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AN EXCESSIVE LAKE-ENHANCED SNOWFALL EPISODE OVER NORTHEAST WISCONSIN ON DECEMBER 13-15, 1989

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1. Introduction

During the late fall and early winter months, the well known lake effect snows frequently develop over portions of the western Great Lakes. Areas most susceptible to heavy lake snows are typically in Upper Michigan, along Lake Superior and along the eastern shoreline of Lake Michigan. These areas commonly experience a cold and dry northwesterly wind flow which gathers moisture from the lakes and deposits it in the form of snow. Orographic lifting, such as along the Gogebic Range in Upper Michigan, helps to enhance and localize the heaviest snowfall. In comparison, heavy lake effect snow along the western shores of Lake Michigan is not as common since the prevailing wind direction in the winter is northwest, and not a more favorable northeast.

The purpose of this paper is to examine a heavy lake enhanced snowfall episode which occurred over northeast Wisconsin. During a 2-day period from December 13-15, 1989, up to 30 inches of snow fell over a portion of Wisconsin's Door Peninsula. This event was characterized by a snowband which initially formed over Lake Michigan and moved westward before becoming quasi-stationary over northeast Wisconsin. The snowband was then observed to rotate cyclonically over northeast Wisconsin in concert with a mid-level shear axis. It will be shown that the heavy snowfall was caused by a combination of lake induced mesoscale and synoptic scale weather features.

First, a brief review of the conditions conducive to lake effect snow will be given, followed by a description of the initial snowband formation. Then the evolution of upper air features will be described. Finally, the evolution of synoptic and mesoscale surface and upper air features will be related to the life cycle of the snowband. Surface, upper air and radar data were used in this study.

2. Formation of the Snowband

A. Review of Conditions Required for Lake Effect Snow

Basic conditions that have been shown to be required for lake effect snowfall are summarized below (Changnon 1972, and Mecikalski 1989).

Pure Lake Effect:

1. Land-lake temperatures difference greater than 10°C.
2. Temperature difference between the lake water and 850 mb is more than 13°C.
3. Depth of cold air mass greater than 3000 feet (an inversion below this height would tend to suppress cumulus growth).
4. Favorable low level wind fetch over the lake.
5. Significant topographic features to enhance upward motion.

Lake Enhanced Snow:

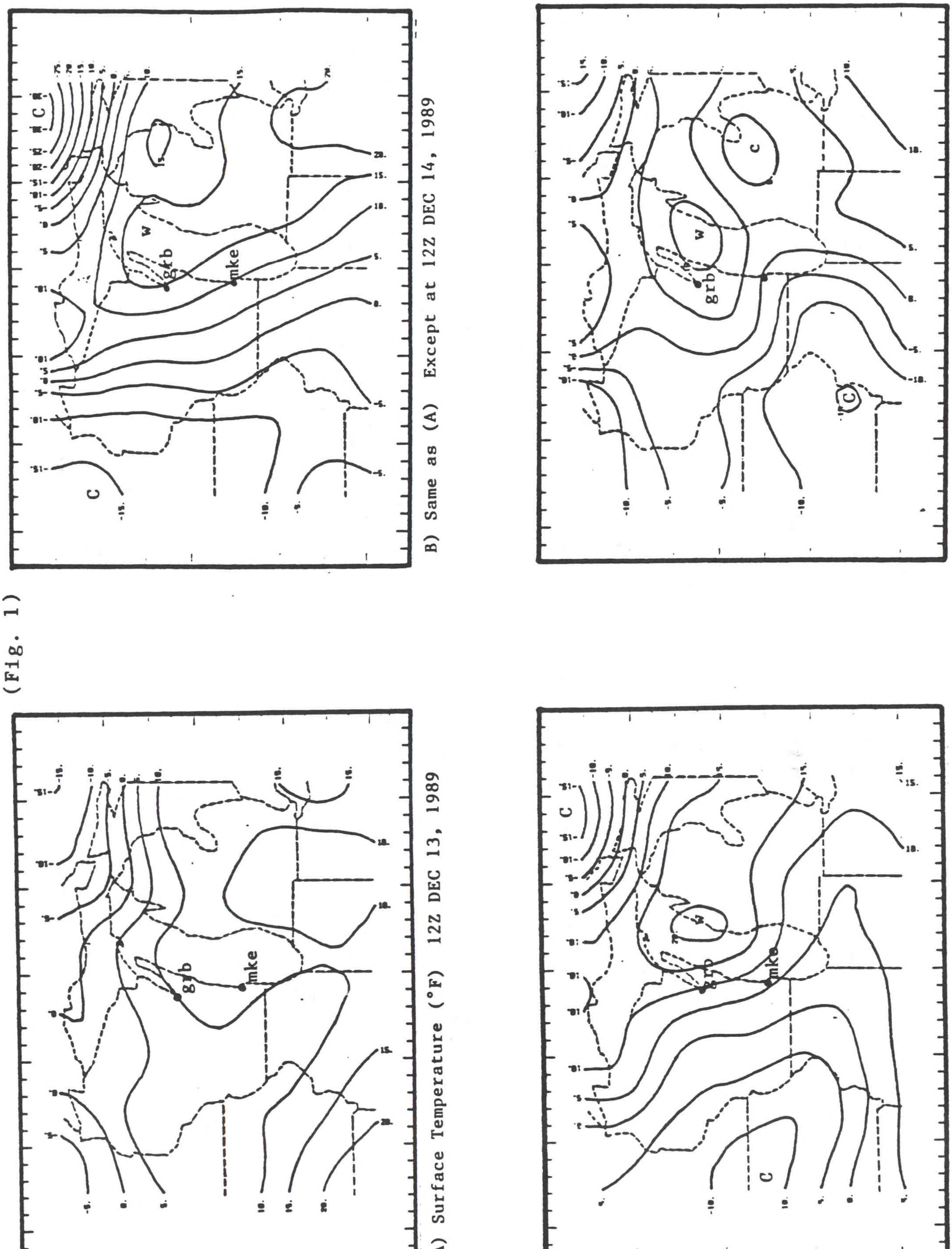
1. Conditions 1 through 4 for pure lake effect snow.
2. Synoptic scale and/or mesoscale feature or features that interact with the pure lake effect snow conditions to enhance upward motion.

B. Discussion

By 12Z December 13, conditions were favorable for lake effect snowfall in eastern Wisconsin. The 12Z surface temperature analysis shows that the air mass over Lake Michigan was cold enough to satisfy the land-lake temperature criteria (Fig. 1A). The Sturgeon Bay Coast Guard station reported a water temperature of 33°F (1°C), while surface land temperatures around Lake Michigan were about 10°F or less. The 12Z sounding at Green Bay, Wisconsin (GRB), indicated that the lake-850 mb criteria had also been satisfied, with a difference of 14°C (Fig. 2A). No inversion was evident in the sounding, which might inhibit cumulus development. Winds above GRB veered from the light northerly at the surface to southeast at 920 mb. The southeast flow continued upward to about 800 mb. The light northerly surface wind represented a land breeze component toward Lake Michigan.

The objectively analyzed surface pressure and wind fields at 12Z, showed a weak gradient over the lake resulting in light winds (<2 m/s), which were noticeably convergent (Figs. 3A and 4A). The convergent surface winds over the lake were in response to low pressure induced by the relatively warm water, compared to the surrounding land. Mesoscale upward motion, caused by thermal convergence, can often lead to snowband formation over Lake Michigan (DeLisi and Przybylinski 1990, Hjelmfelt 1989, and Peace and Sykes 1969).

(Fig. 1)



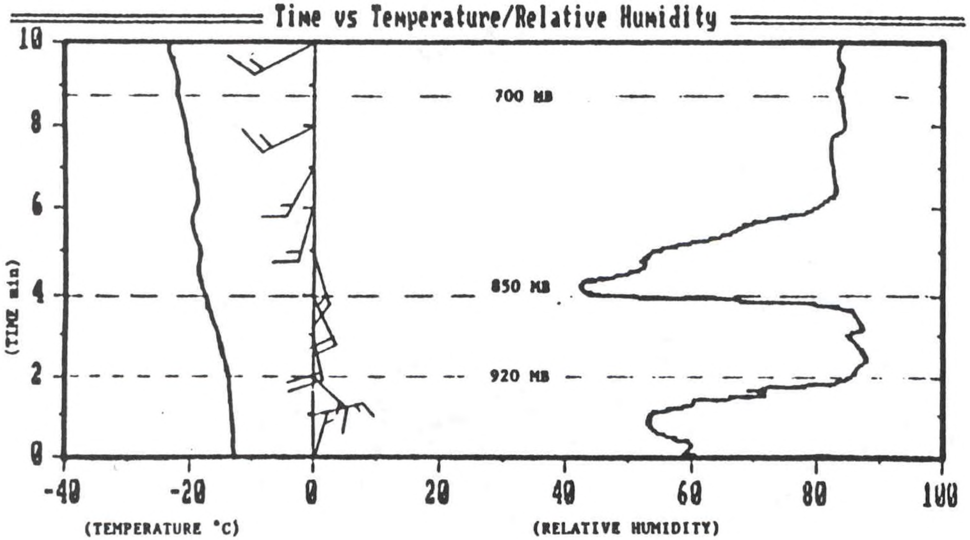
A) Surface Temperature (°F) 12Z DEC 13, 1989

B) Same as (A) Except at 12Z DEC 14, 1989

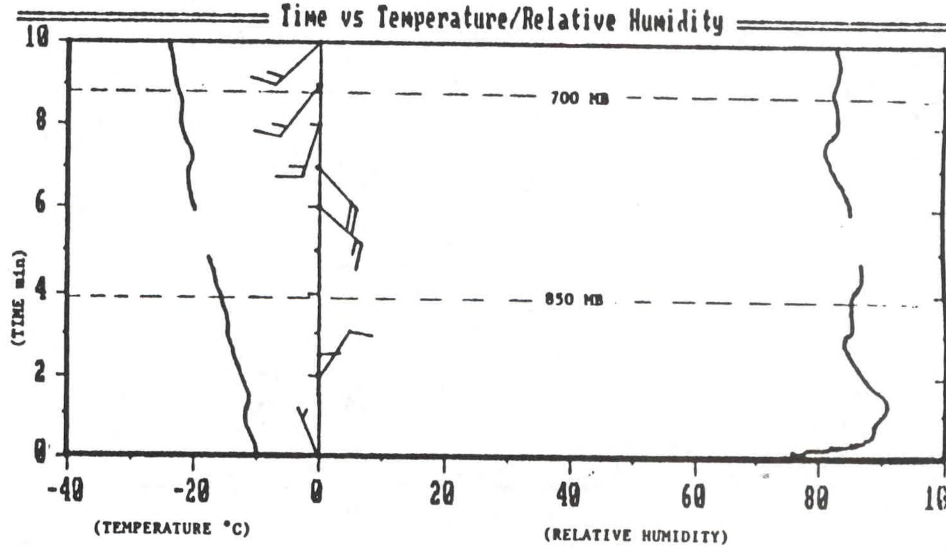
C) Same as (A) Except at 00Z DEC 15, 1989

