Cold Air Outbreaks over Lake Michigan During the 1982-1983 Winter Season

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Introduction

Shallow convection studies at Purdue University have been focused largely on atmospheric manifestations of Benard-Rayleigh convection, both observationally and theoretically. These studies by the mesoscale-convection group at Purdue have included a considerable effort in identifying related phenomena in real atmosphere events (see Agee and Chen (1); Agee and Lomax (2); Rothermel and Agee (7)). This type of convection is created in the atmosphere by the displacement of cold air masses over relatively large bodies of much warmer water.

A study of such convection was conducted by the Purdue group through participation in the Air Mass Transformation Experiment (AMTEX), a Japanese field program conducted over the East China Sea in 1974 and 1975. In this case, cold Asian air masses would periodically be advected by weather systems out over the much warmer Kuroshio or Japan Current (See Lenschow and Agee (6)). Similar events can occur over the Great Lakes during the winter season. Though there are obvious differences—such as air-sea contrasts ($\triangle T \sim 5\,°C$ to $10\,°C$ in AMTEX, and as much as $25\,°C$ at times over the Great Lakes), longevity of the cold air outbreak (CAO), and the size of the body of water involved (or fetch length)—the objectives and methods of study are similar.

During the winter of 1982-83, a study of CAOs over the Lake Michigan region was conducted. This winter was characterized by abnormally warm temperatures in the Great Lakes region. Figure 1 gives the temperature plot at West Lafayette, Indiana

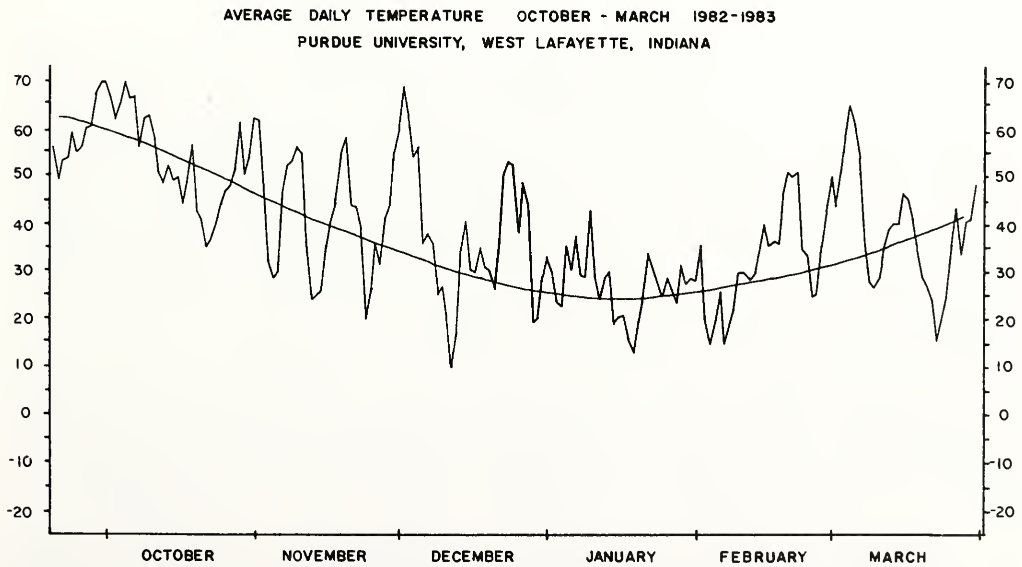

FIGURE 1. *Average daily temperature for the 1982-83 winter season at West Lafayette, Indiana.*

(approximately 130 km south of Lake Michigan) for October 1982-March 1983, showing above normal temperatures throughout most of the winter season. There were, however, five distinct cold air outbreaks which produced significant lake-effect snow in the Lake Michigan region. An appropriate definition of a cold air outbreak (CAO) might be when the air-water temperature difference is $\geq 5\,^{\circ}C$. This is consistent with a previous definition and findings by Sheu and Agee (8), Burt and Agee (4), and Agee and Sheu (3); but this will need scrutinizing for Great Lakes events.

Meteorological events produced by a CAO are the formation of convective clouds in a well-mixed boundary layer, which is formed due to strong quasi-uniform heating from below, and perhaps aided to a lesser extent by cold air advection aloft as well as cloud-top radiative cooling. Clouds from this boundary layer in the Great Lakes region are capable of producing measurable snowfall in regions downstream of the lakes. In fact, the areas south and east of the lakes annually received about three times more snowfall than do upwind regions (see Eichenlaub (5)). The lake-effect convective clouds and snow squalls occur in what would otherwise be fair weather dominated by an approaching high-pressure system with cold temperatures following the passage of a synoptic-scale weather system.

Observational studies of the lake-effect snows for each of the five CAOs during the 1982-83 winter season have been conducted. The results from one of these events, namely the 25 February 1983 case, are presented in some detail in this paper. This event was characterized by northerly flow down the main axis of Lake Michigan, with significant snowfall occurring in northwest Indiana. Pertinent surface and upper-air data have been collected and analyzed to determine the manner in which this snow event happened, based on assessment of all possible dynamic and thermodynamic fields (both upstream and downstream). This analysis will show 1) the effect of the lake on the air mass, 2) why the snow occurred where it did, and 3) kinematic and thermodynamic fields producted by the analysis schemes used. These analysis schemes will present both the horizontal and vertical structure of the snow system. The analyses are presented below with a detailed discussion of the results.

Data and Analysis Schemes

Surface data for the 25 February 1983 case study were obtained from the National Weather Service surface hourly reports and the marine coastal weather log for stations in the Lake Michigan region, as shown in Figure 2. A total of 70 weather stations provided the surface data (63 on the map in Figure 2, plus 7 near boundary stations). The analysis scheme used in this study is the Purdue Regional Objective Analysis of the Mesoscale (PROAM). This is a Barnes-type of analysis package implemented at Purdue by Smith and Leslie (9). Using input data of dry-bulb temperature, dew-point temperature, wind speed and direction, and altimeter setting for the reporting surface stations, this analysis package determined distributions of the following quantities: 1) surface streamlines (ψ_s), 2) geostrophic streamlines (ψg), 3) pressure field (p), 4) dry-bulb temperature (T), 5) vertical vorticity (ζ), 6) horizontal divergence (D), 7) virtual potential temperature (θ_v), and 8) equivalent potential temperature (θ_e). The domain of the analyzed region was 800 X 800 km, with a square grid spacing of 40 km. The mean grid spacing of the 70 stations used was equal to 63 km.

