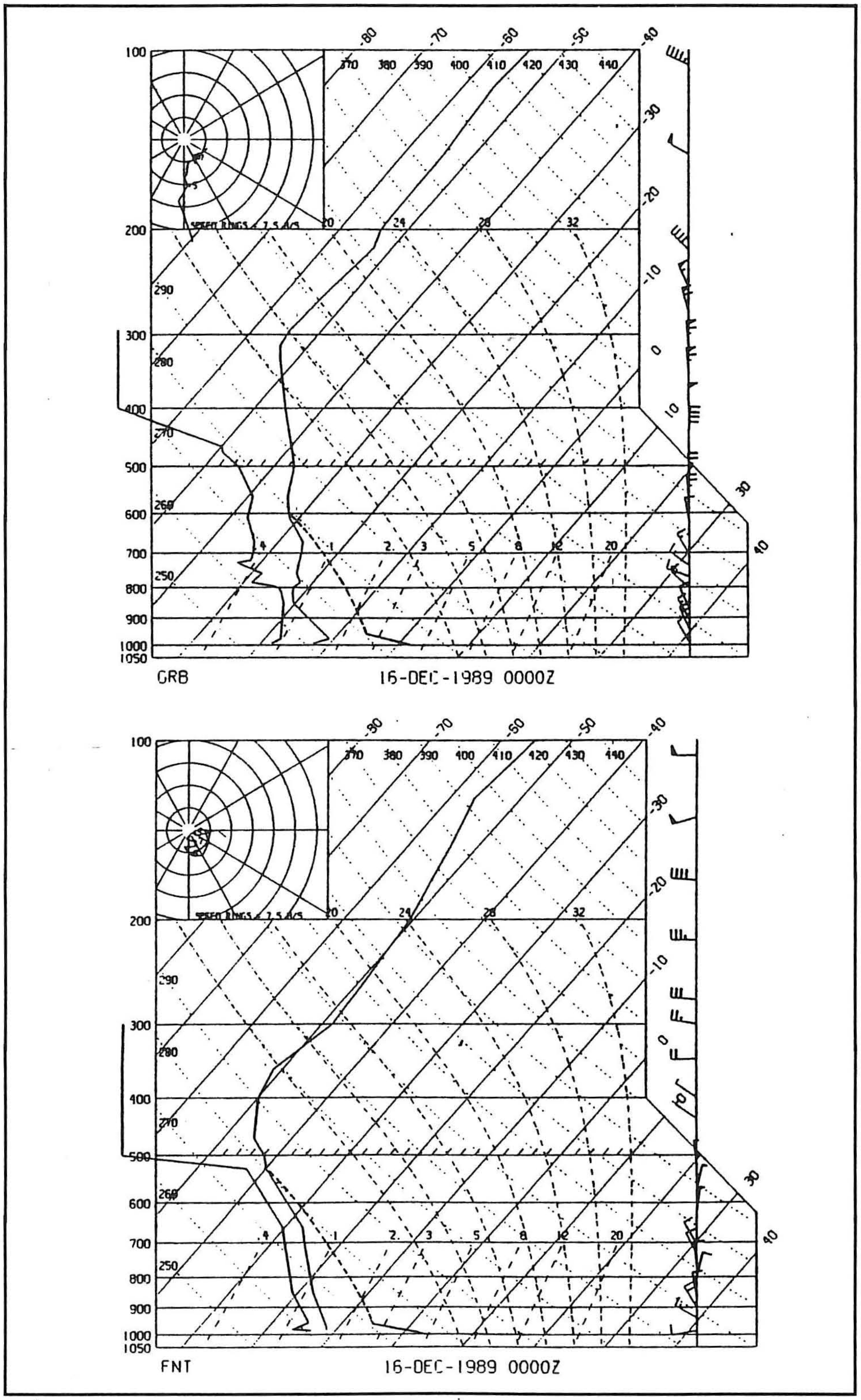

Fig. 13a. Green Bay (GRB) and Flint (FNT) soundings and hodographs at 0000 UTC 16 December, 1989. Units of wind barbs on Skew T Log P are in knots and hodograph in m/sec.

