Mesoscale Spiral Vortex Embedded within a Lake Michigan Snow Squall Band: High Resolution Satellite Observations and Numerical Model Simulations

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ABSTRACT

It is known that Great Lakes snow squall convection occurs in a variety of different modes depending on various factors such as air-water temperature contrast, boundary layer wind shear and geostrophic wind direction. An exceptional and often neglected source of data for mesoscale cloud studies is the ultrahigh resolution multispectral data produced by Landsat satellites. On 19 October 1972, a clearly defined spiral vortex was noted in a Landsat-1 image near the southern end of Lake Michigan during an exceptionally early cold air outbreak over a still very warm lake. In a numerical simulation using a 3-D Eulerian hydrostatic primitive equation mesoscale model (8 km grid, 36 × 46 × 11), with an initially uniform wind field, a definite analog to the observed vortex was generated. This suggests that intense surface heating can be a principal cause in the development of a low-level mesoscale vortex.

1. Introduction

The Great Lakes profoundly impact the atmosphere from the microscale through the synoptic scale, especially during the fall and early winter when cold continental air masses sweep across the still warm lake waters. The development of intense polygonal convection cells and towering "steam devils," no more than 100 m wide, were reported by Lyons and Pease (1972). Synoptic low pressure troughs, the result of intense diabatic warming of the polar air masses by the Great Lakes, have long been documented (Petterssen and Calabrese 1959).

Lake effect snow mesoscale systems have been studied by conventional radar (Peace 1966), Doppler radar (Schoenberger 1984; Kelly 1982), instrumented aircraft (Kelly 1984; Lenschow 1973) and conventional meteorological satellite imagery (Passarelli and Braham 1981). Mesoscale numerical modelers have investigated winter air mass modification and mesoscale precipitation systems including Lavoie (1972), Ballantine (1982) and Hjelmfelt and Braham (1983).

This paper presents a high-resolution satellite image of a mesoscale spiral vortex embedded within a Lake Michigan snow band. A mesoscale numerical model simulation, in which a weak horizontally uniform (geostrophic) flow was perturbed sufficiently by surface heating (similar to that observed), produced a mesoscale vortex resembling that of the satellite image. In the absence of any synoptic scale dynamic forcing, strong surface heat fluxes appear capable of playing a major role in mesoscale vortex development.

2. Previous investigations of mesoscale vortices

Kelly (1986) notes three major categories of mesoscale organization for lake effect snow storms over Lake Michigan. The most frequently occurring category

* This paper serves as a memorial to Professor Steven R. Pease, Associate Professor of Geography, San Francisco State University, who passed away at the untimely age of 36 as a result of reactions to medications for an illness contracted while on sabbatical leave in Indonesia. Dr. Pease obtained his Ph.D. from the University of Wisconsin-Milwaukee (under W. A. Lyons) in 1975. In 1973, during his graduate studies, he co-authored with Lyons the original paper which discovered the existence of Great Lakes mesoscale vortices, using satellite imagery.

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(51%) was stratocumulus cloud streets oriented roughly parallel to the low-level wind. This is dramatically illustrated using Landsat-1 imagery (Fig. 1). There is, however, a very pronounced, though relatively rare feature which can occur during lake effect snow regimes—the mesoscale cloud vortex. Forbes and Merritt (1984) investigated GOES visible satellite images (1.0 km resolution) over the Great Lakes for the period of 1978–82. They found 14 distinct mesoscale circulations ranging from 50 to 120 km in width. These frequently (64%) resembled miniature tropical storms. The mesoscale circulations usually occurred under conditions of relatively weak surface pressure gradients, with a ridge of high pressure over or west of the region. Surface convergence into the lake was generally detected, this being related to land-breeze circulations. Forbes and Merritt (1984) concluded that the vortices are usually relatively insignificant weather producers; generally resulting in gusty surface winds, brief snow squalls and pressure drops on the order of 1.0 mb as the cyclonic circulation moved onshore. The average land–water temperature contrast was 12°C, indicative of the intense diabatic heating occurring in the lower boundary layer. Lake Michigan appeared to be the most fertile ground for mesoscale vortices (57% of those observed).

Earlier researchers (Peace and Sykes 1966) suggested the possibility of mesocyclones within major snow bands based upon examination of barograph traces. Peace (1966), using conventional radar, observed what appeared to be a vortex embedded within a lake effect snow squall. Miyazawa (1967) discussed similar radar observations over the Sea of Japan. Asai and Miura (1981) performed more quantitative observations in the same area. The vortices, which appeared to last for at least several hours, were 50 to 100 km across and had clear evidence of cyclonic rotation (vorticity approaching 10^{-3} s^{-1}). These disturbances were associated with pressure deficits of approximately 1.0 mb and could be associated with several millimeters per hour of precipitation.