The upper-air data were obtained from the FAA 604 data circuit, using stations in the rawinsonde network over appropriate regions of the United States and Canada. Two different types of analysis were performed on the upper-air data set. The first scheme generates vertical cross-sections for the virtual and equivalent potential

FIGURE 2. *Locations of 63 of the 70 weather stations used for the surface analyses. (Seven stations, near the boundary, are not depicted.)*

temperature fields. The second was a kinematic analysis of the mesoscale as used by Sheu and Agee (8). This scheme determines localized fields of horizontal divergence, vertical vorticity and vertical motion (ω) using triangular regions for analysis. For this northerly flow case (25 February 1983), the vertical cross-sections were prepared for stations YMO-SSM-GRB-PIA (see Table 1 and Figure 3). The triangular analysis regions

TABLE 1. *Rawinsode stations selected for study of the 25 February 1983 lake-effect snow in northwest Indiana.*

Station Name	Symbol	Latitude	Longitude	Elevation (m)
Moosonee, Ont (CAN)	YMO	50°16′	80°39′	0
Maniwaki, Que (CAN)	YMW	46°22′	75°59′	170
Sault Ste. Marie, MI (USA)	SSM	46°28′	84°22′	221
Green Bay, WI (USA)	GRB	44°29′	88°07′	212
Flint, MI (USA)	FNT	42°57′	83°44′	238
Peoria, IL (USA)	PIA	40°39′	89°41′	201

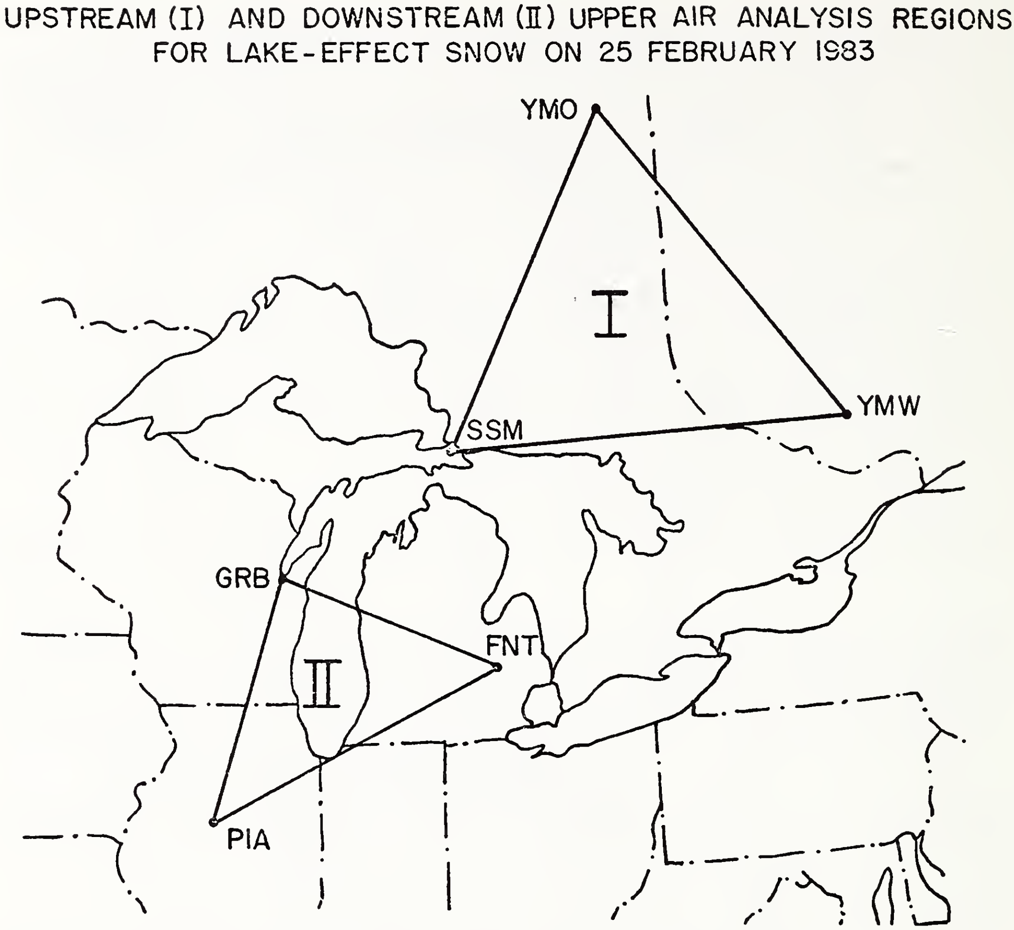

FIGURE 3. *Rawinsonde sites and triangular regions selected for thermodynamic and kinematic analyses.*

selected are shown in Fig. 3, (also see Table 1) with triangle I (YMO-SSM-YMW) designated as upstream region and triangle II (GRB-FNT-PIA) as the modified downstream region.

Other data examined in this study were the surface snowfall reports provided by the National Climatic Center and the 10-cm weather radar microfilm from Marseilles, Illinois (MMO). The analysis of snowfall reports will show the amount of snow that was deposited in the affected area of northwest Indiana. The radar analysis will show the mid-lake cloud band which was responsible for the snow in northwest Indiana.

Synoptic-scale weather conditions for 25 February 1983.

A low pressure center (~1000mb) moving eastward across southern Canada along with a weaker low-pressure system which propagated from South Dakota southeastward through Tennessee brought areas of light rain, snow and fog to the Great Lakes region on 23-24 February 1983. High pressure (~1030mb) moved in behind these systems, bringing cold Canadian air into the Midwest. As this colder air moved across Lake Michigan, a very narrow band of snow developed over the southern end of the Lake Michigan extending into northwest Indiana. At Ogden Dunes, Indiana, located at the extreme southern tip of the lake, 16 cm of snow fell between 0500 GMT 25 February and 0500 GMT 26 February. This narrow band of snow propagated very slowly westward through the morning of the 25th, with light snow falling in northeast Illinois between 1500 and 2200 GMT before the band dissipated.

The air-lake temperature contrast through this time ranged from about 5 °C to 10 °C, from south to north. By 0000 GMT 26 February, no snow was reported at any station along the southern end of the lake. At this time the high pressure ridge had moved through the Great Lakes, resulting in a shift to southerly flow, breaking up the lake-induced cloud band.