D) Same as (A) Except at 12Z DEC 15, 1989

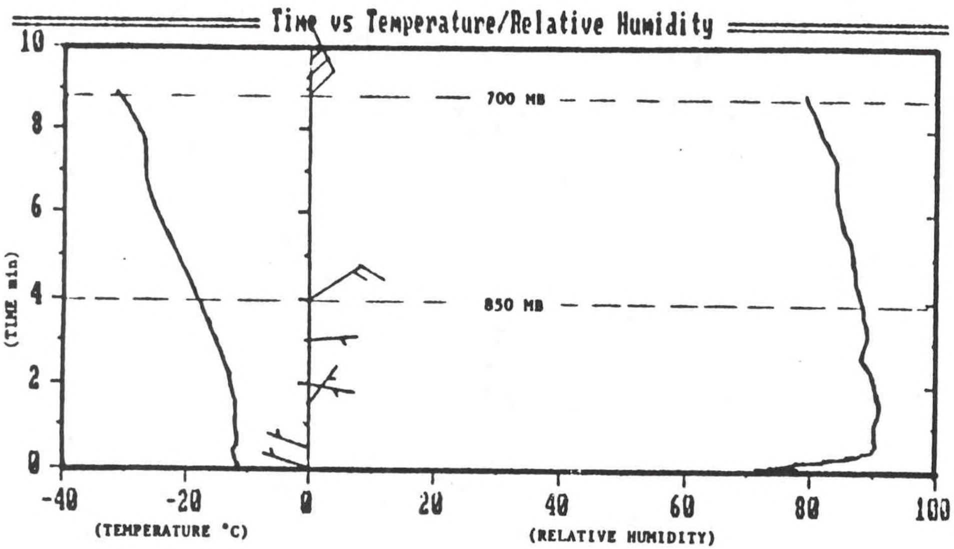
(Fig. 2)



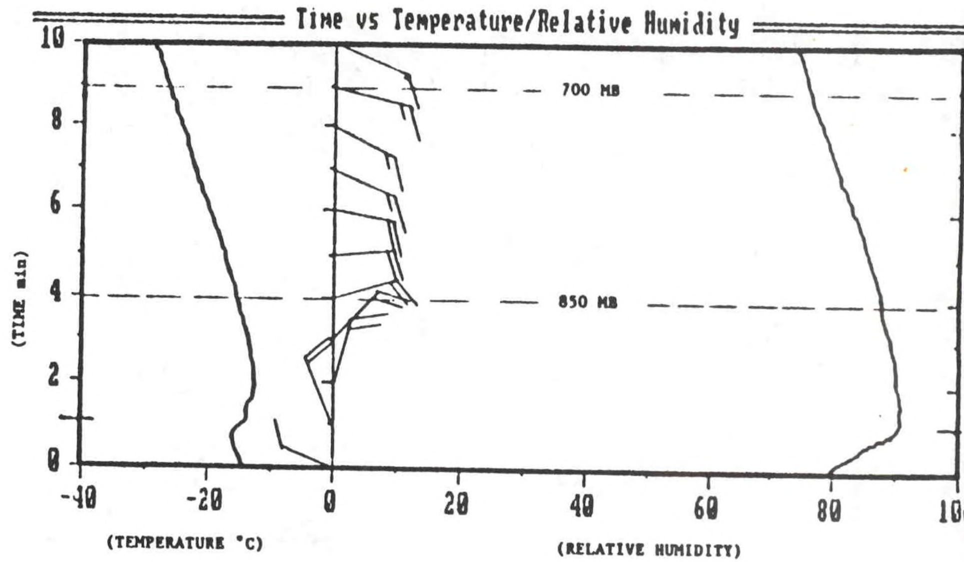
A) Green Bay, WI Sounding (Micro-arts Plot)
12Z Dec 13, 1989



B) Same as (A) Except at 00Z Dec 14, 1989

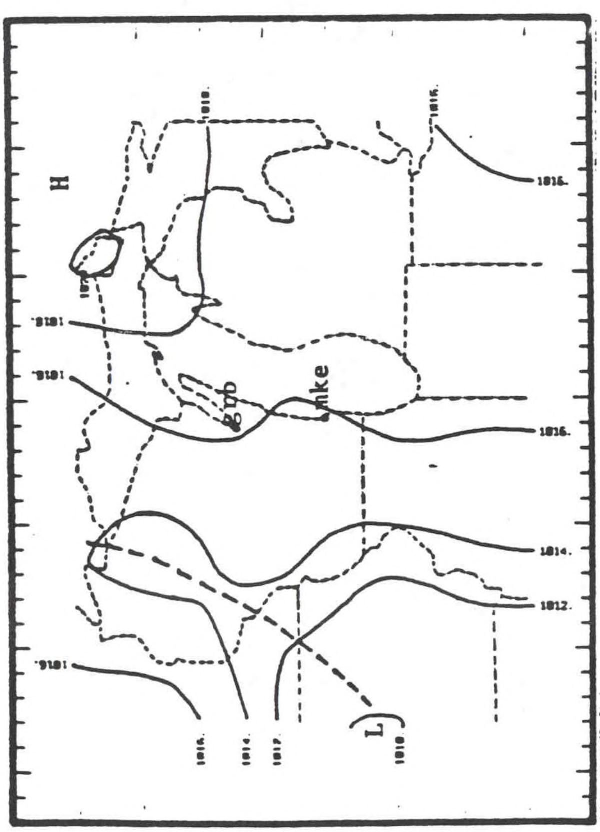


C) Same as (A) Except at 12Z Dec 14, 1989

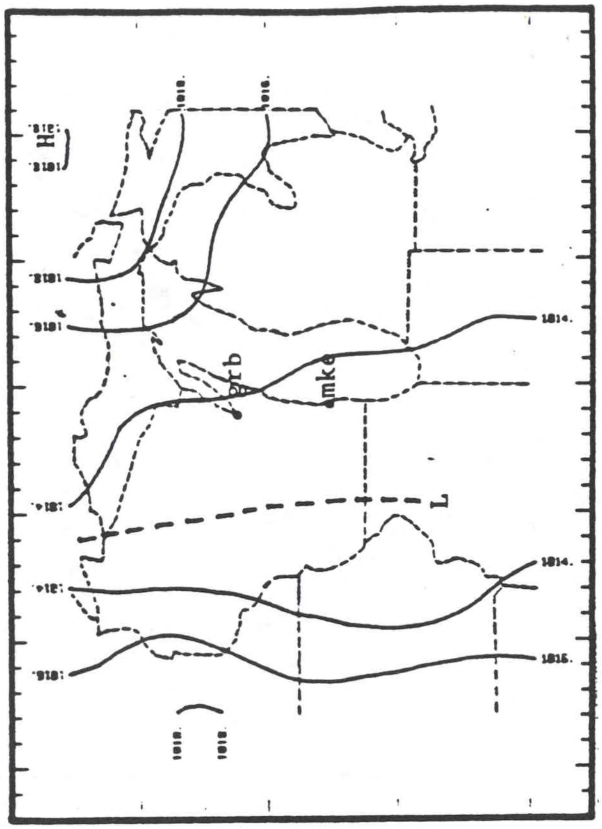


D) Same as (A) Except at 00Z Dec 15, 1989

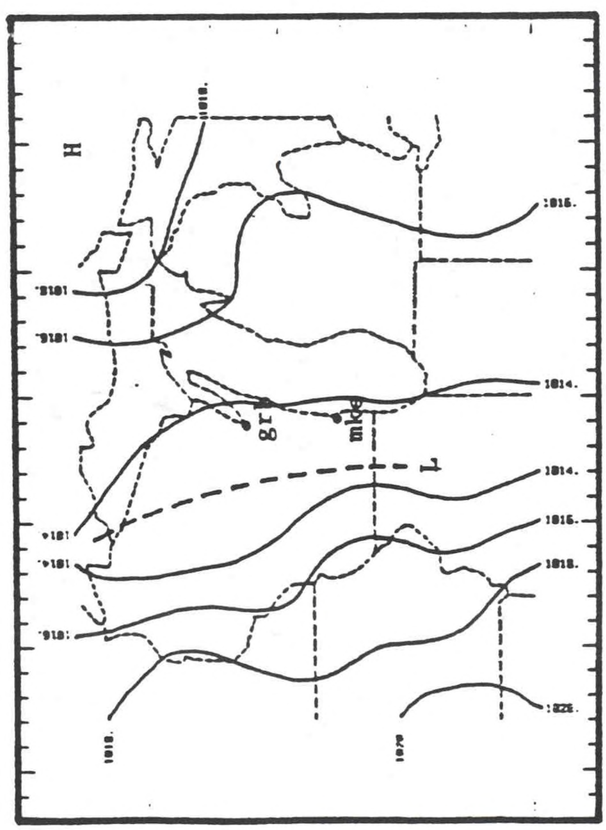
(Fig. 3)
a-d



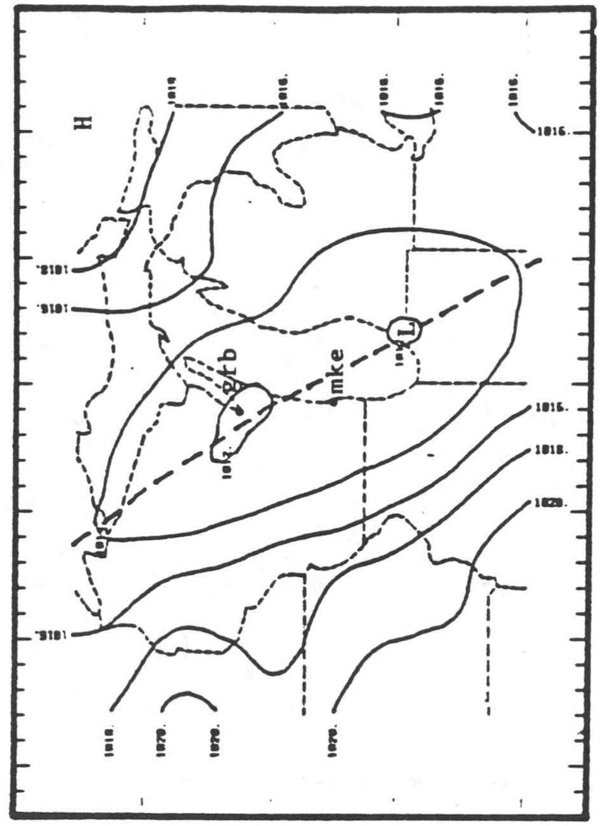
A) Objectively Analyzed Surface Pressure (mb)
12Z DEC 13, 1989