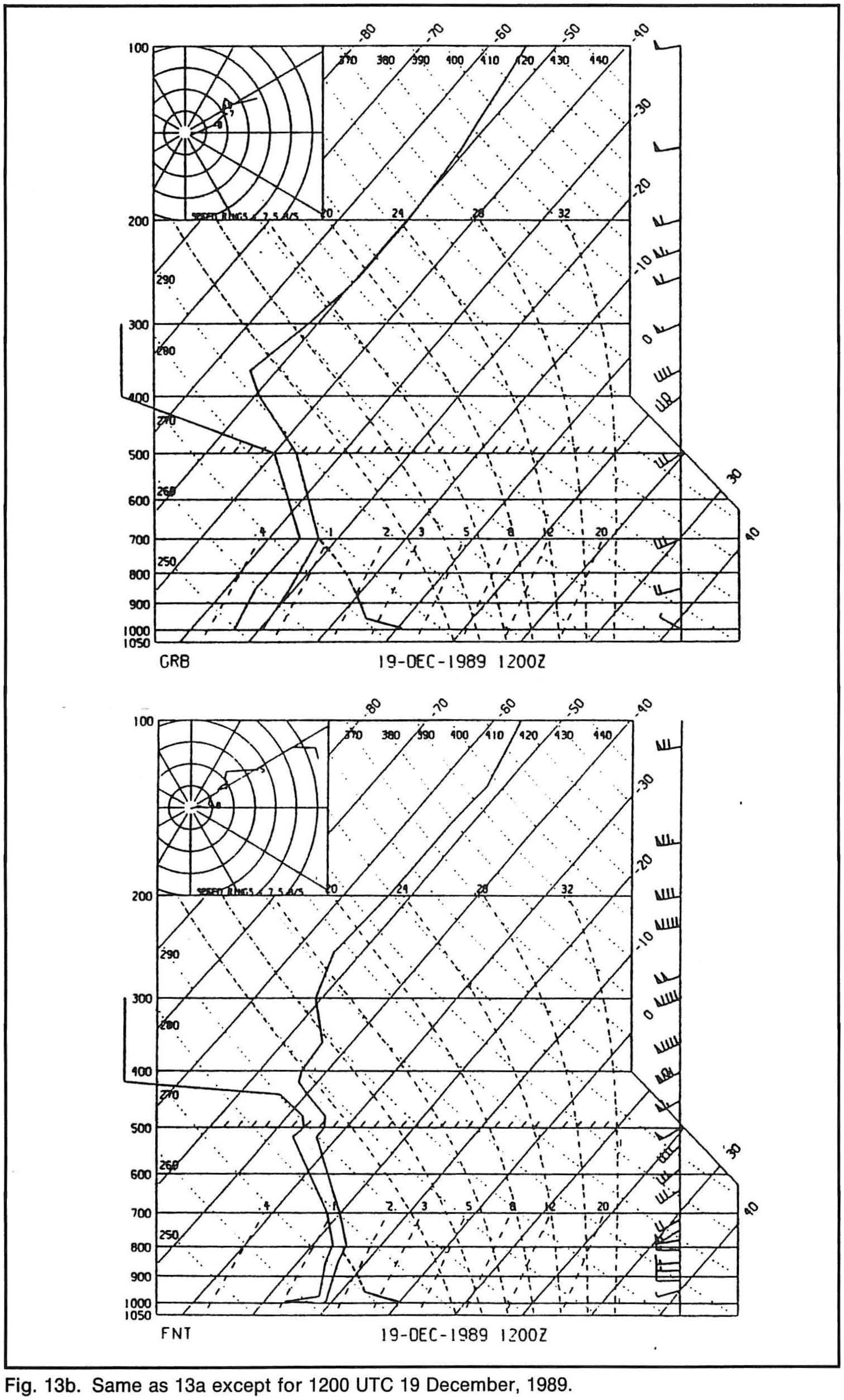

Fig. 13b. Same as 13a except for 1200 UTC 19 December, 1989.

soundings from GRB and FNT at 1200 UTC 19 December, only a few hours before the beginning of Case 2.

Figure 13b depicts soundings that were at practically no level convectively unstable. There was a convectively unstable layer between 500 mb and 400 mb at FNT, but there was no indication that had any practical effect.

No temperature or dewpoint data were available over the Lake for any of the three cases. Therefore, the study assumed a parcel at the Lake surface at the ambient surface pressure with a temperature near freezing and a mixing ratio of 2.5gKg^{-1} (a dewpoint in the lower 20s F); this requires superadiabatic conditions near the surface. That parcel has a lifting condensation level of around 950 mb and would have reached 700 mb at GRB (approximately 10,000 feet MSL) before becoming colder than the ambient atmosphere, thereby becoming negatively buoyant. An identical parcel raised simultaneously at FNT would have reached 820 mb (approximately 6,000 feet MSL) before becoming negatively buoyant. A simple process of weighting the above value for GRB three times as heavily as that for FNT, because of its upwind orientation and greater proximity to Lake Michigan, and then averaging the weighted values yields a level of 9,000 feet MSL before an ascending parcel over the Lake would have become negatively buoyant. Entrainment of colder and somewhat drier ambient air would have made the parcel negatively buoyant at an even lower level. Therefore, the temperature profile for Case 2 was a factor working against deep convective development and heavy snowfall, even when low level conditions were conducive to shore-parallel band development.

The 0000 UTC 16 December sounding at GRB (Fig. 13a, top) depicts a convectively unstable layer between approximately 980 mb and 850 mb. In contrast, the 0000 UTC 16 December FNT sounding (Fig. 13a, bottom) did not exhibit a convectively unstable layer, although the layer between 660 mb and 520 mb was nearly so. Again, we assumed a parcel at the Lake surface at the ambient surface pressure with a temperature near freezing and a mixing ratio of $2.5 gKg^{-1}$ (a dewpoint in the lower 20s F). That parcel has a lifting condensation level of around 950 mb and would have reached a level of 590 mb at GRB (approximately 14,000 feet MSL) before becoming negatively buoyant. Such a parcel at FNT would have reached a level of 520 mb (approximately 17,000 feet MSL) before becoming negatively buoyant. Using the same procedure as above, a level of 14,750 feet MSL would have been reached before an ascending parcel over the Lake would have become negatively buoyant. Entrainment also would have been a factor here, but these soundings were conducive to considerably deeper convection than the soundings from 19 December.