Representative Streamlines for a Convectively Mixed Boundary Layer

The 24-hour snowfall amounts for the period 0500 GMT 25 February to 0500 GMT 26 February and the MMO radar coverage at 1205 GMT 25 February are shown in Figures 4 and 5, respectively. The locations of significant amounts of snowfall

Figure 4. *Snowfall amounts (in cm) from 0500 GMT 25 February to 0500 GMT 26 February 1983.*

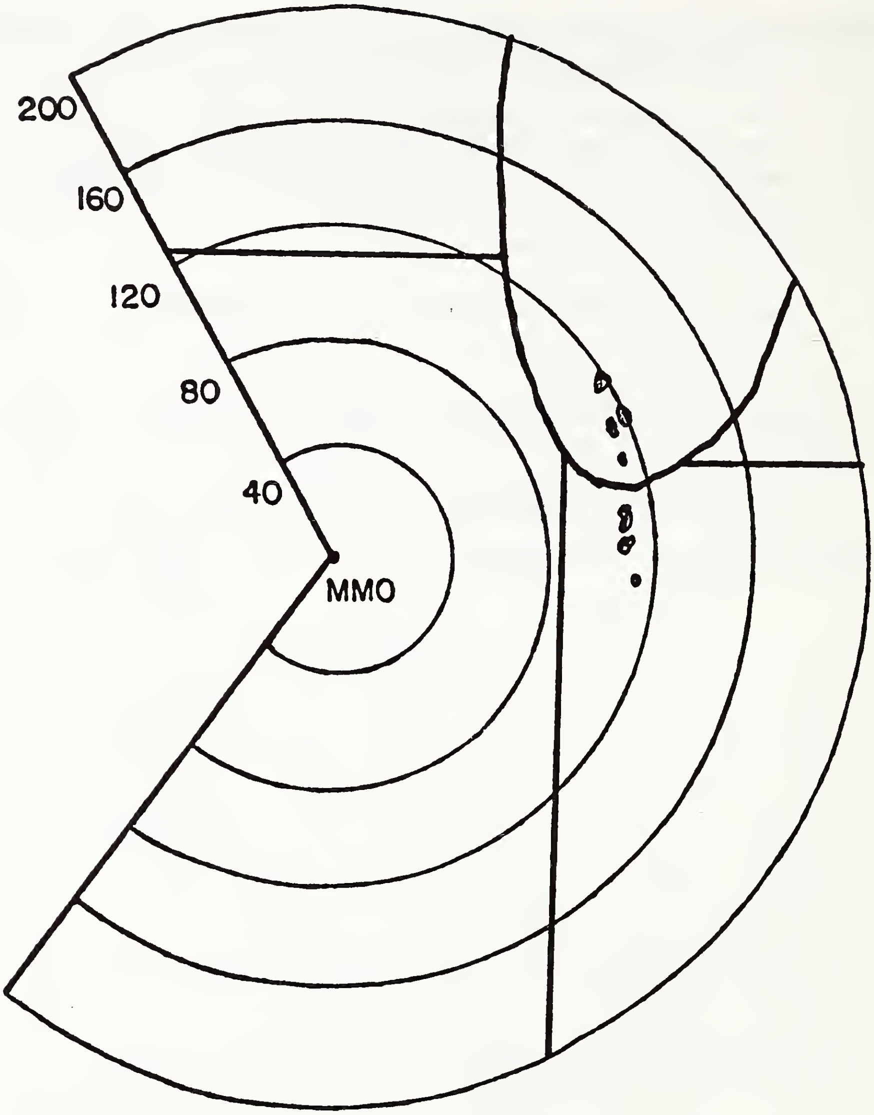

FIGURE 5. *Marseilles, Illinois, (MMO) radar analysis at 1205 GMT 25 February. This is a 10-cm radar PPI pattern with range circles of 40 km radius.*

correspond well with the locations of the radar echoes over the south end of Lake Michigan at 1205 GMT, the time of maximum intensity snowfall during this event. However, the surface streamline pattern for 1200 GMT 25 February, based on surface winds, shows the longest fetch length and landfall of these streamlines to be near the Michigan and Indiana border, east of where the snow is actually falling. Also, the geostrophic streamline pattern, based on the surface pressure field, is not representative of the convective boundary layer (CBL) flow. The geostrophic winds, which were judged to be representative of the flow at the top of the CBL, show a more northeasterly flow across the lake, with the longest fetch length and landfall in northeast Illinois.

Therefore, in the absence of a mesoscale network of rawinsondes over Lake Michigan, it was decided that a resultant streamline pattern would be more representative of the flow through the CBL that produced the lake-effect snowfall in northwest Indiana. By averaging the actual surface winds and the geostrophic winds, the resultant streamline pattern was obtained, which is presented in Figure 6. This pattern, unlike

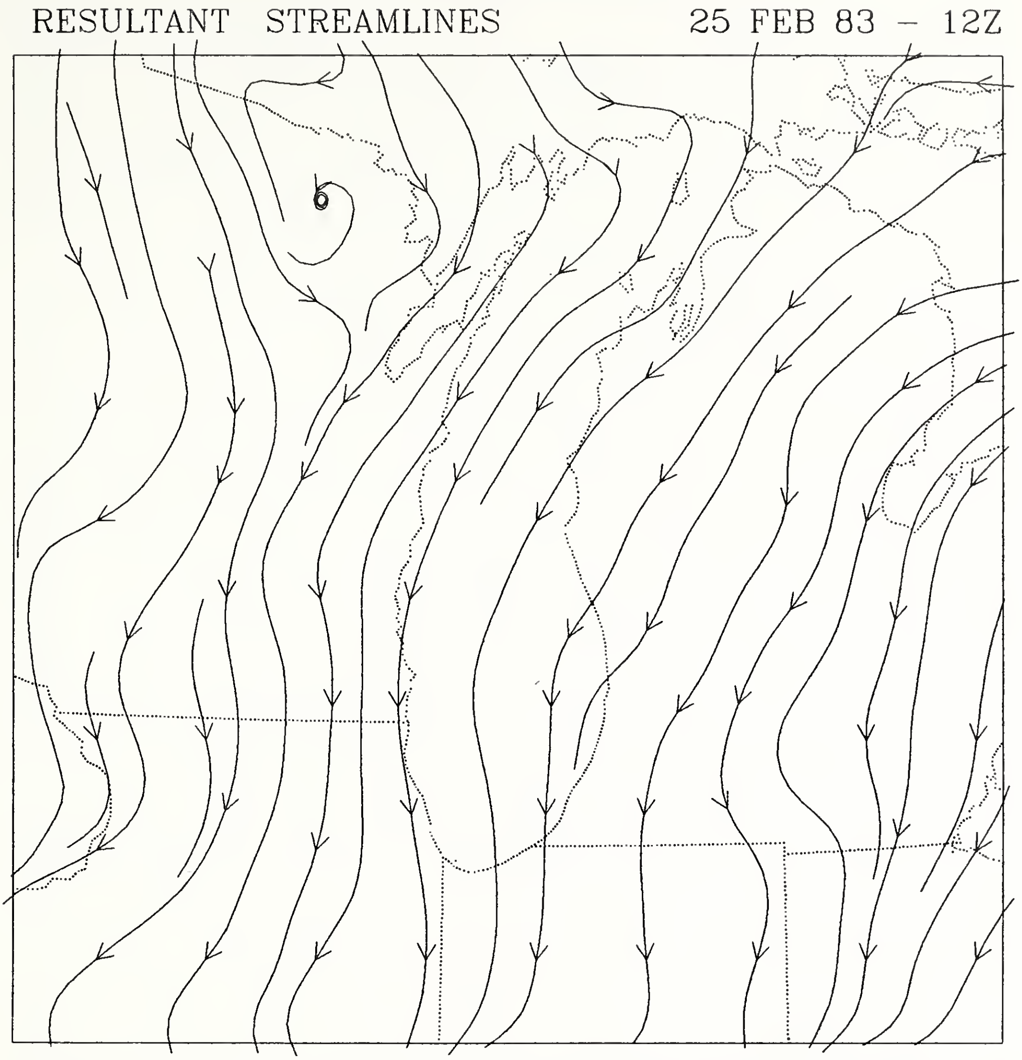

FIGURE 6. *Resultant streamline pattern (derived from surface and geostrophic wind fields) for 1200 GMT 25 February 1983 that represents flow through the CBL.*

the surface and geostrophic streamlines, matches well with the location and alignment of the radar snow band and the snowfall reports in northwest Indiana.