B) Same as (A) Except at 21Z DEC 13, 1989

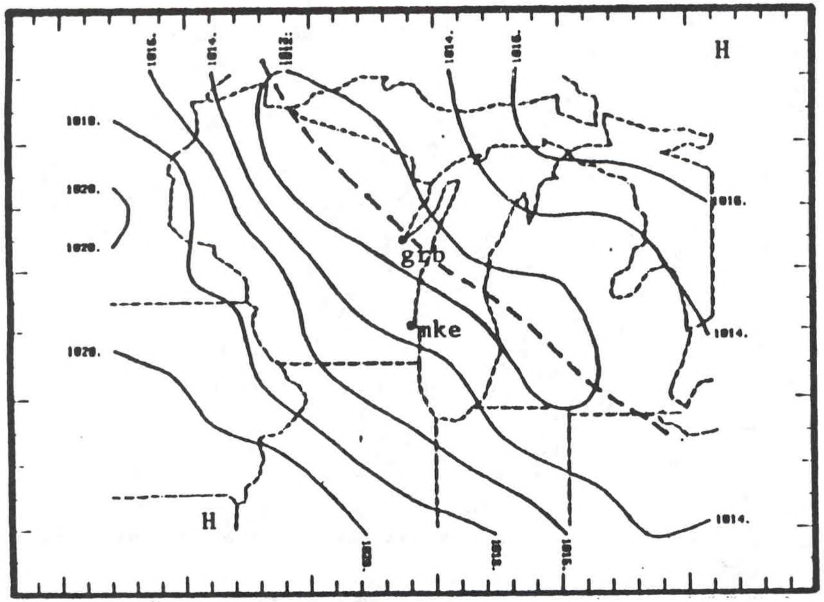


C) Same as (A) Except at 00Z DEC 14, 1989

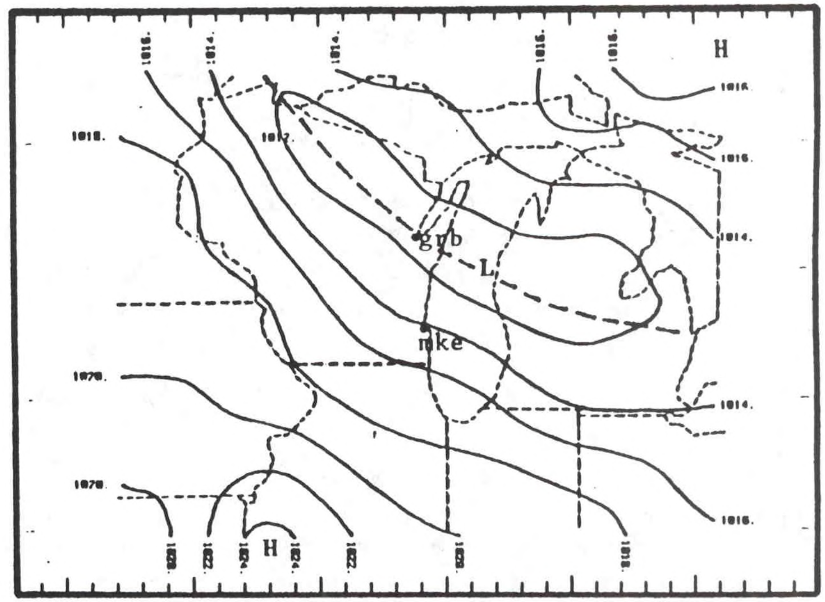


D) Same as (A) Except at 06Z DEC 14, 1989

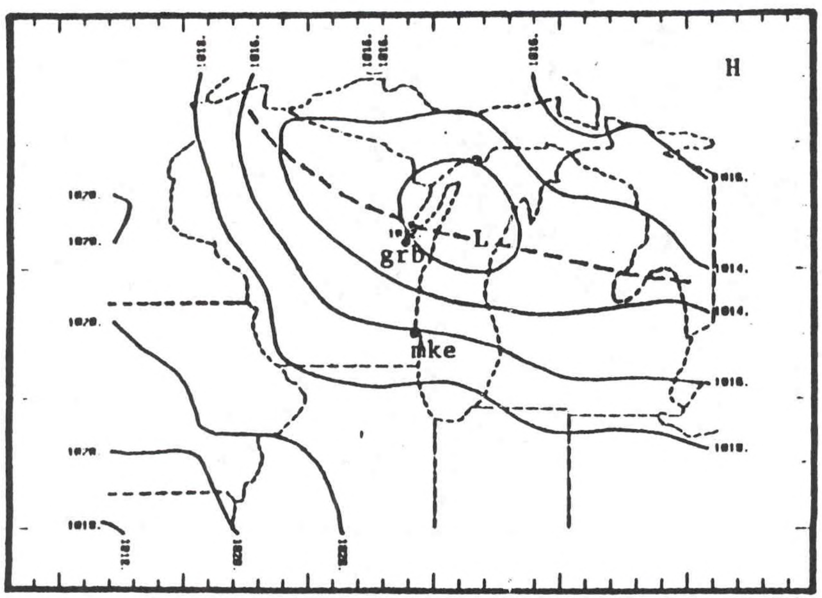
(Fig. 3)
e-h



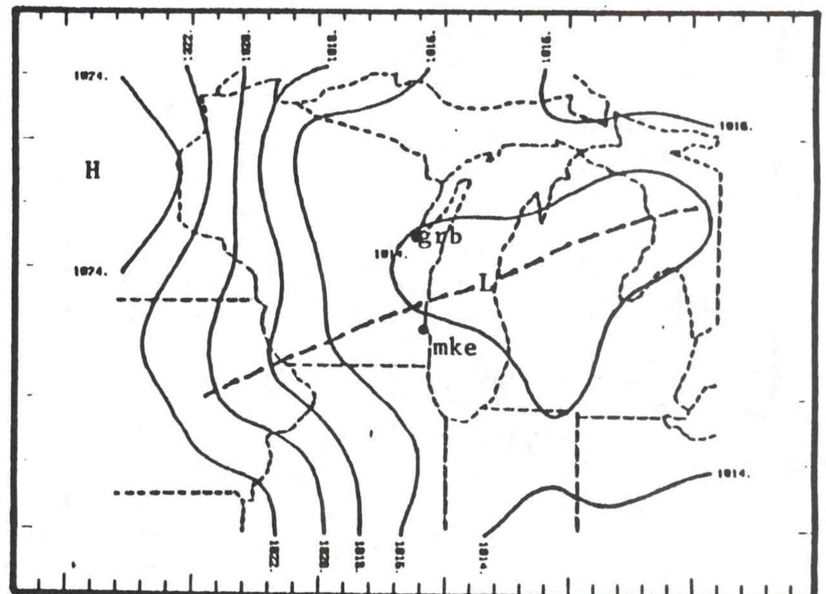
E) Objectively Analyzed Surface Pressure (mb)
12Z DEC 14, 1989



F) Same as (E) Except at 18Z DEC 14, 1989

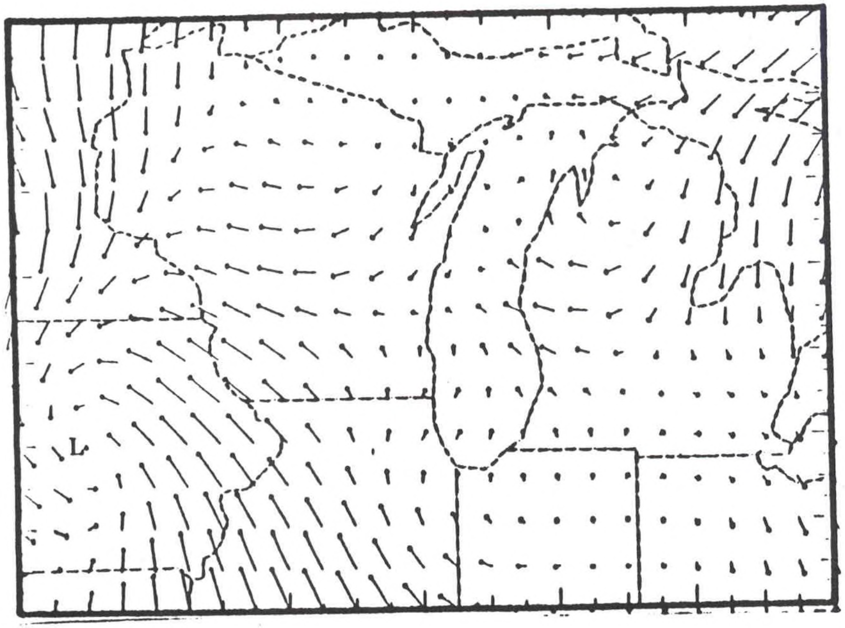


G) [Same] as (E) Except at 00Z DEC 15, 1989

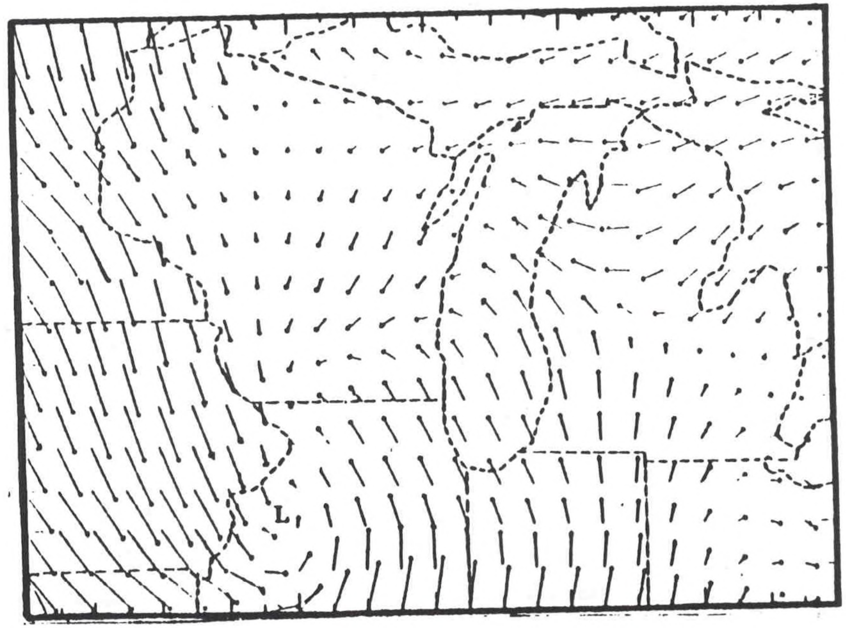


H) Same as (E) Except at 12Z DEC 15, 198[9]

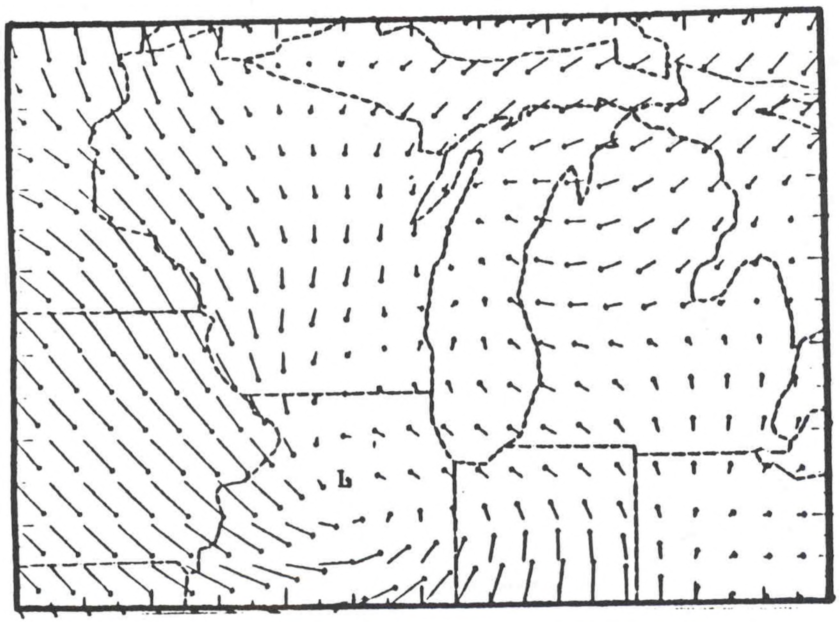
(Fig. 4)
a-d



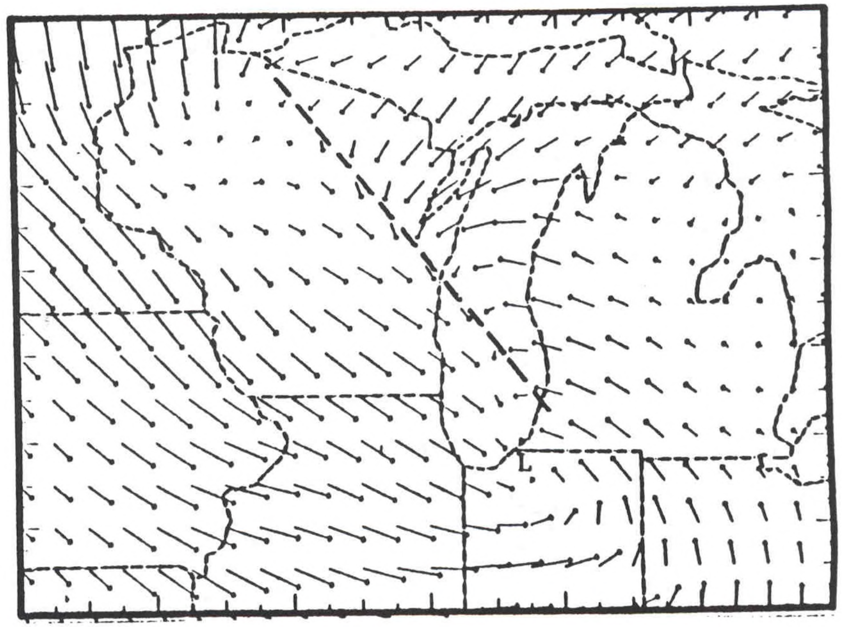
A) Objectively Analyzed Surface Wind (m/s)
12Z DEC 13, 1989