In a pioneering numerical model study of lake effect storms on Lake Erie (Lavoie 1972; and personal communication), no vortical motions were noted in the total computed wind fields. However, when only the perturbation winds were examined, distinct mesoscale vortices were resolved. During a period of intense cold air advection over Lake Michigan, as discussed in Braham (1983) and Hjelmfelt and Braham (1983), a well defined quasi-stationary mesolow was found over the southeastern shoreline of Lake Michigan although GOES imagery failed to reveal any apparent closed circulation.

Thus it appears that well defined mesoscale vortices are a distinct mode of organization of low-level flow over large lakes and oceans during periods of intense cold advection. As pointed out by the National

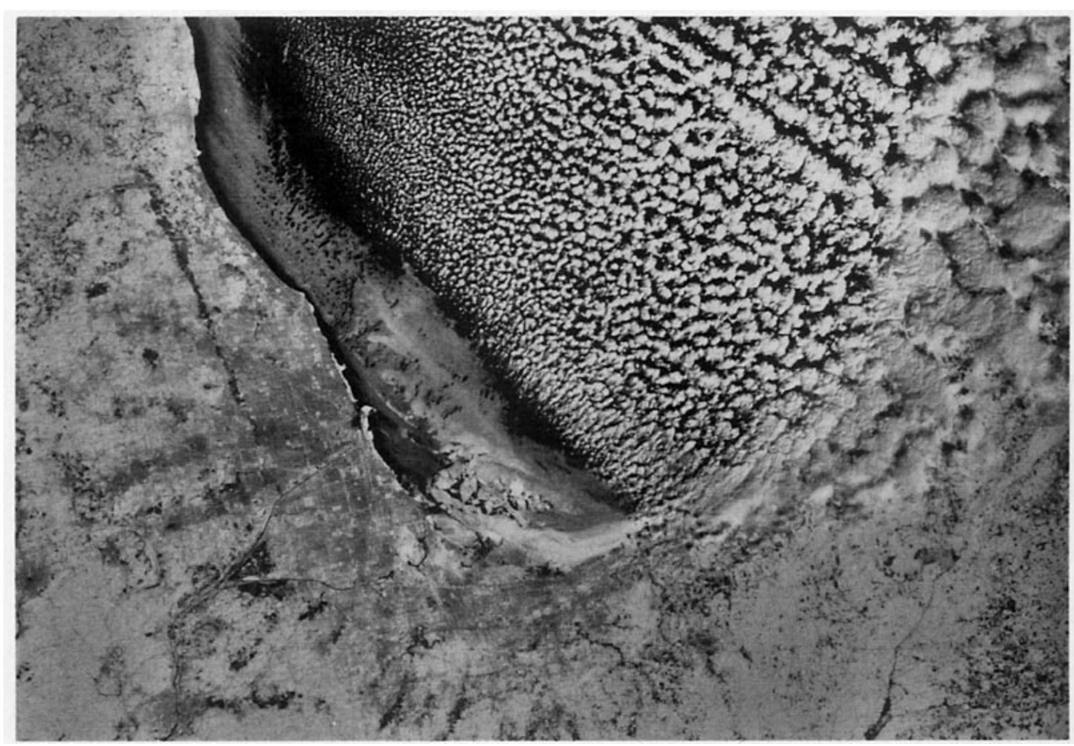

FIG. 1. Landsat-1 image, MSS Band 7 (0.8–1.1 μm) of snow squalls over the southern basin of Lake Michigan, 0930 LT 12 January 1974. Considerable ice buildup extends lakeward from the western shoreline. Cloud streets are aligned roughly parallel to the northwest flow during an outbreak of arctic air over the region.

STORM Program (UCAR, 1983) there are many unanswered questions about the nature of mesoscale forcing in lake effect storms. Peace and Sykes (1966) argue that synoptic scale dynamical forcing from aloft might be crucial in determining the surface layer responses. In contrast, Passarelli and Braham (1981) strongly suggest that differential surface heat fluxes and resulting land breezes play the major role in organizing the low-level convection. One can further speculate how such small systems (less than 100 km diameter) might be related to those superficially similar, although larger scale vortices observed in polar air streams over the Pacific and Atlantic oceans (Locatelli et al. 1982; Rasmussen and Lystad 1987).