Also, recall that with respect to the conditions outlined in MEB, Case 1 met surface and 850-mb temperature conditions well, but met wind and pressure conditions only marginally. Case 2 met the 850-mb temperature conditions well, but met surface temperature conditions only marginally. Case 2 met wind and pressure conditions well. Case 3 met surface and 850-mb temperature conditions well, and it also met wind and pressure conditions well.

Case 2 was the most transient of the three, lasting only about six hours and dropping about eight to 12 inches of snow from near Laporte to MGC. Case 1, which lasted 15 hours, resulted in 25 to 30 inches of snow in an area from just west of SBN to just west of Laporte. The bulk of that snow fell over an 11 hour period. The evidence from the sounding data is consistent with the above. Case 3 lasted about 23 hours, and resulted in 12 to 16 inches of snow. The bulk of that snow fell over a 12-hour period.

MEB does explain why Case 3 was a greater snow producing event than Case 2, but it does not explain why Case 1 generated more snow than the other two events combined. One factor was the relatively favorable sounding that existed during Case 1. However, this study suggests that Case 1 was the only event out of the three that was not a pure shore-parallel event.

A plausible explanation of how the conditions described previously resulted in Case 1 is presented below. Remember that WSO SBN radar data from before 0430 UTC 16 December were not available, and that data would have added credence to the explanation.

D. Peculiarities of Case 1

1. Development and Metamorphosis

Case 1 began under low level synoptically related confluence over northern Lake Michigan, as can be seen in Figure 11. As mentioned previously, Figure 11 also gives evidence of a low level trough moving over the Lake. At the same time, there was, as can be seen in Figure 2, a north northwest flow over Lake Michigan at 850 mb. It does not appear the speed of the flow was very high, but combined with the direction, the velocity was conducive to the development of wind-parallel streets according to Dockus (1985), who constructed the Dockus Decision Tree (DDT) for wind-parallel snow band development over the Great Lakes.

All of the above could have combined to initiate wind-parallel cloud streets that were enhanced by confluent flow and a low level trough. Figures 14 and 15 are identical to Figures 5 and 6 (the surface plots from Case 1), except they are on a larger scale and they include isobars and isotherms.

Figure 14 shows a pattern indicative of a general trough oriented northeast to southwest across the region. In Figure 14, there appear to be as many as four ripples in the general cyclonic flow: The first ripple was over Ohio into southeast Indiana; the second was over northwest Indiana into southern Illinois; the third was over southeast Wisconsin into southern Iowa; the fourth was over southern Minnesota into northwest Iowa.

Figure 15 also shows the pattern of a general trough, but by this time the pattern was relaxing as high pressure was building east into the region. Only two ripples were apparent in the flow by this time. One (the third in Fig. 14) was over north central Indiana into southern Missouri, and the other (the fourth in Fig. 14) was over northern Illinois into southeast Iowa. The former was associated with a thermal ridge just to its southeast in Figure 14. Both ripples were associated with thermal ridges in Figure 15, although the ripple over north central Indiana retained the more pronounced thermal ridge.

Using the latest NGM guidance, the DDT for wind-parallel type snow events indicated twelve hour snowfall amounts of six to 12 inches. If the ambient upward 700-mb vertical velocities had been greater than 1 μbs^{-1}, the DDT predicted 12-hour snow amounts of 12 to 18 inches, about a foot less than what actually fell. Moreover, the snow band was stationary for eight hours or more, and the band did not at all resemble wind-parallel streets at around 0500 UTC 16 December. One is therefore led to suspect that what may have begun as a wind-parallel snow event with a degree of low level enhancement developed into a different phenomenon.

Subsequent surface plots and synoptic scale pressure fields (not shown) indicated to forecasters on duty at WSFO IND that any surface-based conditions conducive to the enhancement of wind-parallel streets had broken down by 0700 UTC as high pressure from the Great Plains built east (ie., surface winds had relaxed and lost their component along the expanse of Lake Michigan). Also, the 850-mb wind velocities at 1200 UTC (not shown) had become incompatable with wind-parallel streets. Since 850-mb winds are observed at 12-hour intervals, there is no way of knowing at what time between 0000 and 1200 UTC the 850-mb winds became incompatable with wind-parallel streets.