Air Mass Modification (surface analysis)

As previously mentioned, extensive analysis of surface features was performed for this case study using the PROAM scheme. All results presented below are based on the 1200 GMT 25 February 1983 surface data, although analyses were performed for several different times throughout the snow event. The analyses are divided into thermodynamic and kinematic results, which show the effect of the relatively warm water on the cold air which crossed the lake during this event.

a. Thermodynamic analysis

The surface pattern of dry-bulb temperature for 1200 GMT 25 February is presented in Figure 7. The effect of Lake Michigan on the cold air mass is clearly seen in the axis of warm temperatures along the western half of the lake. This matches well with the resultant flow in Figure 6. In the extreme northeast section of the lake, where

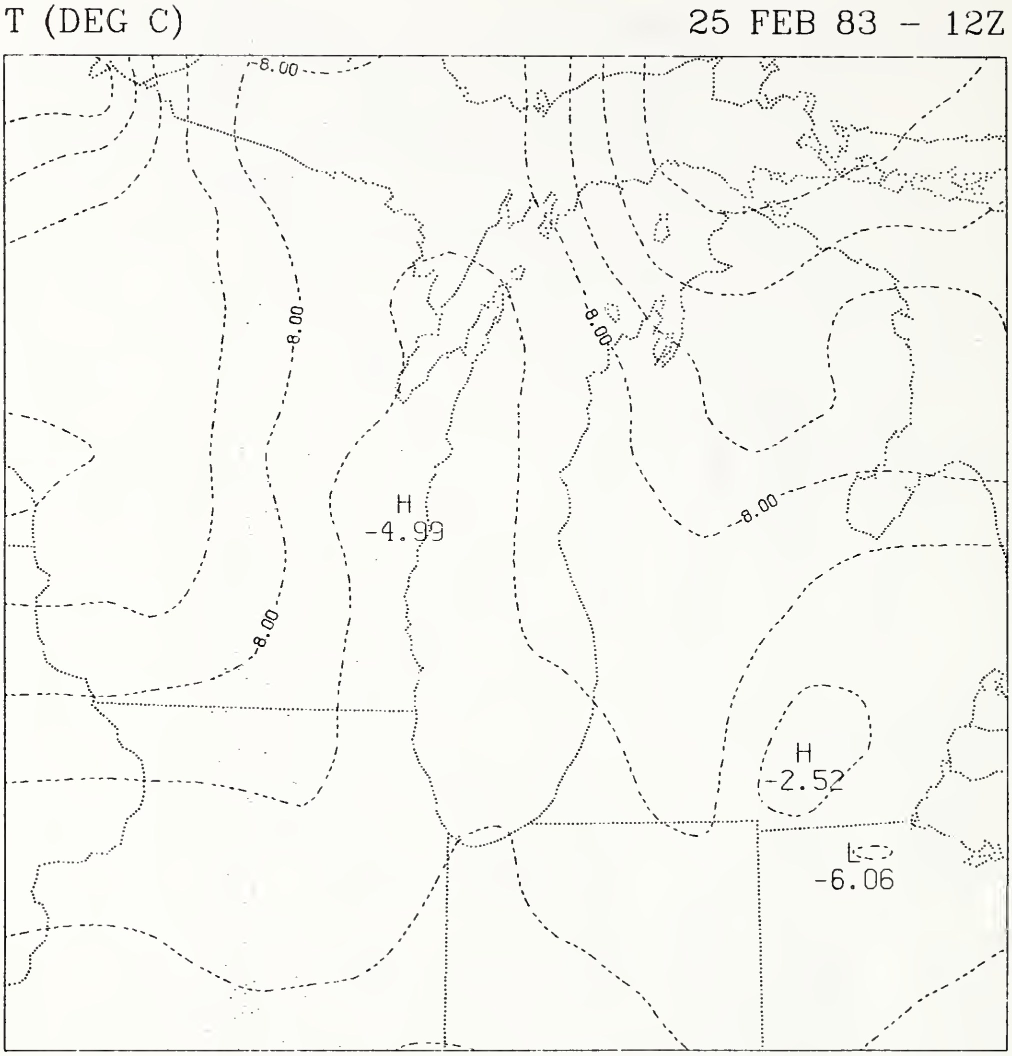

FIGURE 7. *The surface air temperature field at 1200 GMT 25 February 1983, showing the warm axis of modified polar air over Lake Michigan.*

the flow is northeasterly and the air is least modified, the surface temperature is -14 °C. After passing over the warmer lake, the air has become heated over the southern and western part of the lake, with on-shore temperatures >-5 °C. The ΔT across the lake from northeast to southeast is ~10 °C, reflecting the modification process at work. Just 150 km west of the lake, in central Wisconsin, the temperature of unmodified air is <-10 °C. The warming and moistening of the air mass as it crosses the lake could be seen also in the equivalent potential temperature (θ_e) and virtual potential temperature (θ_v) plots, but these are not shown because of their similarity to the temperature plot.

b. Kinematic analysis

The analyses of horizontal convergence and relative vertical vorticity are shown in Figures 8 and 9, respectively. An area of strong convergence (maximum of 5.7 X $10^{-5}s^{-1}$) is centered over the southern half of Lake Michigan. This area is where the most significant convection is ocurring in the boundary layer. The vertical vorticity is also at a maximum over the center of the lake. In both cases, the region west of the lake shows conditions associated with a stable air mass. Strong divergence and negative