3. The observation: mesoscale cloud vortex over Lake Michigan

At 1200 UTC 19 October 1972, an exceptionally early outbreak of cold air was dominating the midwestern United States. An intense anticyclone centered over Iowa resulted in northerly surface flow over Lake Michigan. The 850 mb analysis suggested the unperturbed winds across Lake Michigan were north-northwest at less than 5 m s^{-1} and temperatures were very cold for the season (−12°C). Winds at 700 mb were generally northwest with velocities increasing to 16 m s^{-1}. Since Lake Michigan water surface temperatures ranged between +10° and +15°C, widespread convective cloudiness and snow squalls developed as expected. Snow accumulations during the prior evening in northwestern Indiana ranged up to 12 cm. At 0930 LT, on 19 October 1972, the Landsat-1 (formerly ERTS-1) satellite scanned the region. The polar orbiting Landsat was equipped with high resolution multispectral scanning (MSS) radiometers operating in four bands, ranging from 0.5 to 1.1 micrometers. On 19 October 1972, a band of stratocumulus clouds spanned the warm waters of southern Lake Michigan. Over southwestern Lake Michigan a well defined spiral vortex, approximately 60 km in diameter, was centered east of Chicago (Fig. 2). While available for over 15 years, the meteorological community has made relatively little use of this excellent resource for studies of mesoscale cloud morphology.

Figure 3 summarizes conditions at the approximate time of the Landsat overflight. Inland, the low-level winds were light from the northerly quadrant. There is a tendency for a land-breeze component at shoreline stations, indicating an organized convergence into the lake, similar to the patterns noted by Passarelli and Braham (1981). Surface winds in the Chicago area suggested a disturbance in the wind field entirely consistent with the presence of a mesoscale vortex to the northeast. Radar operator logs from the Chicago WSR-57 indicated snow squall elements moving to the southwest at approximately 7 m s^{-1}. As is typical of lake effect snows, reported precipitation echo tops were shallow, limited to about 1250 m. Water temperatures over Lake Michigan were determined by reports from merchant ships during the 72-hour period on either side of the observation time. Note the band of water in central Lake Michigan with temperatures as warm as 14°C. Ship reports (available only over central and northern Lake Michigan) indicated air temperatures ranging from −1° to +2°C with deck level winds generally from the northwest between 5 and 10 m s^{-1}. Snow was reported at the Chicago lake front (CGX) and had ended during the past hour at Chicago's Midway Airport (MDW), approximately 15 km inland to the southwest. The area of snow covered ground on the Landsat image extended more than 50 km inland from the southern end of the lake.

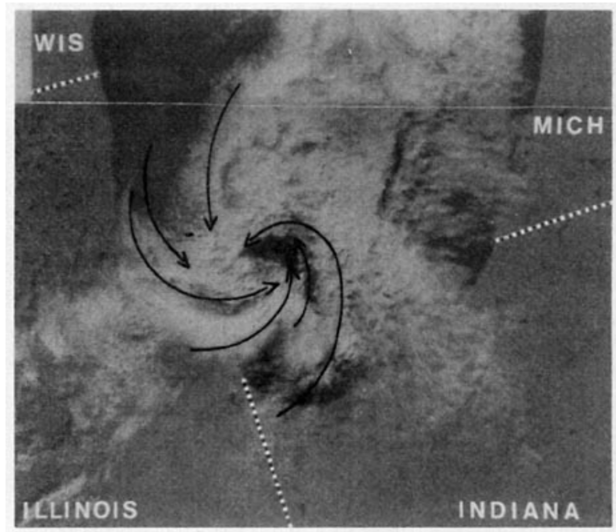

FIG. 2. A Landsat-1 image, MSS Band 6 (0.7–0.8 μm), showing lake effect clouds over southern Lake Michigan with an embedded mesoscale spiral vortex east of Chicago, 0930 LT 19 October 1972. The axes of the visible spiral bands are highlighted. This image was first presented to the scientific community in 1973 by S. R. Pease and W. A. Lyons, at the NASA Goddard Space Flight Center's "Symposium on Results from ERTS-1", and is the first known satellite observation of a Great Lakes mesoscale cloud vortex.

4. Numerical simulation

a. Model description

It has been suggested that mesoscale vortices may be the result of lake/land thermal contrasts and shoreline shape, or additionally, they may require the added support of atmospheric dynamic features aloft. A simple simulation was performed to examine whether the topographic forcing alone (i.e., a semicircular area of enhanced heat flux) could produce such a circulation over the southern end of Lake Michigan.

The simulation was made with the Colorado State University Prognostic Three-Dimensional Mesoscale (P3DM) model (Pielke 1974, 1984; Mahrer and Pielke 1977; McNider and Pielke 1981). The version used in