B) Same as (A) Except for 21Z Dec 13, 1989

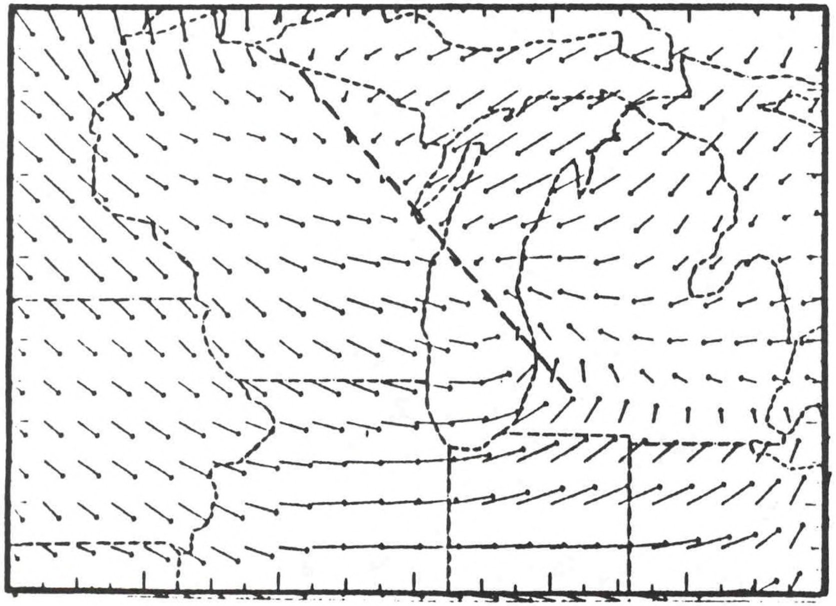


C) Same as (A) Except at 00Z DEC 14, 1989

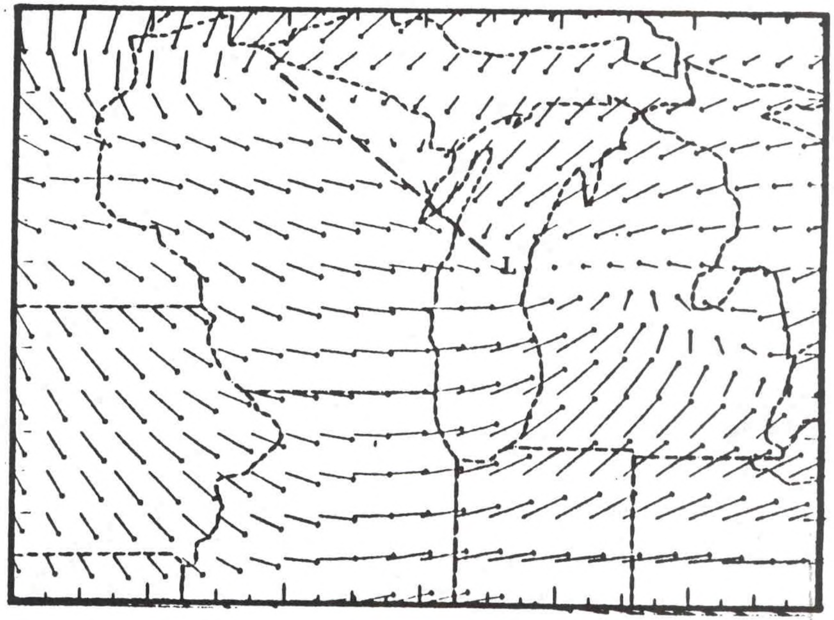


D) Same as (A) Except at 06Z DEC 14, 1989

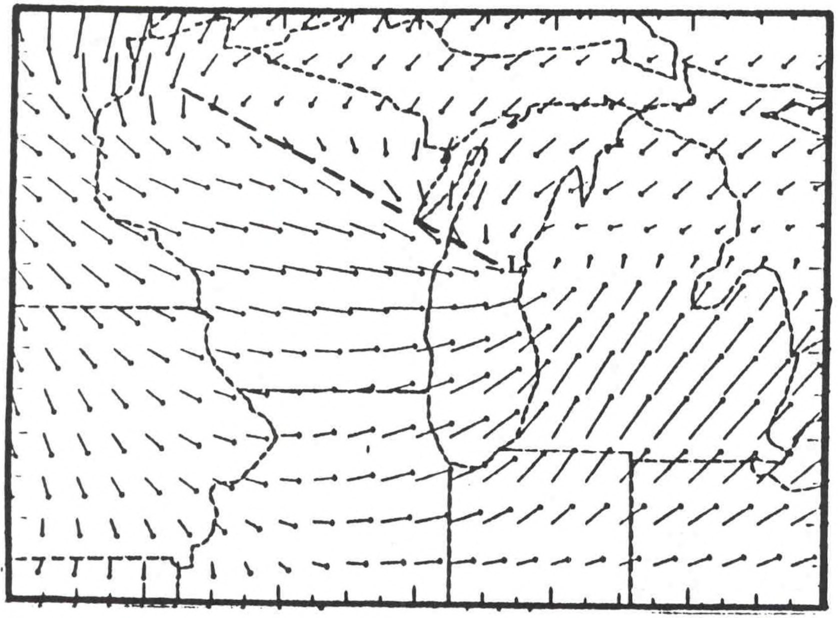
(Fig. 4)
e-h



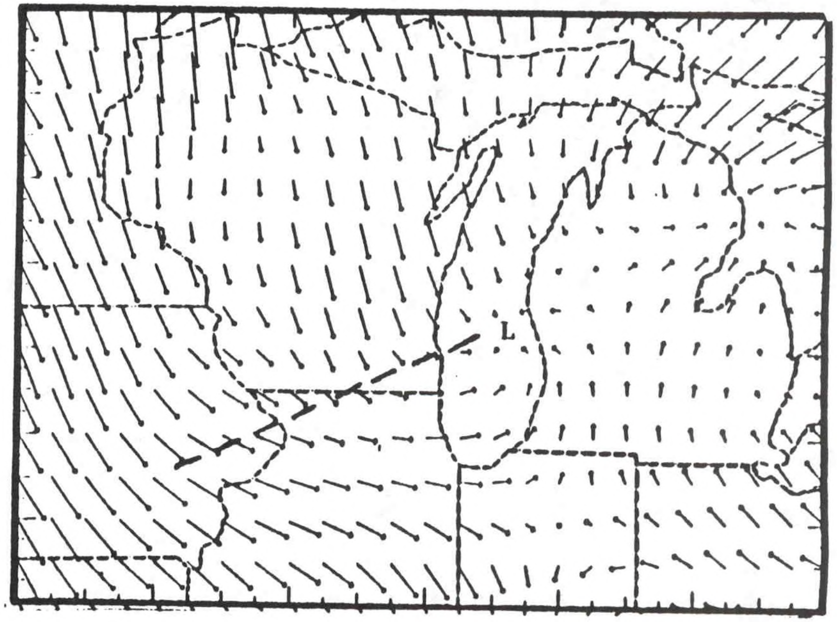
E) Objectively Analyzed Surface Wind (m/s)
12Z DEC 14, 1989



F) Same as (E) Except at 18Z DEC 14, 1989



G) Same [illegible] (E) Except at 00Z DEC 15, 1989



H) Same as (E) Except at 12Z DEC 15, 1989

Examination of Neenah, Wisconsin (EEW), radar data showed that a snowband had developed over central Lake Michigan during the early morning hours of December 13. In response to a gradient low level easterly flow, the snowband drifted westward and became poised just off the eastern Wisconsin shoreline by around 12Z (Fig. 5A). During the subsequent 6-hour period, the northern portion of the snowband moved onshore and had become quasi-stationary over extreme northeast Wisconsin by around 21Z (Fig. 5B).

By 18Z on the December 13, moderate to heavy snow showers were reported from Sturgeon Bay southward to Manitowoc, with up to 2 inches in 90 minutes falling near the town of Kewaunee. Thus, WSFO Milwaukee (MKE) issued a heavy snow warning for the northeast Wisconsin lakeshore counties of Door, Kewaunee and Manitowoc for the afternoon and evening hours of December 13.

3. Upper Air

The 500 mb flow at 12Z December 13 was dominated by a broad trough, which encompassed the entire central United States, and a low pressure system centered east of Lake Winnipeg in southern Canada (Fig. 6A). Weak short waves were rotating around the low center. The weak short wave moving through the upper Mississippi Valley, provided weak positive vorticity advection (PVA) over the western Great Lakes. By 00Z December 15, the low dropped southward to southeast Minnesota, with a positively tilted trough axis and shear zone, stretching from Wisconsin northeastward to southeast Canada (Figs. 6B and C).

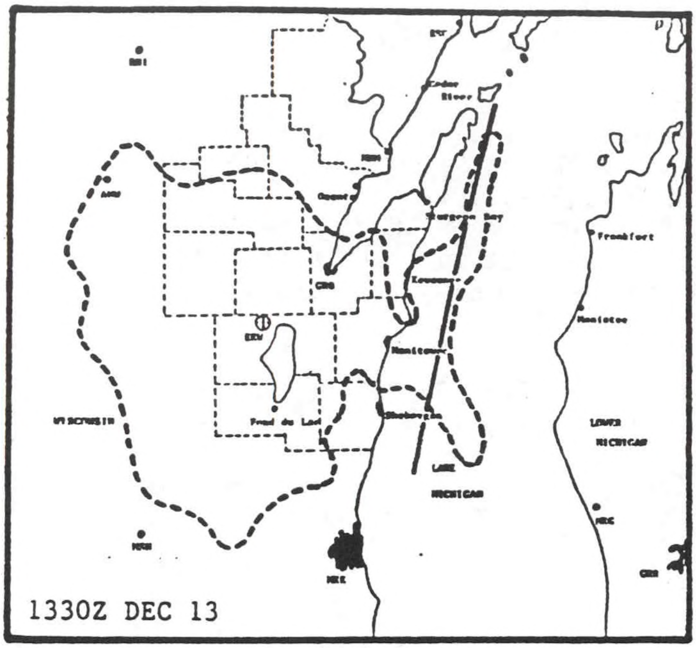
The embedded short wave that was moving through the upper Mississippi Valley, lost it's identity as it swept into Wisconsin. The 500 mb winds above northeast Wisconsin and northern Lake Michigan, had become rather light and diffluent by this time. The low center moved eastward to southern Wisconsin by 12Z December 15, with a well defined shear zone evident across the trough axis over Lake Michigan (Fig. 6D).

A similar scenario had evolved at 700 mb, with the low center moving to southern Minnesota, while the embedded short wave phased with the long wave positively tilted trough over Wisconsin (Figs. 7A through C). By 12Z December 15, the 700 mb trough axis had also become orientated from southwest to northeast across Wisconsin and central Lake Michigan (Fig. 7D).