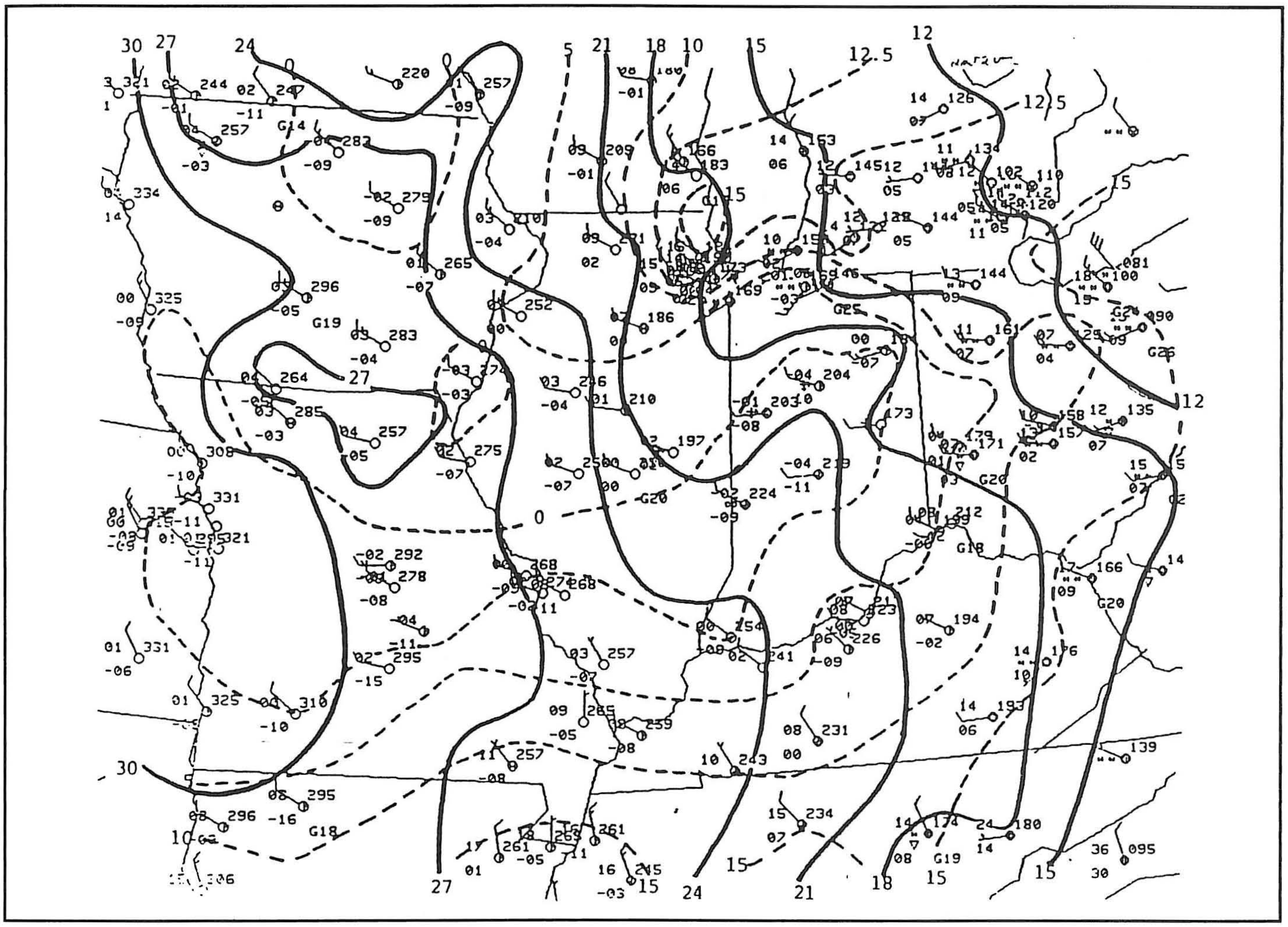

Fig. 14. Surface analysis at 2300 UTC 15 December, 1989. Isobars are solid lines (mb), isotherms are dashed lines (deg F).

By 0500 UTC it may be inferred from Figure 15 that the penultimate surface ripple (associated with the most significant surface thermal ridge) related to the central Pennsylvania low had rotated through extreme northern Indiana. The ripple was from south central Michigan to just south of central Illinois, placing it just through the area of heavy snowfall over extreme southwest lower Michigan and extreme north central Indiana. Subsequent surface plots showed the final surface ripple had lost its definition by 0700 UTC. Snowfall occurred over this narrow area for another five to seven hours (until 1200 UTC), and significant snowfall occurred for another three to five hours (until 1000 UTC).

Figure 15 shows surface winds had relaxed to the necessary speed to support shore-parallel band development everywhere except MKE by 0500 UTC, even before the final ripple had dissipated. Given the combination of ambient Lake temperature, surrounding surface temperatures, area surface wind fields over land, and 850-mb temperatures over the Lake, the environment likely was favorable for a shore-parallel snow situation.

There is an indication of a transition from wind-parallel to shore-parallel snow by around 0500 UTC in Figure 1a. It is possible to see in Figure 1a (top, 0435 UTC) a large apparent shore-parallel band modulated by another band along its northeast flank, rotated slightly counterclockwise to the larger band. It is suggested this other band was the remnants of a wind-parallel street as the transition was occurring. By 0505 UTC (Fig. 1a, bottom), the suggested transformation was moving toward completion, as the band along the northeast flank had lost much of its definition.