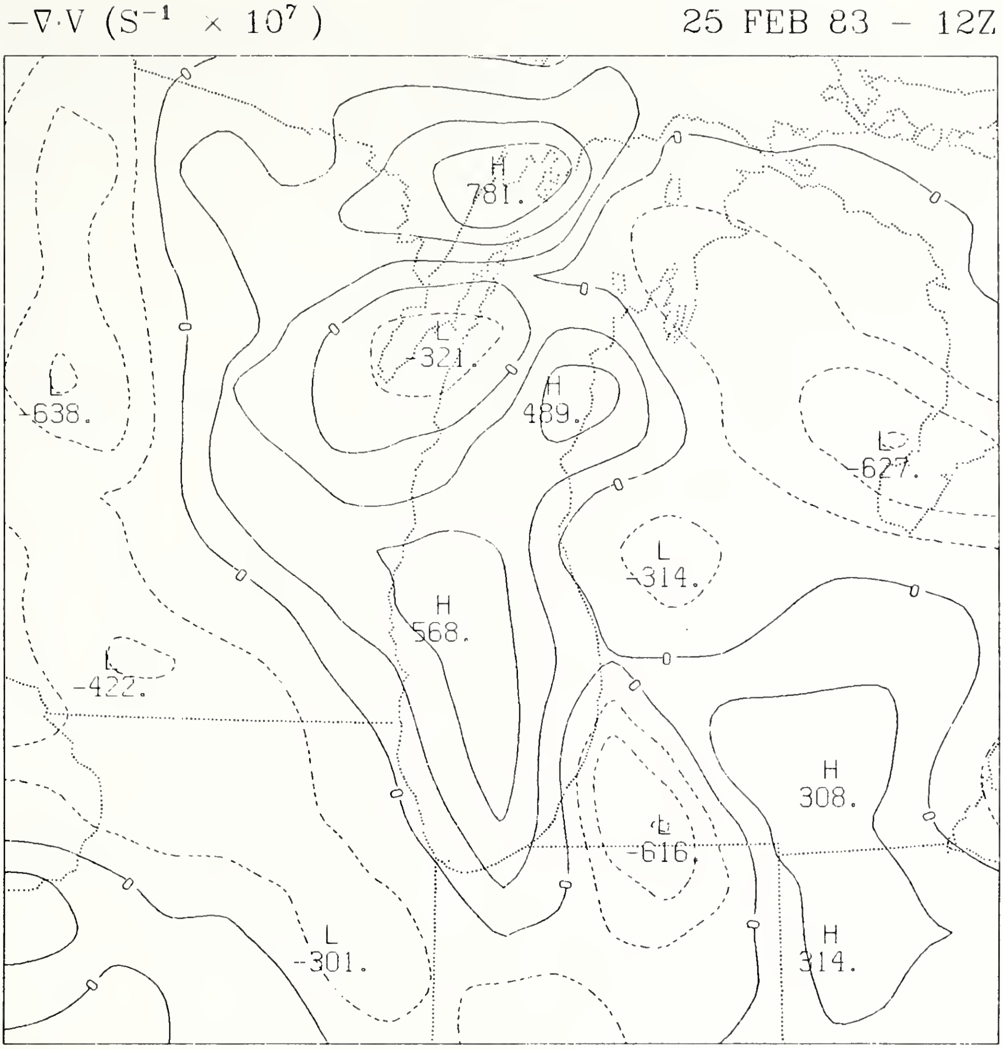

FIGURE 8. *Same as Figure 7, except for the horizontal convergence field (-∇·$\vec{V}$). The large (positive) convergence region over Lake Michigan corresponds well with clouds and precipitation.*

relative vorticity are prominent through most of the western half of Wisconsin, in a region unaffected by Lake Michigan.

Air Mass Modification (upper-air analysis)

The upper-air analyses presented below were performed using the 1200 GMT 25 February 1983 rawinsonde observations for the stations mentioned previously. The thermodynamic analysis is a vertical cross-section of virtual potential temperature (θ_v). The kinematic analysis has yielded upstream and downstream analyses of horizontal divergence, relative vertical vorticity and vertical motion. Once again, the modifying effect of the warmer lake is clearly seen in the convective boundary layer, as discussed below.

a. Thermodynamic cross-section

Figure 10 shows the θ_v vertical profile for 1200 GMT 25 February. In the upstream region (YMO and SSM), the air is stable with a rather strong θ_v gradient with height

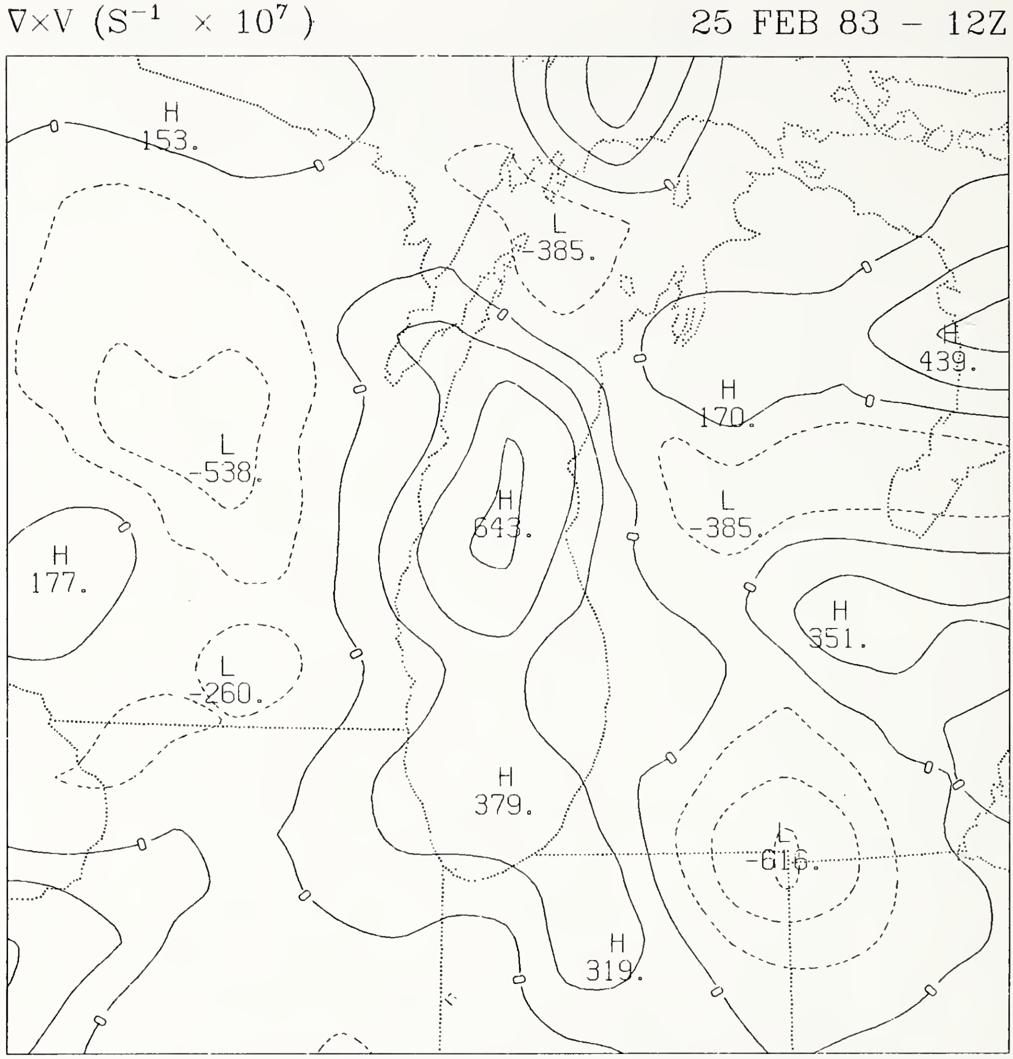

FIGURE 9. *Same as Figure 7, except for the relative vertical vorticity field ($\nabla \cdot X\vec{V}$). Strong cyclonic vorticity is centered over Lake Michigan.*

through the lower troposphere. But in the downstream region (GRB and PIA) the evidence of a convectively mixed boundary layer is apparent. Here the air is almost neutral through the boundary layer, as seen by the very small θ_v gradient up to about 820 mb. At Peoria, Illinois, θ_v increases by just 1.5 °K from the surface to 850 mb, showing downstream effect of a well-mixed convective layer. Upstream of the lake though, at Sault Ste. Marie, Michigan, θ_v increases by 13 °K over the same height, showing a very stable air mass. Above approximately 820 mb, however, the effect of the lake is not too evident, as the θ_v values are very nearly uniform over the entire cross-section. This indicates that convection is occurring only in the boundary layer region, where the lake-effect is present.