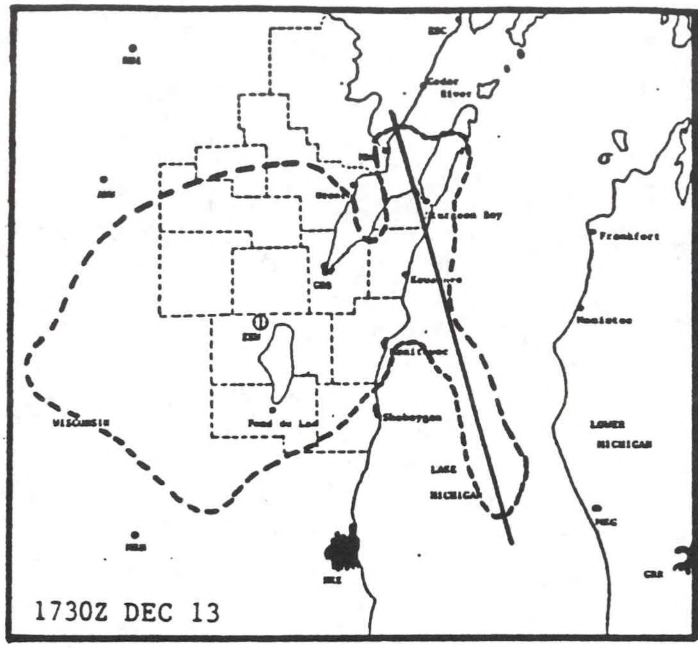
At the 850 mb level, a broad low pressure circulation was elongated along a approximate north-south axis and was centered over extreme northern Iowa at 12Z December 13 (Fig. 8A). Unseasonably cold Arctic air was moving southward across the Northern Plains behind the 850 mb trough axis. In the southerly flow further east, weak warm advection was occurring over eastern Wisconsin and Lake Michigan. By 12Z December 14 (Figs. 8C and 9), the 850 mb trough axis had also pivoted cyclonically to a position extending roughly from northern Minnesota to Lower Michigan. A weak baroclinic zone was evident across the 850 mb trough axis by 12Z on December 14, with cold and dry Arctic air advecting southeastward across southern Wisconsin and northern Illinois.

(Fig. 5)

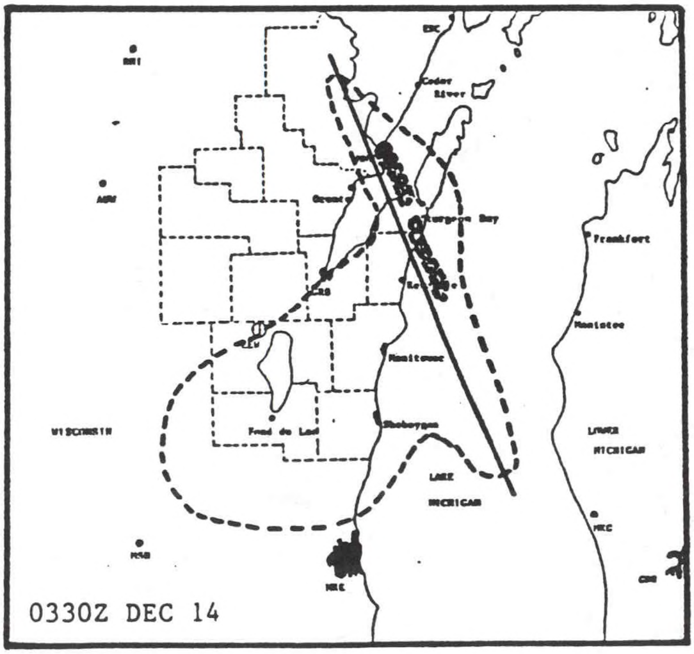
a-d



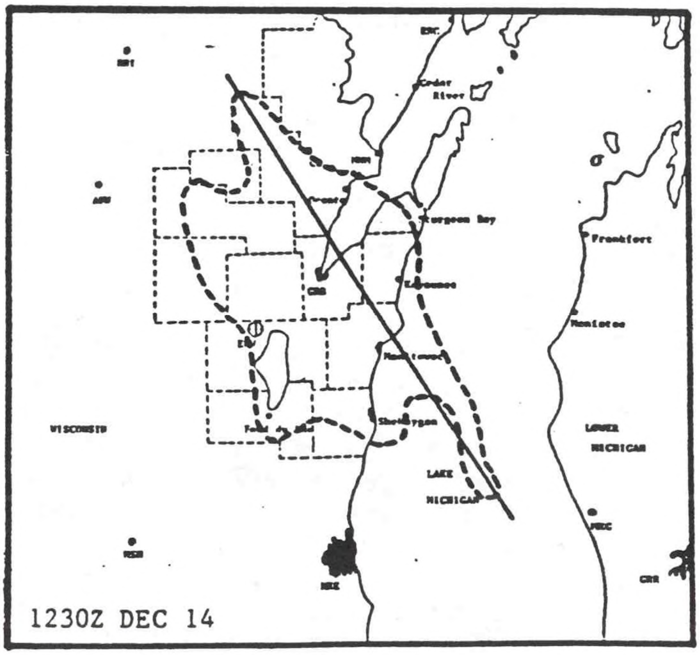
A) Radar Overlay from Neenah, WI (EEW)
(Dotted line is detectable precip)
(Solid bar is approx. location of snowband) 1330Z DEC 13, 1989



B) Same as (A) Except at 1730Z DEC 13



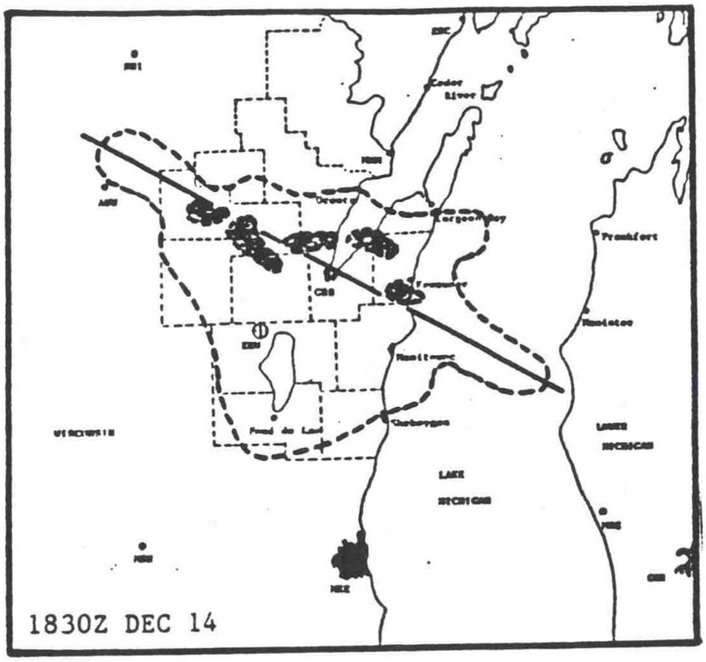
C) Same as (A) Except at 0330Z DEC 14



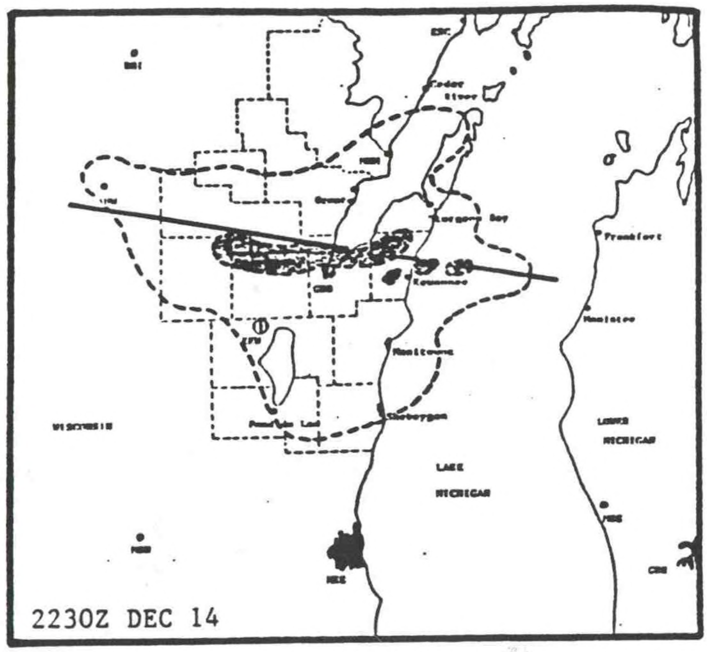
D) Same as (A) Except at 1230Z DEC 14

(Fig. 5)

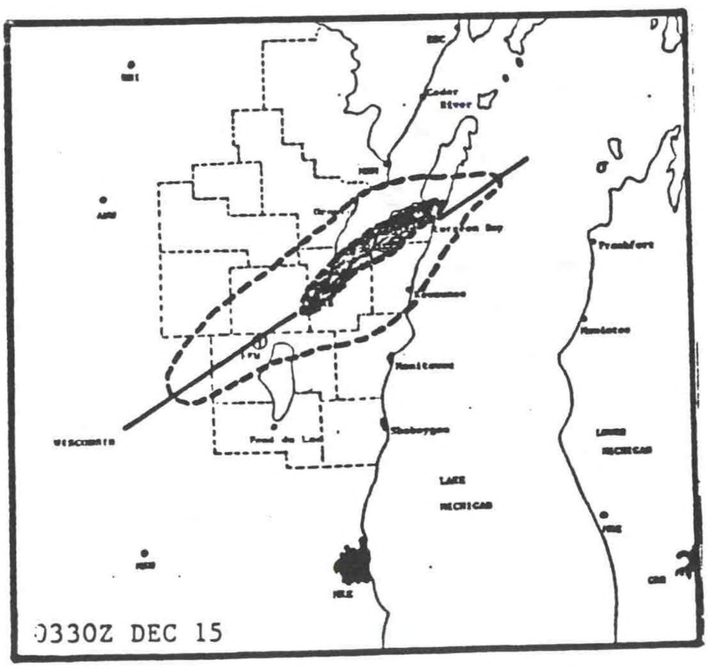
e-h



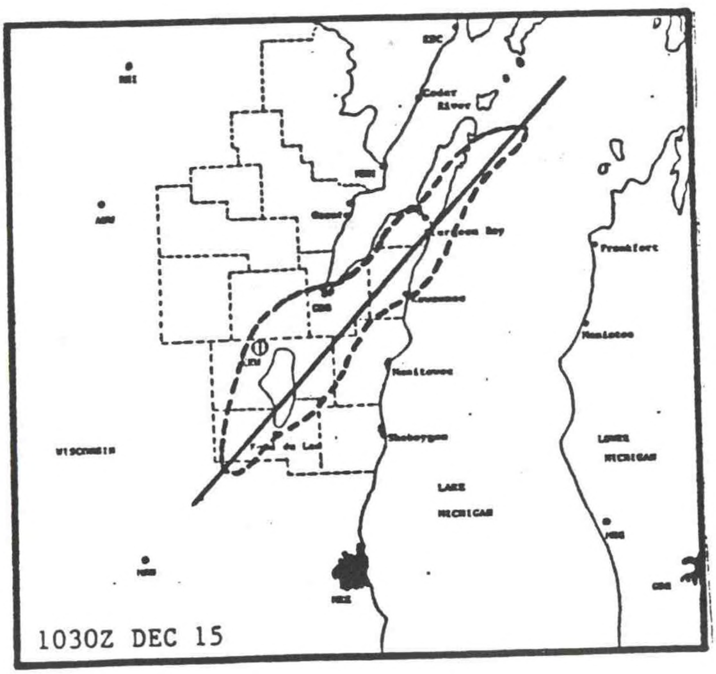
(E) Radar Overlay from Neenah, WI (EEW)
(Dotted line is detectable precip.)
(Solid bar is approx. location of snowband) 1830Z DEC 14, 1989