Given the observation by MEB that shore-parallel bands are capable of producing snowfall rates of two inches per hour, this would explain why significant snow during Case 1 fell from around 0500 UTC until 1000 UTC. The dissipating ripple to the northwest of the area of maximum snowfall between 0500 and 0700 UTC could have been a factor early in that period. Subsequent surface plots indicated temperatures around Lake Michigan warmed to a level not supportive of shore-parallel bands after 1200 UTC. By 1200 UTC, snow had tapered off to flurries in northwest Indiana.

The above explanation addresses the appearance of the snow band at 0500 UTC 16 December and the heavy snowfall from around or just before that time until the end of the event. It also addresses the initiation of the event. It does not address completely the question of why such heavy snow fell from around 2300 UTC 15 December until around 0500 UTC 16 December. Snowfall rates from the DDT, even when one enhances them with conditions that did not exist (upward motion at 700 mb), do not explain what occurred.

Assuming the soundings in Figure 13a represent adequately the ambient atmosphere at the time of Case 1, the vertical temperature profile was a factor in the generation of heavy snow during the first part of the event. There was another factor.

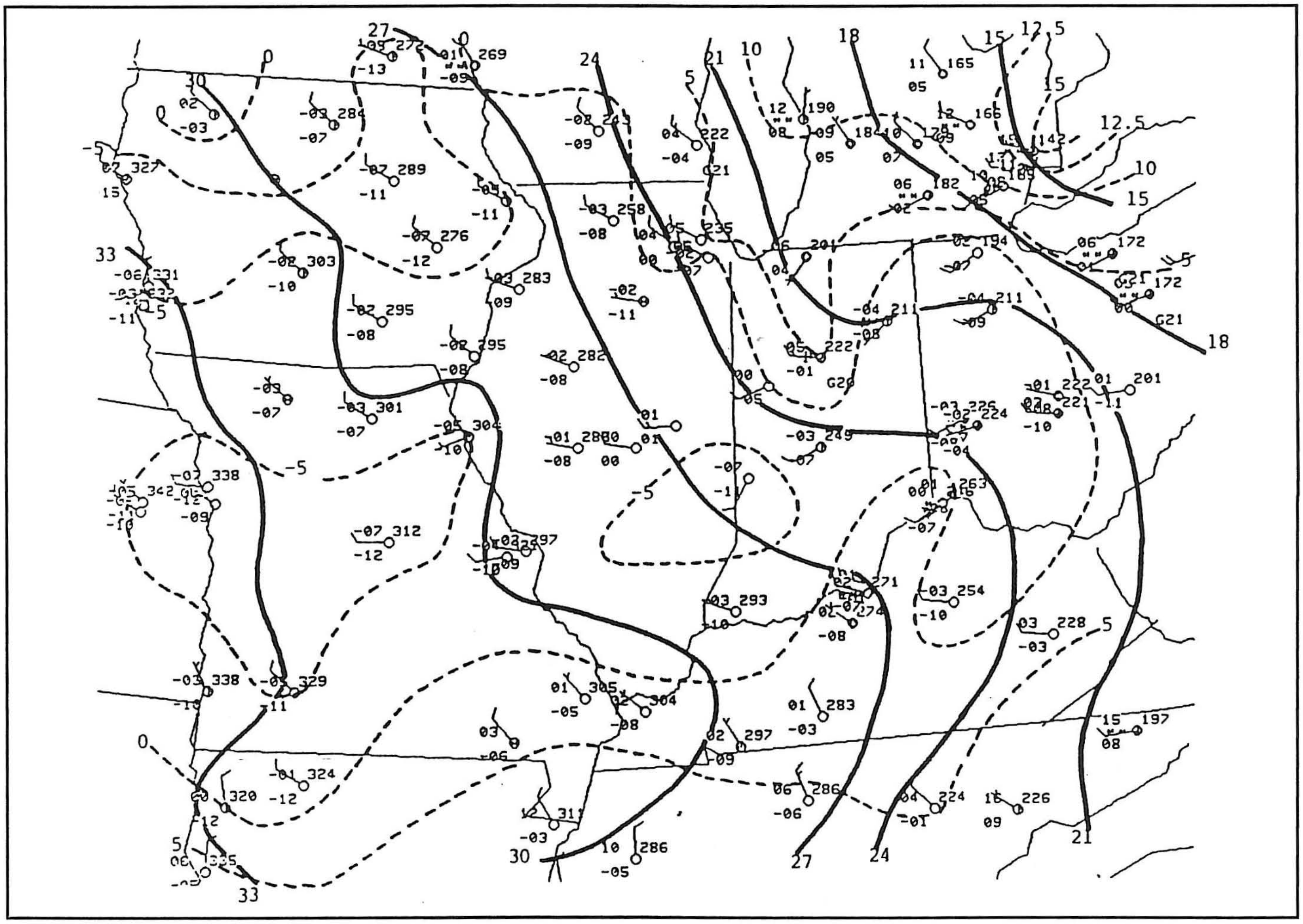

Fig. 15. Same as Figure 14 except at 0500 UTC 16 December, 1989.

2. The Role of Warm Advection

Note in Figure 14 (2300 UTC) the mesoscale thermal ridge from north central Illinois through southern Lake Michigan to central lower Michigan associated with the aforementioned surface ripple.