b. Kinematic analysis

The comparison of the kinematic variables in the upstream and downstream regions also shows the effect of the lake on the air mass. Figure 11 gives the relative vertical vorticity plot in the upstream region (shown in Fig. 3) while Figure 12 shows the horizontal divergence and vertical velocity (ω) in the same region. All three plots seem to be consistent with earlier observations of strong stability in the region upstream of

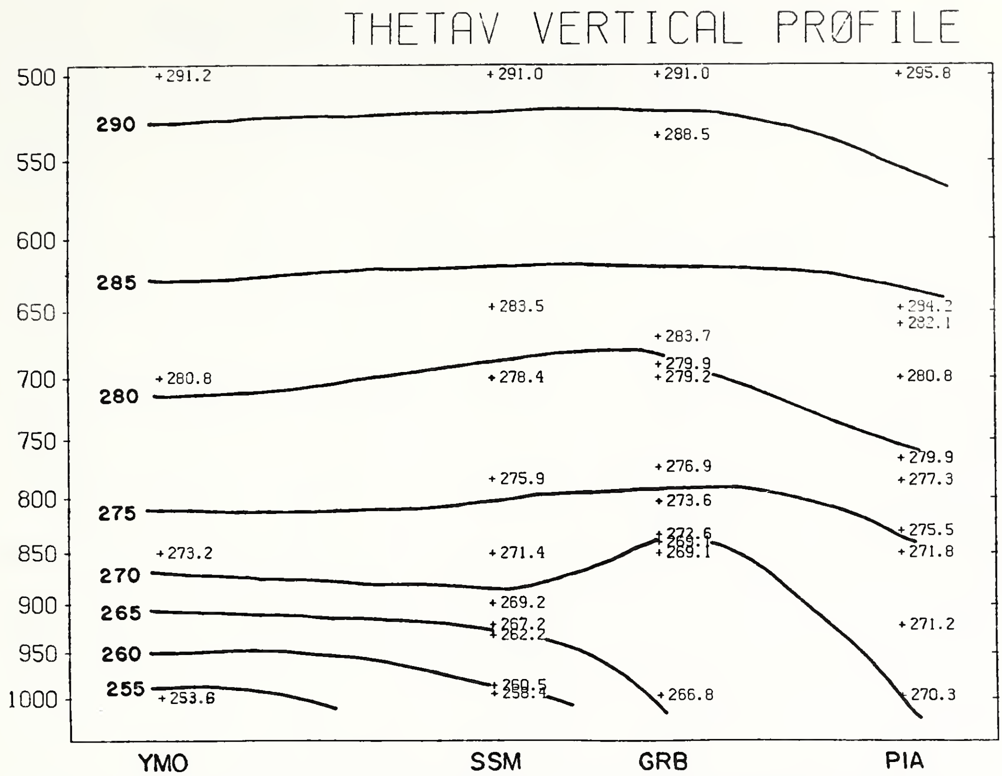

FIGURE 10. *Vertical cross-section of virtual potential temperature (θ_v) at 1200 GMT 25 February 1983, for the stations YMO-SSM-GRB-PIA (see Figure 3 and Table 1).*

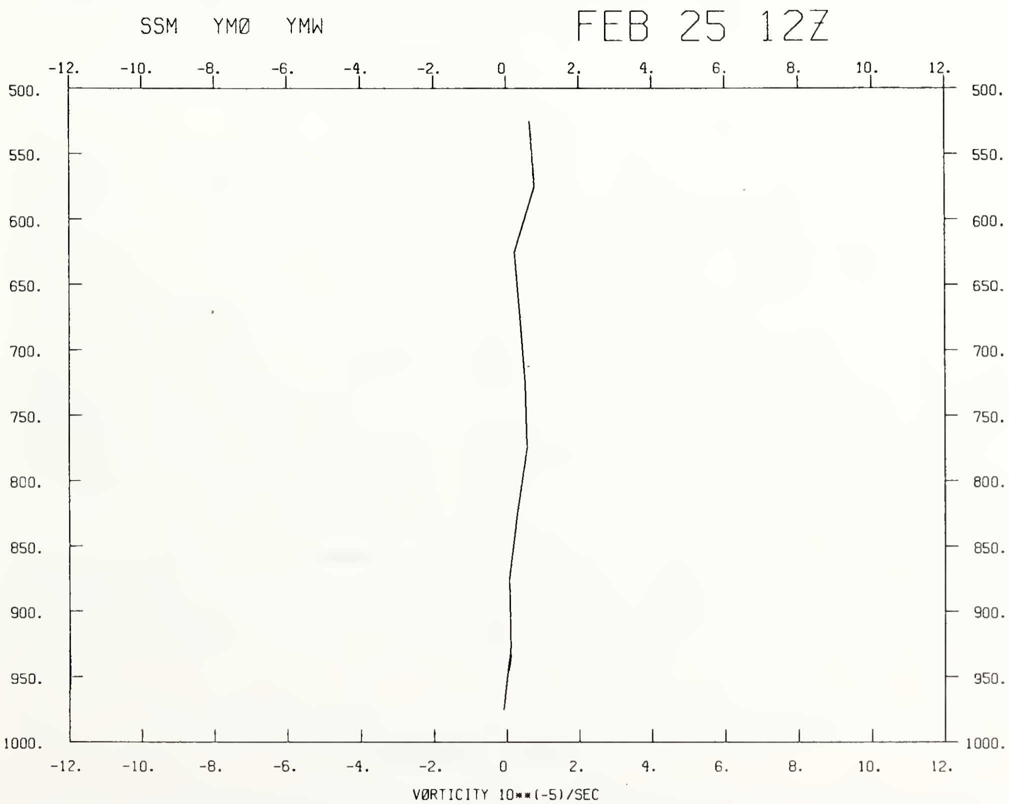

FIGURE 11. *The vertical profile of relative vertical vorticity for the upstream triangle region (SSM-YMO-YNW) of unmodified polar air at 1200 GMT 25 February 1983.*