(F) Same as (E) Except at 2230Z DEC 14

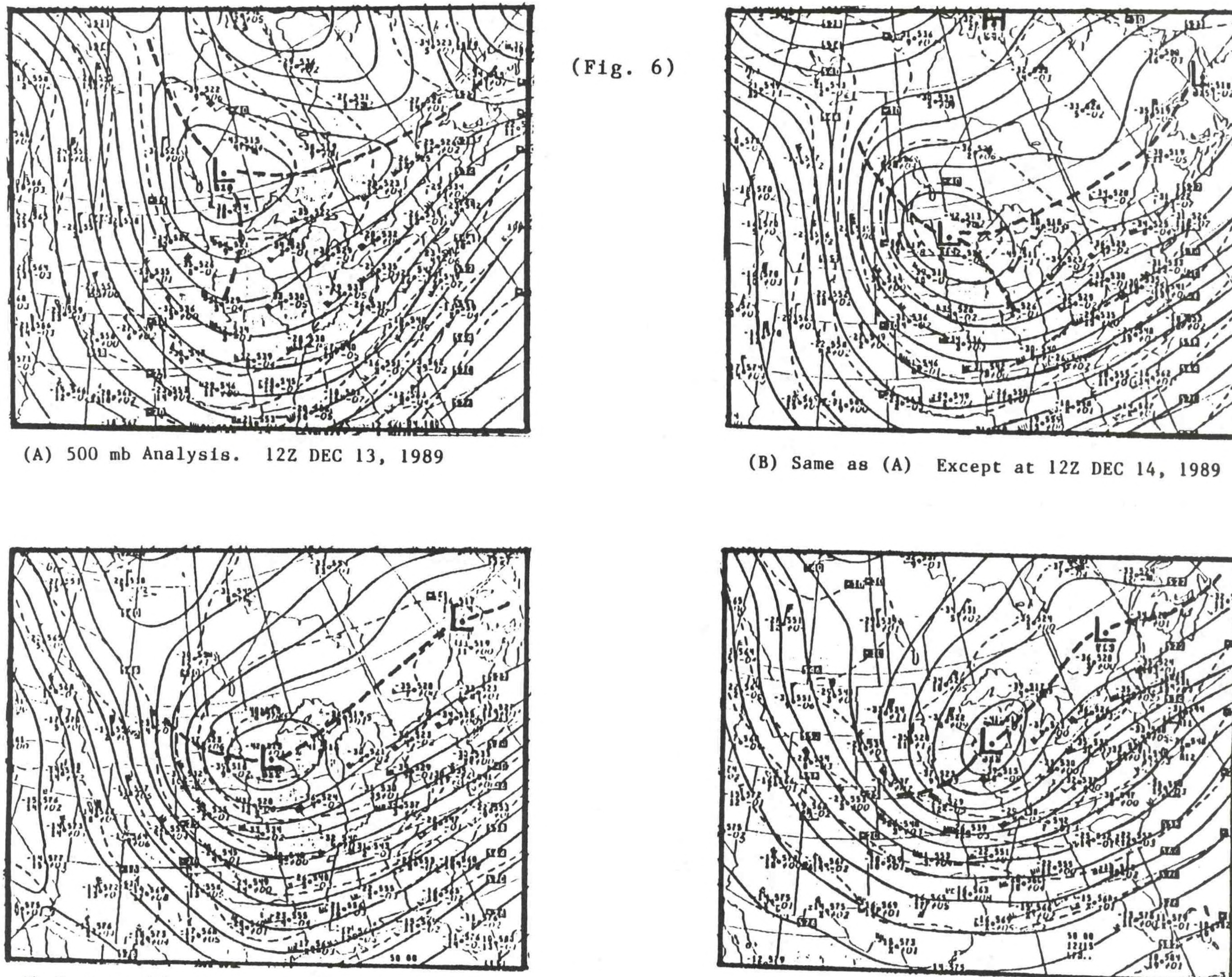


(G) Same as (E) Except at 0330Z DEC 15



(H) Same as (E) Except at 1030Z DEC 15

(Fig. 6)



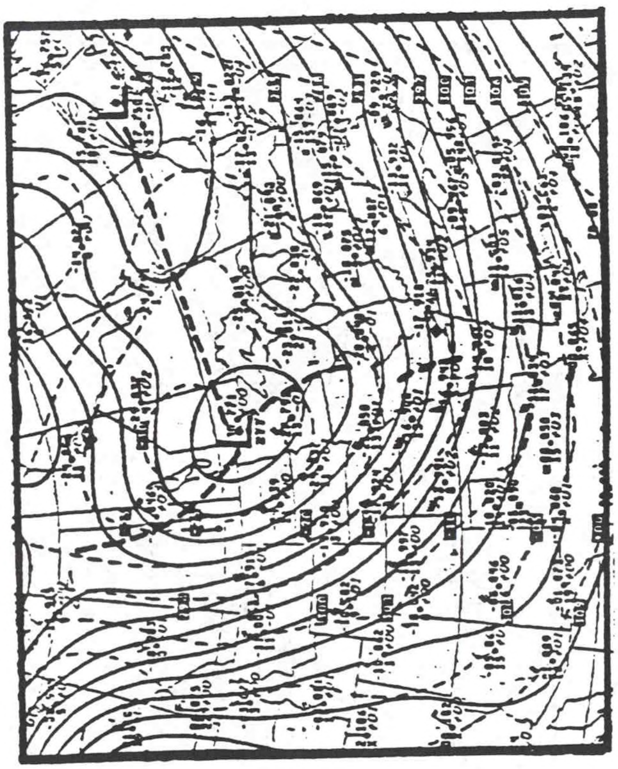
(A) 500 mb Analysis. 12Z DEC 13, 1989

(B) Same as (A) Except at 12Z DEC 14, 1989

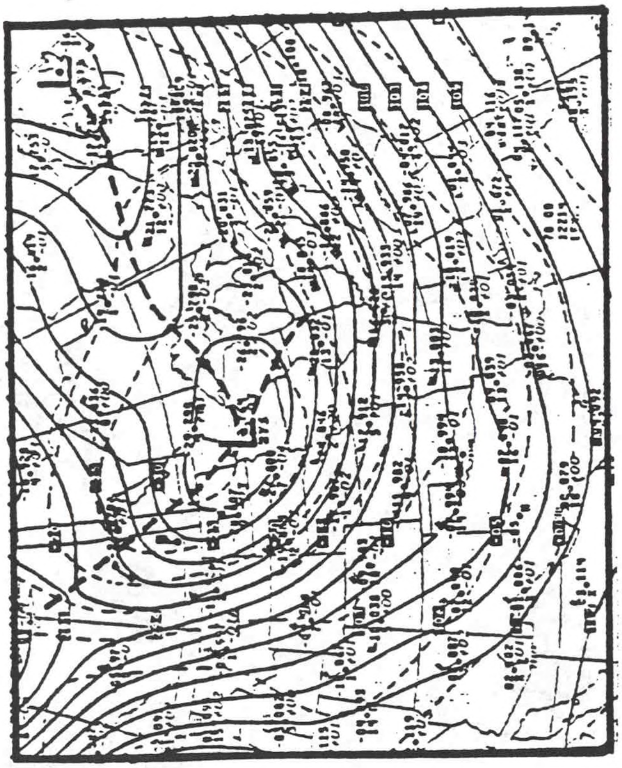
C) Same as (A) Except at 00Z DEC 15, 1989

D) Same as (A) Except at 12Z DEC 15, 1989

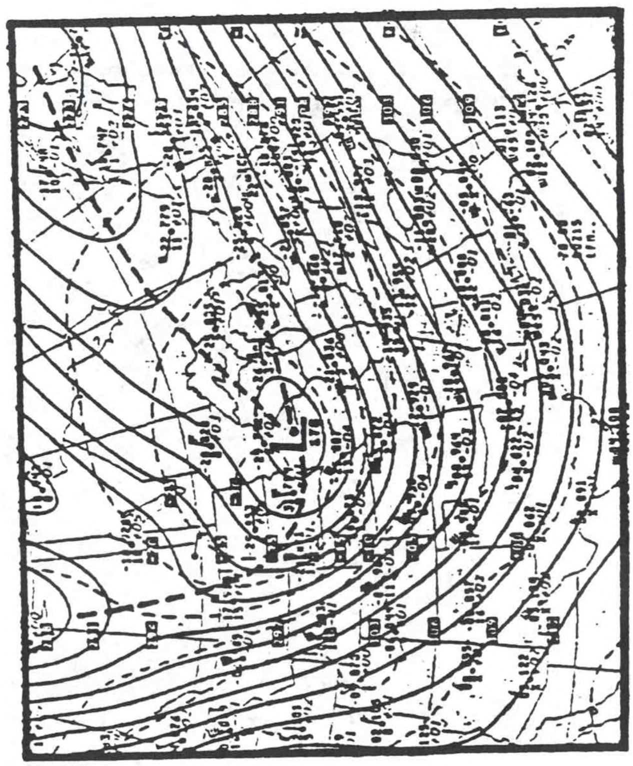
(Fig. 7)