At 2300 UTC, the thermal ridge ran through the newly developed wind-parallel streets, as it was located from near MKG to about 50 miles north of Chicago. It was in position to enhance the wind-parallel streets by increasing the destabilization of the low level environment (warming of the layer just above the surface), increasing the amount of moisture the low level snow band environment could hold, and generally enhancing upward vertical motion. The surface warm advection could have contributed to the wind-parallel streets producing up to two inches of snow per hour over northwest Indiana, especially if a convectively unstable layer was present.

By 0500 UTC (Fig. 15), the main thermal ridge was from the SBN area through the southeast shore of Lake Michigan to eastern lower Michigan. It was moving away from the snow band. The secondary thermal ridge (associated with the final and dissipating surface ripple) was over the Chicago area. The secondary thermal ridge became diffuse as its associated ripple dissipated, but was still in a position to enhance the evolving band for a short period (up to two hours).

During the six hours between the times of Figures 14 and 15, the temperature at WSO SBN rose 5°F, and the temperature at Grissom Air Force Base, about 60 miles south of WSO SBN, rose 9°F. Keep in mind this happened during an overnight period. Also keep in mind that, despite the warm advection, inland surface temperatures did not rise above 15°F (within 10°C of the lake surface temperature) before 1200 UTC.

Figures 16 through 20 are ADAP (AFOS Data Analysis Programs; AFOS is the computer system used by the National Weather Service) fields generated at WSO Fort Wayne showing potential temperature (theta) advection over the region from near Lake Michigan to the Ohio Valley. Bothwell (1988) describes the various ADAP fields generated. The fields are generated on a uniform 15 × 15 grid with a grid point resolution of 80 km. Most fields, including the theta advection field, are solely surface based. Data for the fields come from automated and human-generated surface observations interpolated onto the grid (in the case of stability indices, upper air soundings supply the additional data needed).

Figures 16 through 18 pertain to Case 1. Figure 16 (theta advection at 2300 UTC) shows an axis of very strong warm advection from southern Lake Michigan through east central Illinois. The warm advection axis was near the southern extent of the newly developed wind-parallel streets. Heavy snow was just beginning over northwest Indiana. Figure 17 shows that warm advection was weaker but still considerable at 0300 UTC. Heavy snow had been falling for about four

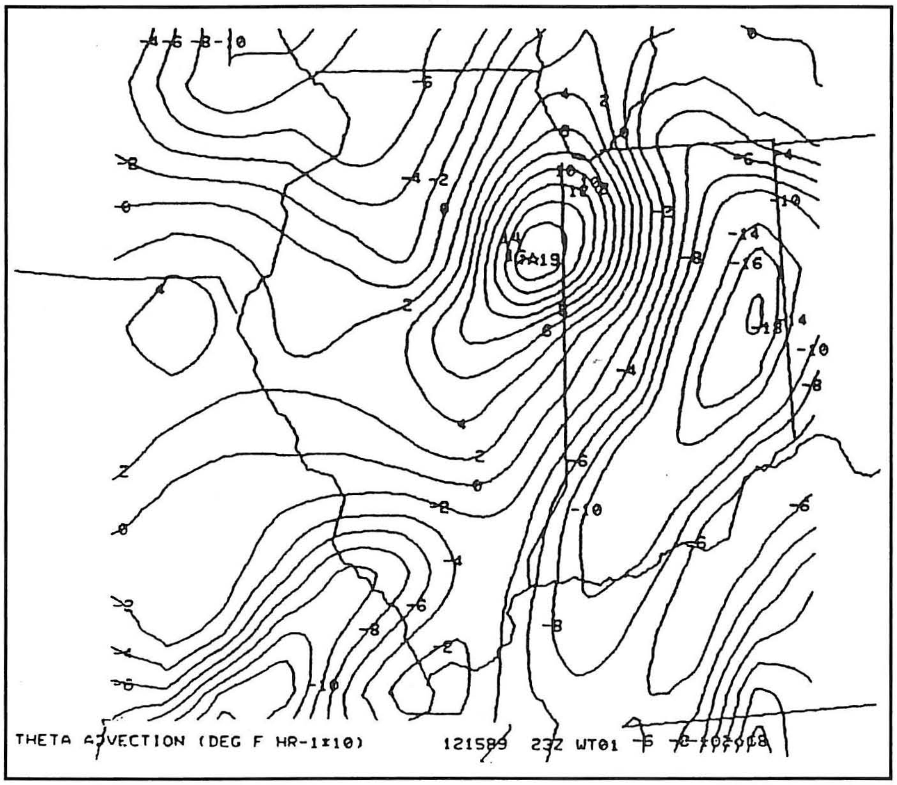

Fig. 16. Surface objective analysis field. Theta advection at 2300 UTC 15 December, 1989. Units Deg F $hr^{-1} \times 10$.