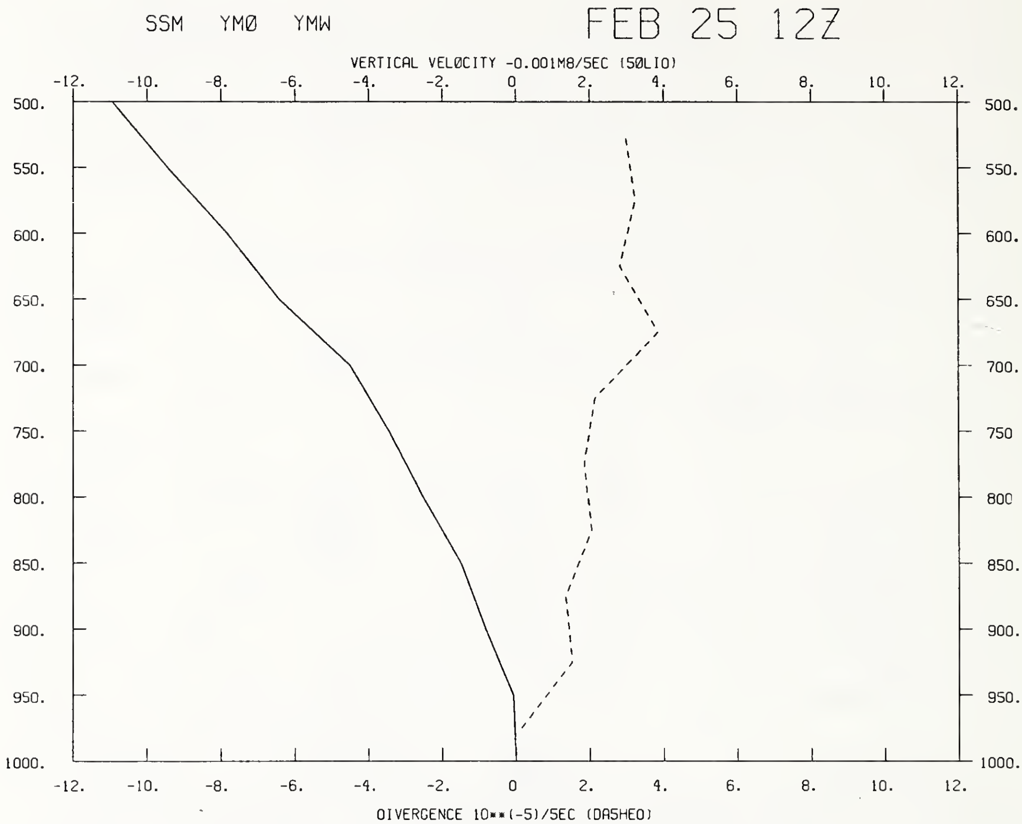

FIGURE 12. *Same as Figure 11, except for vertical motion, ω(solid line) and horizontal divergence (dashed line). The lower half of the troposphere is characterized by a sinking and diverging motion field.*

Lake Michigan. The relative vorticity is negligible through the entire layer (up to 500 mb), downward vertical motion is occurring throughout the same layer, as is positive horizontal divergence. All three of these results show the lower troposphere is under stable conditions, with no convection taking place. Also, no sign of a convective boundary layer is present; however, such is not the case in the downstream region (See Fig. 2).

Figures 13 and 14 give the plots of vertical vorticity, horizontal divergence and vertical motion downstream of Lake Michigan. The values of relative vorticity are significant throughout the entire lower troposphere. In this case there is little indication of a convective boundary layer, although the values of vorticity have been increased substantially. By studying the horizontal divergence and vertical vorticity plots (Figure 14), the presence of a convective boundary layer is clearly seen. Upward vertical motion is occurring up to approximately 800 mb, and negative values of divergence (or convergence) are present up to about the 825-mb level. These two results support the earlier statement that convection is taking place in the boundary layer up to about 820 mb. Above this boundary layer, stable conditions again seem to prevail with positive horizontal divergence and downward vertical motion present.

Summary and Conclusions

A resultant stream field was determined to obtain a representative flow in the convective boundary layer over Lake Michigan during a cold air outbreak. This resultant

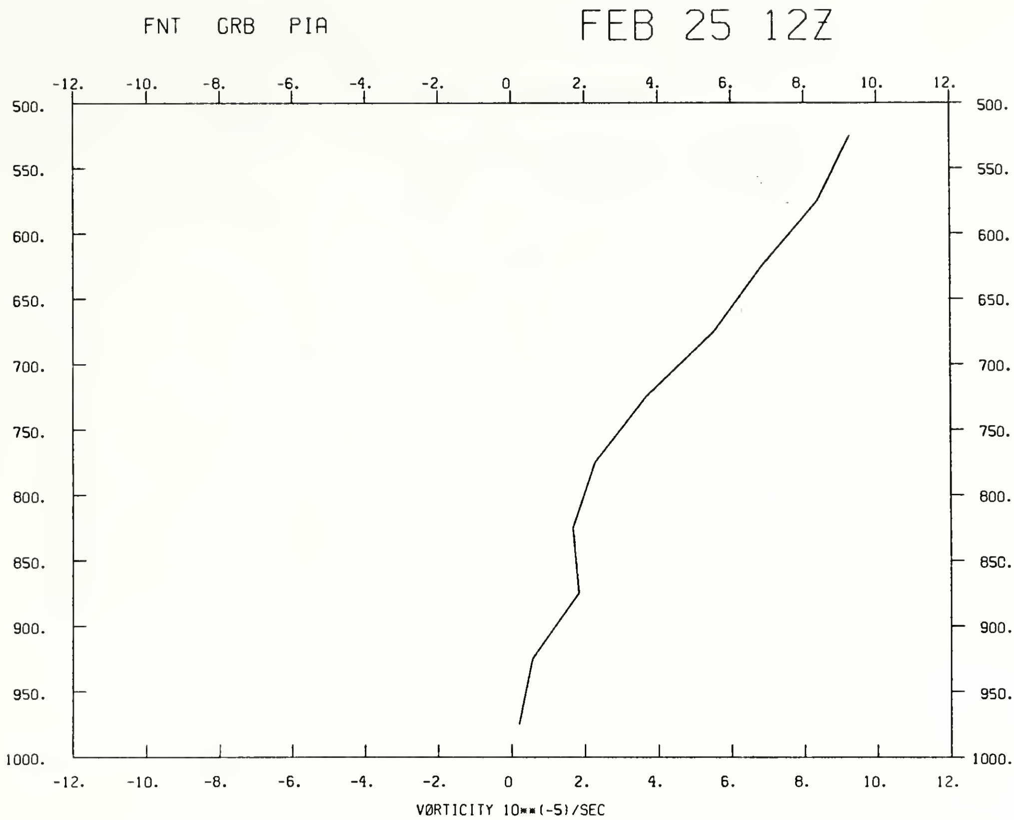

FIGURE 13. *The vertical profile of relative vertical vorticity for the downstream triangle region (FNT-GRM-PIA) of modified polar air at 1200 GMT 25 February 1983. Comparison of Figures 11 and 13 shows a strong increase in cyclonic vorticity.*

was obtained by averaging the surface winds and geostrophic winds (based on surface pressure) and was found to be more representative of flow throughout the convective boundary layer than either of its components.