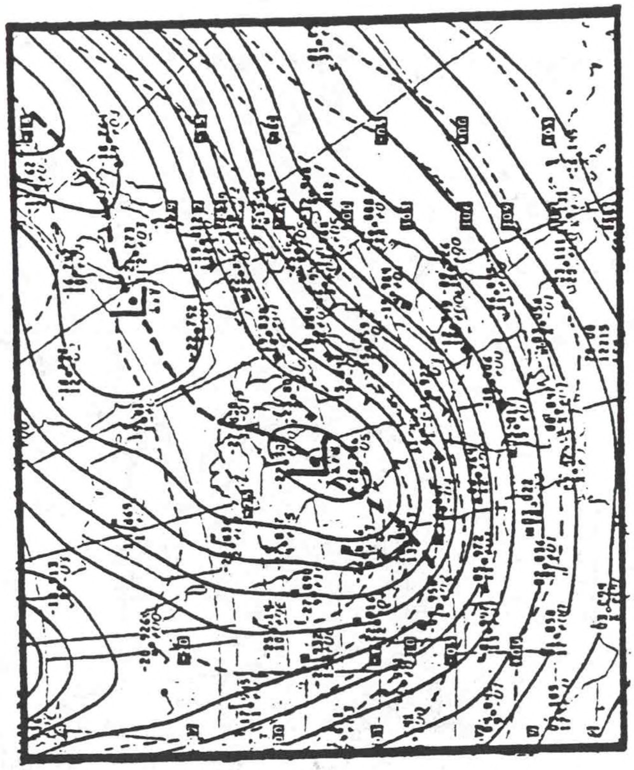
(A) 700 mb Analysis 12Z DEC 13, 1989



(B) Same as (A) Except at 12Z DEC 14, 1989

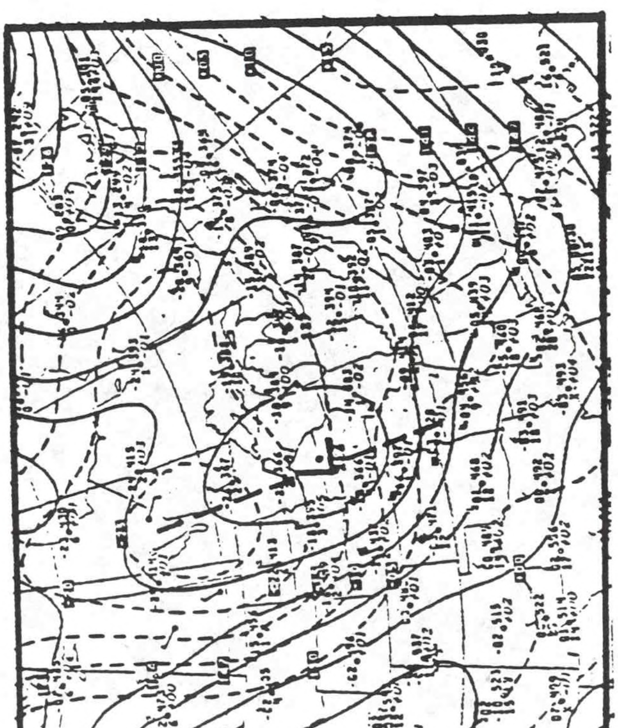


C) Same as (A) Except at 00Z DEC 15, 1989

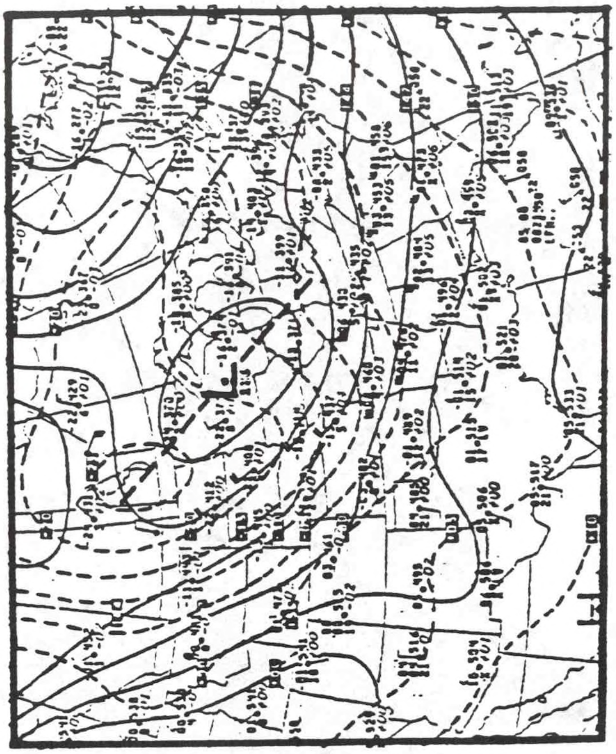


D) Same as (A) Except at 12Z DEC 15, 1989

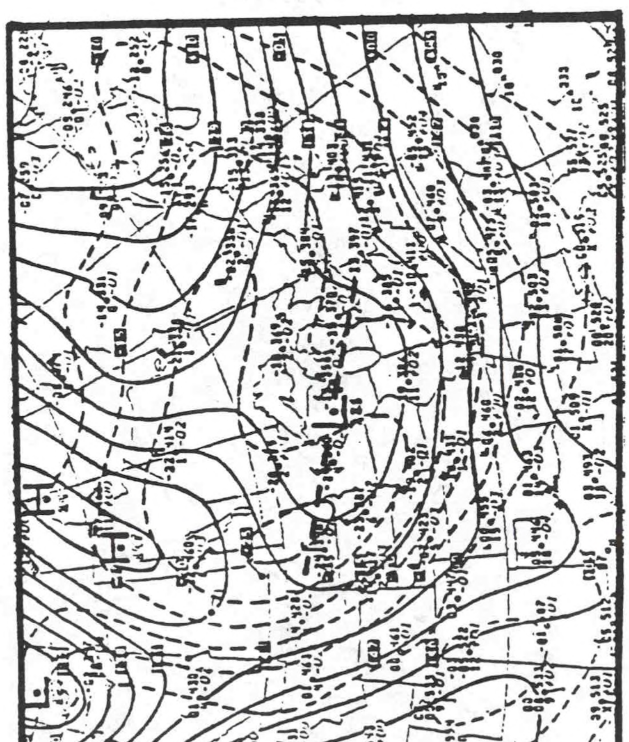
(Fig. 8)



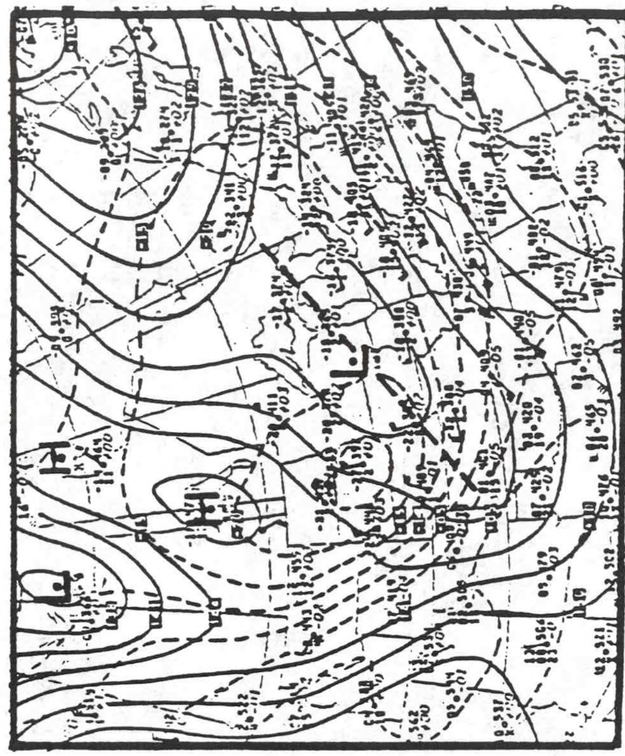
(A) 850 mb Analysis. 12Z DEC 13, 1989



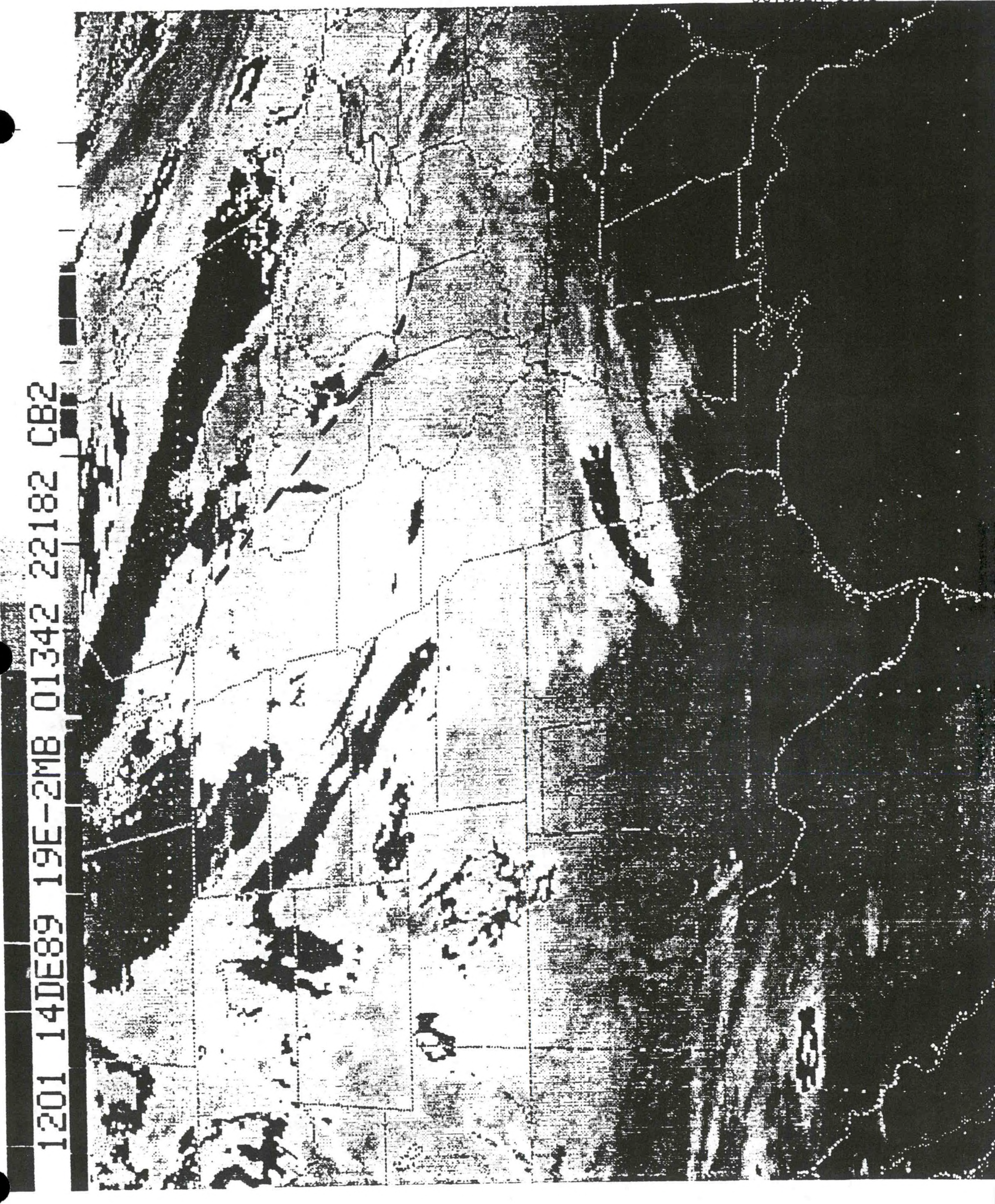
(B) Same as (A) Except at 00Z DEC 14, 1989



C) S as (A) Except at 12Z DEC 14, 1989



D) Same as (A) Except at 00Z DEC 15, 1989



(Fig. 9)

The relatively warmer air to the north of the 850 mb trough axis probably reflects a thermal contribution from the ice-free Lake Michigan below. By 00Z December 15, the 850 mb trough had also become positively tilted across Wisconsin in response to the upper level system (Fig. 8D).

4. Surface Mesoscale Analysis

In response, to some degree, to the evolving upper air features described in the previous section, a surface trough and associated convergence zone developed over northeast Wisconsin, which interacted with the lake-induced snowband.

Another look at the surface pressure and wind fields at 12Z and 21Z on December 13 (Figs. 3 and 4), revealed a weak surface low pressure system moving eastward across the State of Iowa. An inverted trough extended northward from the low across the central part of Wisconsin. Since only limited moisture was available, along with unfavorable upper level dynamics, snowfall associated with these features was generally light. During the 12 hour period ending at 18Z December 13, less than an inch of snow had fallen in the vicinity of the trough over Wisconsin. Somewhat heavier snowfall amounts of 1-3 inches, were reported closer to the surface low in extreme eastern Iowa and northwest Illinois. The surface low was forecast to track eastward into northwest Indiana, with the heaviest snowfall remaining south of Wisconsin.

By 00Z December 14, the surface low had moved to northern Illinois with the inverted trough entering eastern Wisconsin (Figs. 3C and 4C). A weak but convergent wind flow was still evident in the vicinity of Lake Michigan. This mesoscale area of convergence was embedded within a broader area of convergent flow associated with the inverted surface trough.

During the subsequent 6-hour period, the surface trough intensified as it approached Lake Michigan. By 06Z December 14, a well defined convergence zone had developed along the inverted trough axis, which extended from northwest Wisconsin, across central Lake Michigan, to the surface low located over extreme northwest Indiana (Figs. 3D and 4D). The strengthening of the surface trough over northeast Wisconsin was associated with an increase in the northeasterly wind flow over the northern portion of Lake Michigan. This northeast flow gathered moisture from the lake and transported it into the snowband, which had become anchored to the convergence zone. During the 6-hour period ending at 06Z December 14, radar showed an increasing area of VIP-level 2 intensity echoes along the convergence zone from Marinette County, across southern Door County and into western Lake Michigan (Fig. 5C).