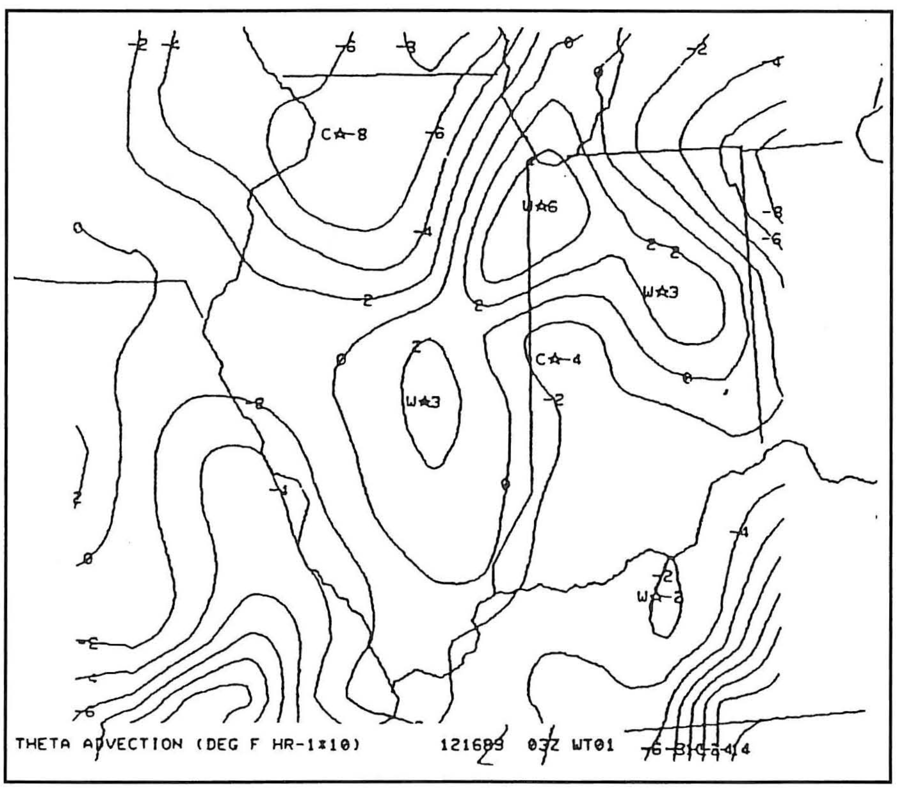

Fig. 17. Same as Figure 16 except at 0300 UTC 16 December, 1989.

hours. By 0700 UTC, warm advection (Fig. 18) and the low level trough had shifted well east of the snow band, which was by then a shore-parallel band. Heavy snow was continuing as the wind-parallel streets, once but no longer enhanced by warm advection, had evolved into a shore-parallel band.

The ADAP theta advection plots gave the information necessary to determine that additional energy was feeding the newly developed wind-parallel streets. Analysis of a surface plot could have yielded the same information. These analyses could have given forecasters the signal that significant snowfall from the supposed wind-parallel streets was about to exceed what the DDT predicted.

Figures 19 and 20, the ADAP theta advection plots from Cases 2 and 3 respectively, are included for comparison. During both Case 2 and Case 3, the ADAP plots indicated cold advection over the area where heavy snow fell.

4. Summary

An outbreak of frigid air over the Great Lakes and Ohio Valley regions will establish the temperature conditions necessary for shore-parallel snow bands to affect northwest Indiana.

Case 3 fits the prerequisites from MEB best. The pressure gradient and resultant surface wind speeds during Case 1 were not conducive to development of a shore-parallel band at the beginning of the event. During Case 2, the surface temperature pattern became less than optimal and the vertical temperature profile was less than optimal. For Case 2, shore-parallel snow band dissipated after only a few hours. In the matter of Case 1, a plausible explanation is that wind-parallel streets developed and later evolved into a shore-parallel band once conditions changed.

This study also found that low level warm advection was a factor in making supposed wind-parallel streets from the first hours of Case 1 rival the shore-parallel band from the latter hours of Case 1 as snow producers. Another factor in favor of heavy snow throughout Case 1, assuming the representativeness of Figure 13a, was a vertical temperature profile conducive to convective development. Such was not the case during Case 2. All this would explain why Case 1 was the greatest snow producing case of the three.

One could have deduced from the ADAP theta advection fields the existence of the thermal ridge associated with the aforementioned warm air advection. Forecasters often think of ADAP fields as useful only during warm season convection. Case 1 might have been an example of their utility, used in conjunction with other sources of information, during other weather events.

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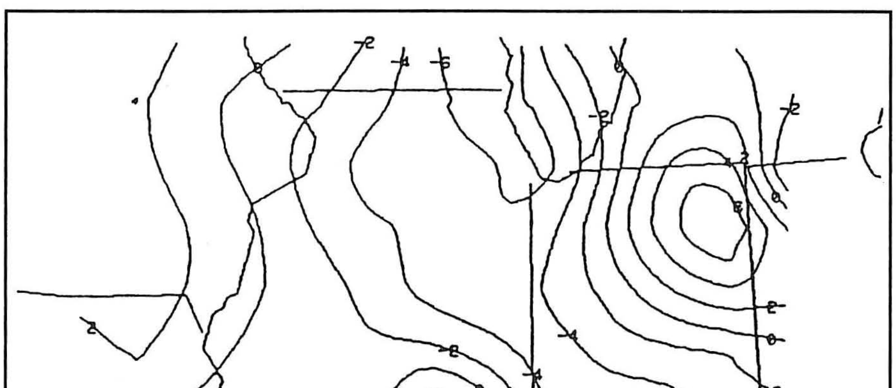

Fig. 18. Same as Figure 16 except at 0700 UTC 16 December, 1989.