Surface and upper-air analyses presented have also provided further quantitative information on the 16 cm lake-effect snow that occurred in northwest Indiana on 26 February 1983. Lake Michigan appears to have warmed the cold air mass by some 10°C at the surface. The lapse rate was modified from strongly stable to almost neutral, while the horizontal wind field changed from sinking and diverging flow to converging and rising motion over Lake Michigan and points downstream. The vorticity field also was altered significantly, changing from almost zero relative vertical vorticity to values in excess of $5 \times 10^{-5}s^{-1}$. The addition of both heat and moisture from the lake was shown also in the θ_e and θ_v fields (for both surface and upper-air analyses).

The University of Chicago Cloud Physics Group and the Purdue Mesoscale Convection Group will be combining their interests (in collaboration with the National Center for Atmospheric Research, NCAR) to undertake an extensive field study of lake-effect convective systems due to CAOs over Lake Michigan. This field program, scheduled for Lake Michigan from 1 December 1983 through 28 January 1984, will allow for a more in-depth study of phenomena associated with the lake-effect snow storms. Special rawinsonde observations will be taken daily at Muskegon, Michigan, on the east shore of Lake Michigan (by the Chicago group), and at the Indiana Dunes National Lakeshore Headquarters in Porter, Indiana, located at the extreme southern end of the lake (by the Purdue group). These observations will conceivably give more detailed downstream and cross-sectional analyses for the upper-air analysis packages.

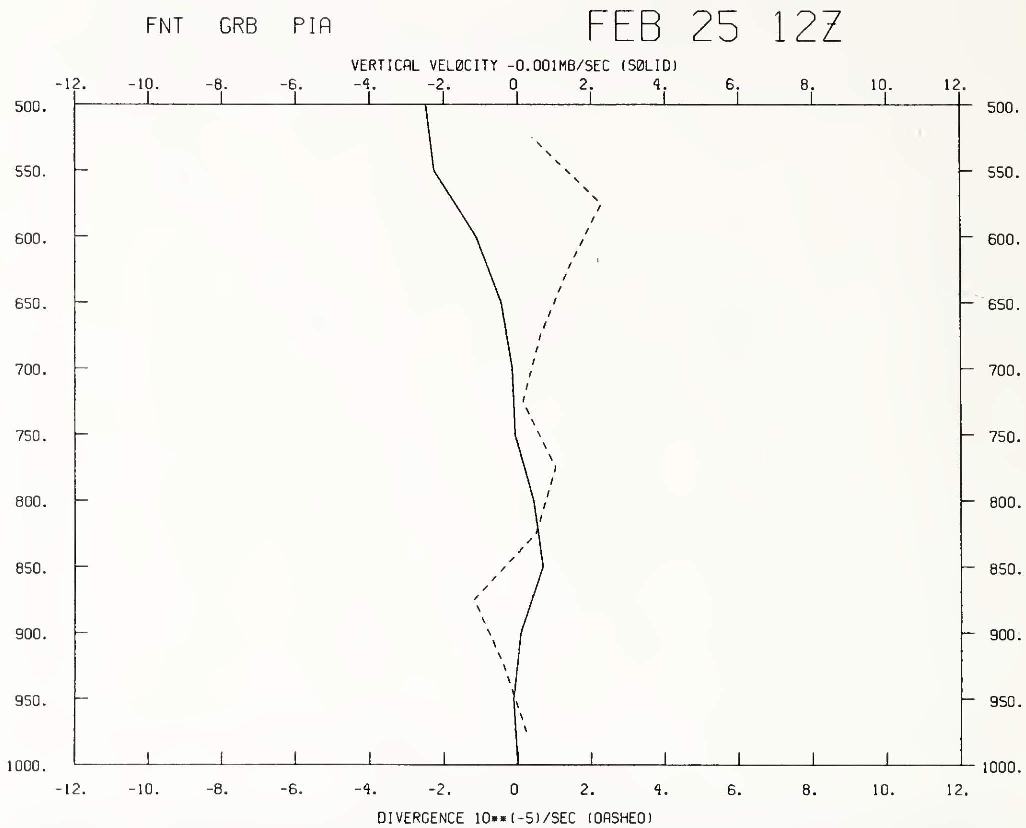

FIGURE 14. *Same as Figure 13, except for vertical motion, ω(solid line) and horizontal divergence (dashed line). Comparison of Figures 12 and 14 shows that the modified air has developed a boundary layer of converging and rising motion, a transformation from the upstream condition of stable, sinking and diverging flow.*

The PAM II mesonet system which will be deployed around the lake will allow also for a denser network of surface observations in the Lake Michigan region, thereby giving a more representative picture of mesoscale conditions.

Acknowledgments

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Literature Cited

1. Agee, E. M., and T. S. Chen. 1973. A model for investigating eddy viscosity effects on mesoscale cellular convection. J. Atmos. Sci. 30: 180-189.
2. Agee, E. M., and F. E. Lomax. 1978. Structure of the mixed layer and inversion

layer associated with patterns of mesoscale cellular convection during AMTEX 75. J. Atmos. Sci. 35: 2281-2301.
3. Agee, E. M., and P. J. Sheu. 1978. MCC and gull flight behavior. Bound. Layer Meteor. 14: 247-251.
4. Burt, W. V., and E. M. Agee. 1977. Buoy and satellite observations of mesoscale cellular convection during AMTEX 75. Bound. Layer Meteor. 12: 3-24.
5. Eichenlaub, V. L. 1979. Weather and Climate of the Great Lakes Region. Univ. of Notre Dame Press, South Bend, IN. 335 p.
6. Lenschow, D. H., and E. M. Agee. 1976. Preliminary results from the Air Mass Transformation Experiment (AMTEX). Bull. Amer. Meteor. Soc. 57: 1346-1355.
7. Rothermel, J., and E. M. Agee. 1980. Aircraft investigation of mesoscale cellular convection during AMTEX 75. J. Atmos. Sci. 37: 1027-1040.
8. Sheu, P. J., and E. M. Agee. 1977. Kinematic analysis and air-sea heat flux associated with mesoscale cellular convection during AMTEX 75. J. Atmos. Sci. 34: 793-801.
9. Smith, D. R., and F. W. Leslie. 1982. Evaluation of a Barnes-type objective analysis scheme for surface meteorological data. NASA Tech. Memo. 82509, Marshall Space Flight Center, Huntsville, AL. 25 p.