At 12Z on the December 14, the orientation of the surface convergence zone and associated snowband (Figs. 3E, 4E, and 5D), were near the 850 mb trough axis position (Fig. 8C). Radar and surface reports had indicated that the snowfall intensity had diminished over northeast Wisconsin. A possible contributing factor may have been a weakening of the northeast low level flow below 850 mb (Fig. 2C), compared to 12 hours earlier (Fig. 2B). The 12Z sounding also indicated that the surface trough was positioned just northeast of GRB. Note the shallow westerly flow near the surface, veering easterly in the lake modified air mass above. The 12Z surface temperature analysis showed a well developed baroclinic zone was associated with the trough axis over Wisconsin (Fig. 1B).

The sequence of surface wind and pressure analysis for the period from 18Z December 14 through 12Z December 15, illustrate the rotation of the surface trough and snowband over northeast Wisconsin (Figs. 4 and 5).

At 18Z on the December 14, convergence along the trough axis intensified once again as surface winds speeds increased, especially to the northwest of a weak surface low that was reforming over east-central Lake Michigan (Figs. 3F and 4F). The formation of the low helped to maintain the northeasterly low level wind flow into the snowband over northeast Wisconsin. The SELS Satellite Discussion issued at 18Z, described a band of cooling cloud tops along the mid-level shear axis from northern Wisconsin to west central Lower Michigan. Radar data supported the satellite observations, as an increasing area of VIP-level 2 intensity echoes again appeared on the EEW radar scope (Fig. 5E). By 21Z, the radar operator noted a cyclonic rotation of the snowband. Heavy snow warnings were again issued for parts of the Door Peninsula and Marinette County. In addition, snow advisories were issued for most of northeast Wisconsin through the late afternoon and evening hours of December 14.

By 00Z December 15, the surface trough and snowband were orientated nearly west to east from central Wisconsin to central Lower Michigan, with a weak low still evident over east central Lake Michigan (Figs. 3G, 4G, and 5F). The 00Z GRB sounding showed that the surface trough was still just to the north of the city of Green Bay (Fig. 2D). Note that the low level winds veered from northwest at the surface to northeast in the lake modified air mass. The temperature and wind profiles at low levels, are typical of a profile on the cold side of a surface warm front. In this case, warmer lake modified air to the north, was overriding the Arctic air to the south. Also note the increase in the northeast flow below 850 mb compared to early soundings.

Shortly after 03Z on December 15, the surface trough and snowband finally passed southward through Green Bay (Fig. 5G). The passage of the trough is illustrated by the sequence of GRB surface observations (Fig. 10). As the trough passed a burst of heavy snow occurred. During the 4-hour period from 00Z to 04Z, over 4 inches of new snow had fallen on the city. Also note the wind shift to the northeast and the increase in temperature as the trough passed (Figs. 10 and 11).

GREEN BAY, WISCONSIN SURFACE OBSERVATIONS
DEC 14,15 1989

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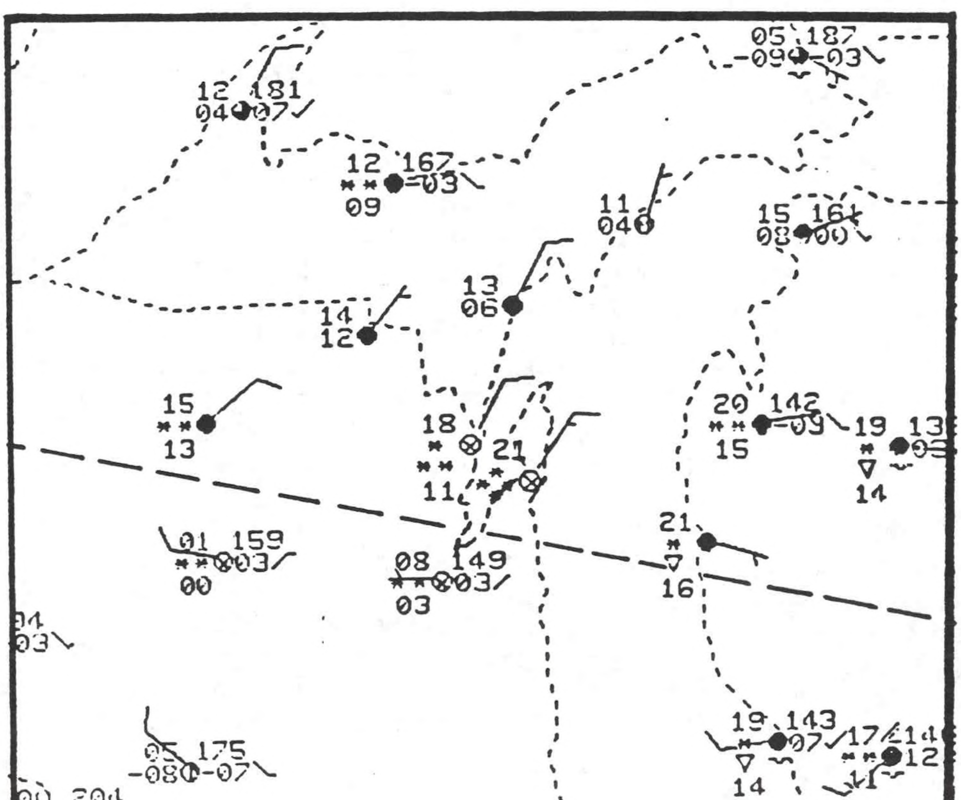
SA 2350 -X M19 OVC 13/4S-F 157/6/1/2906/994  20706 16// 90405 12 RADAT ZERO
SP 0040 W10 X 1S-F 2911/994
SA 0050 W10 X 1S-F 160/5/1/2911/995
SA 0150 W10 X 1S-F 157/4/0/2910/994/ SNOINCR 2/2/7
SA 0250 W10 X 1S-F 157/5/1/2706/994/ SNOINCR 1/3/8
RS 0350 W10 X 1/2SF 160/7/3/2905/995/ SNOINCR 1/4/9
SA 0450 W10 X 1/2SF 159/14/9/0109/995
RS 0550 M33 OVC 21/2S-F 159/13/6/3609/995/ SNOINCR 1/5/10 30310 15// 90410 14
RS 0650 M24 OVC 5S-F 163/11/2/3510/996
```

(Fig.10) Hourly Surface Observations for Green Bay, Wisconsin



(Fig. 11) 23Z Dec 14, 1989 Surface Plot
(Dashed line denotes trough axis)

Finally, by 12Z on the December 15 the surface trough and associated snowband rotated into southeast Wisconsin, in response to the upper level system, thus ending the heavy snow over northeast Wisconsin (Figs. 3 through 5H). Total snowfall amounts in northeast Wisconsin accumulated during the entire episode are shown in Figure 12.

5. Summary and Conclusion

This study described an excessive lake-enhanced snowfall event over northeast Wisconsin, which resulted from the interaction between Lake Michigan, and synoptic and sub-synoptic scale weather features. The most notable aspects of this snowfall event are summarized below:

1. The first major Arctic outbreak of the season established the necessary temperature conditions for the formation of the snowband over Lake Michigan.

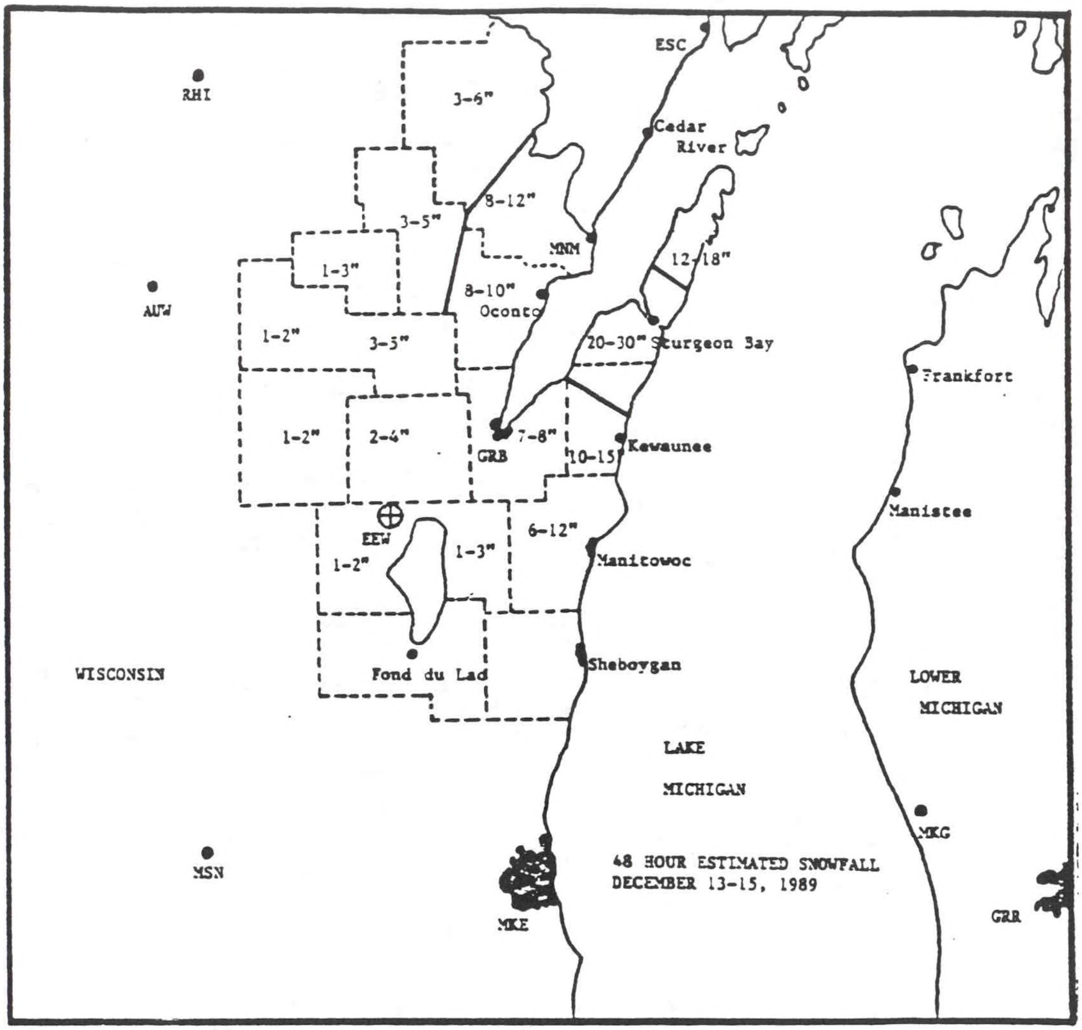
2. Synoptic scale upward motion, provided by weak low-level warm advection and a weakening mid-level shortwave trough, probably enhanced the lake-induced circulation, which ultimately lead to the initial snowband formation.

3. A synoptic scale inverted surface trough intensified as it approached Lake Michigan. This intensification was characterized by increased convergence and baroclinicity along the trough axis over northeast Wisconsin.

4. Lake-induced low pressure, which formed over the warmer waters of the lake, acted on the surface trough by creating a persistent northeasterly low level wind flow that enhanced the moisture convergence and low level warm advection over northeast Wisconsin.

5. The persistence of the snowband was related to the fact that it had become anchored to the convergence zone, associated with the surface trough and subsequently, rotated cyclonically over northeast Wisconsin in response to a mid-level shear axis.

Although heavy snowfall associated with pure lake effect conditions are rare in northeast Wisconsin, lake-enhanced events are much more likely to occur. It is important for a forecaster to be aware of the potential interaction between synoptic and/or mesoscale weather features and Lake Michigan that can lead to heavy snowfall in eastern Wisconsin.



(Fig. 12) Estimated 48 hour snowfall totals (inches) over northeast Wisconsin.

6. Acknowledgements

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