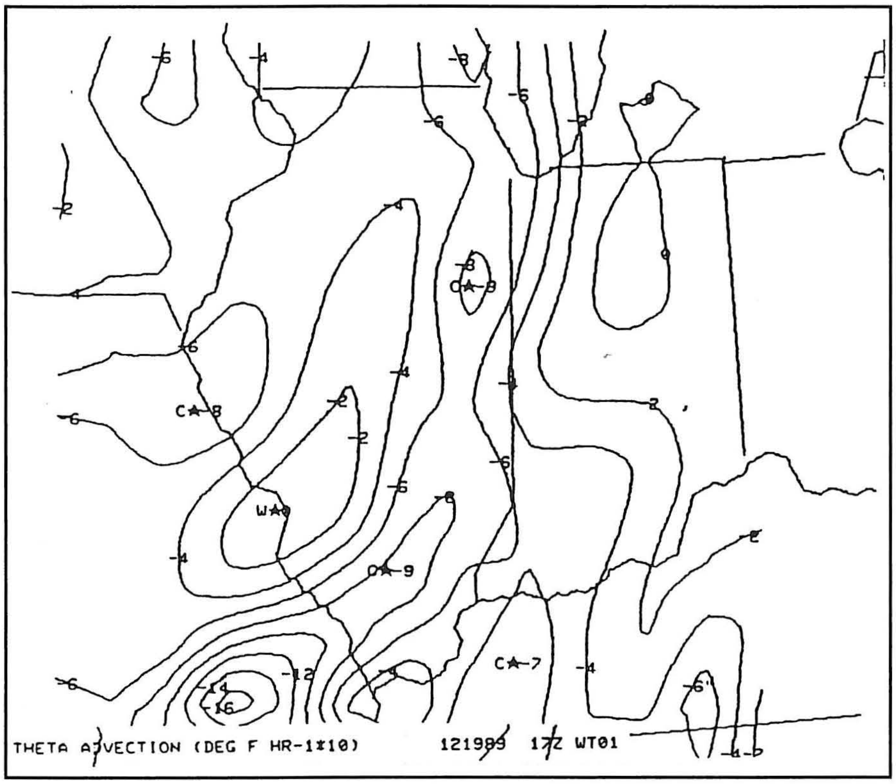

Fig. 19. Same as Figure 16 except at 1700 UTC 19 December, 1989.

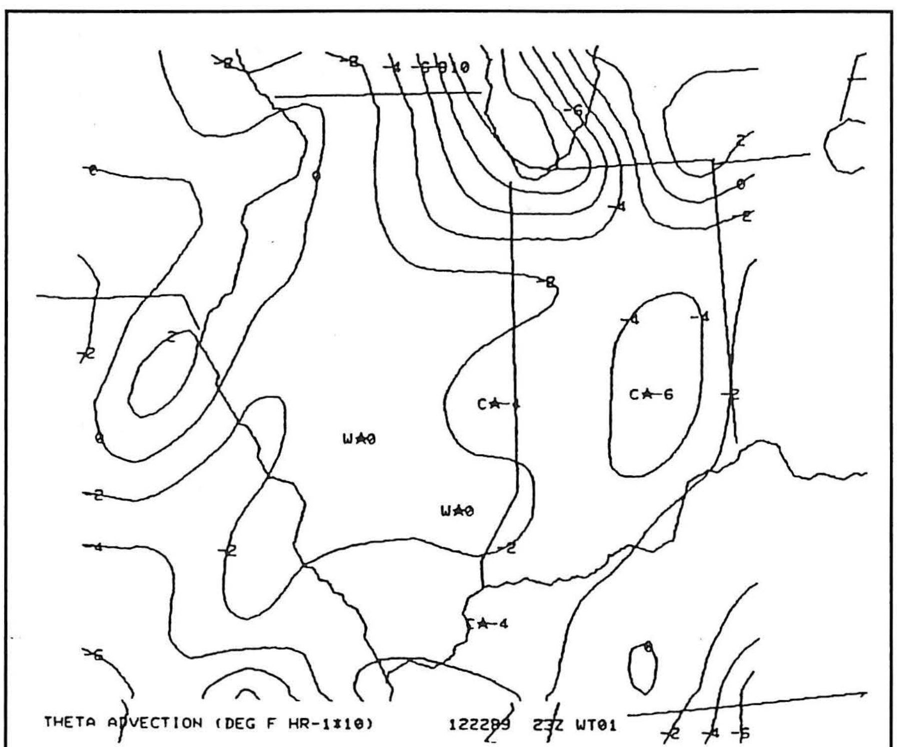

Fig. 20. Same as Figure 16 except at 2300 UTC 22 December, 1989.

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