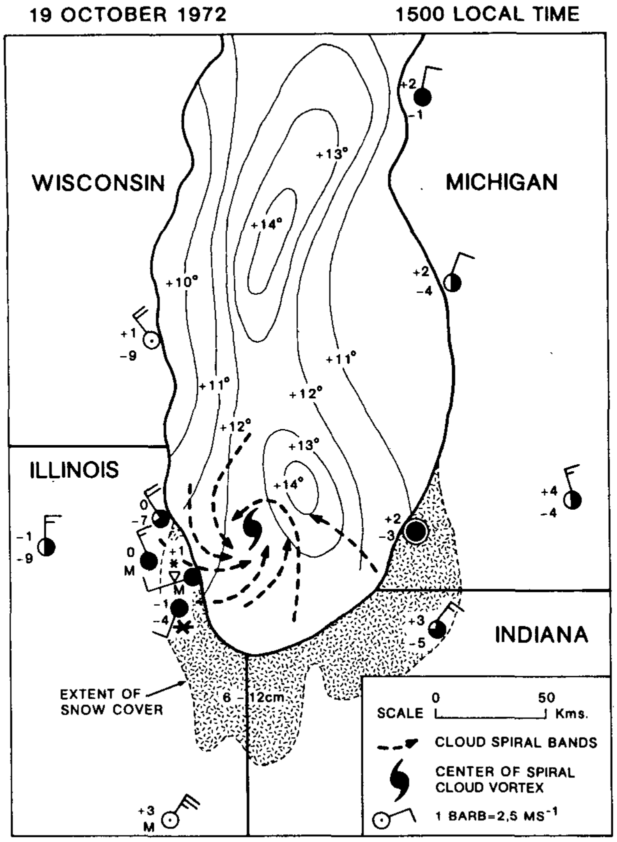

FIG. 3. Conditions over Lake Michigan, 1000 LT 19 October 1972. Isotherms of surface water temperatures are drawn at 1°C intervals. The extent of the snow cover from the preceeding snow is indicated. Snow flurries are reported at the Chicago lakefront airport, and snow has ended during the previous hour at Chicago's Midway Airport (about 15 km inland).

this study is similar to that used by Hjelmfelt and Braham (1983) in their simulation of another lake effect storm over Lake Michigan.

The model is an Eulerian, hydrostatic, three-dimensional, primitive equation-model in Cartesian coordinates. The surface layer fluxes of heat, moisture and momentum are based on the work of Businger (1973). Above the surface layer, turbulent mixing is parameterized using the exchange coefficient formulation described by O'Brien (1970) in nonstable conditions. In stable conditions, exchange coefficients are determined based on local Richardson numbers according to the method of Blackadar (1979). The depth of the boundary layer (inversion height) is predicted with the formulation of Deardorff (1974). The precipitation scheme used by Hjelmfelt and Braham (1983) is employed.[1] Computational aspects are discussed in Maher and Pielke (1978).

The simulation was performed on a $36 \times 46 \times 11$ grid. The horizontal grid spacing was 8 km, except at the outermost four grid points where the grid spacing expanded linearly to 40 km. Zero gradient conditions were employed at the lateral boundaries. The vertical grid levels were defined at 10, 100, 500 and 1000 m. Above 1000 m, a vertical grid spacing of 500 m was maintained. A time step of 90 s was used.

At the initial time, a horizontally uniform synoptic field with an Ekman balanced boundary layer was assumed. Figure 4 shows the model sounding based on the 1200 UTC radiosonde taken at Green Bay, Wisconsin. Surface temperatures and specific humidities were prescribed at each grid point, based on the 1200 UTC observations. Water temperatures were as shown in Fig. 3. Surface roughness (Zo) over land was assumed to be 20 cm and was computed as a function of the wind stress over water as suggested by Clarke (1970). The surface conditions are held constant. The atmospheric flow is allowed to develop from the initially uniform synoptic wind field in response to the forcing due to differentials in heat, moisture and roughness between the land and water surfaces.

b. Results of the simulation

Upon initialization, the P3DM model was executed for a thirty hour period. This allowed the initial horizontally uniform synoptic flow to respond to the perturbations caused by the surface heating over the lake. A low-level wind circulation gradually developed. After approximately 16 hours, conditions remained essentially steady state for the remainder of the run.

Figure 5 shows the simulation at hour 20. At 100 m above the surface (Fig. 5a), the wind vectors reveal a closed circulation at virtually the same location as observed in the Landsat image. The circulation is maintained to a height above 1000 m, with the axis appearing nearly vertical. The 2000 m (Fig. 5b) level shows a strongly divergent flow present aloft above the low-level circulation center. At 2500 m, the winds largely revert to that determined by the synoptic pressure field, although there is still clear evidence of a lake induced disturbance. As indicated by Fig. 6a, rather intense vertical motions are present, in excess of 30 cm s^{-1} at 1000 m over the southern end of Lake Michigan. The computed precipitation rates in this region reached a maximum of 0.7 mm h^{-1}. The pressure field over the center of Lake Michigan suggests a pressure deficit in the mesoscale vortex center of between 1.0 and 1.5 mb. This is the same order of magnitude as observed in previous investigations. There is a horizontal temperature contrast between inland Wisconsin and central Lake Michigan in excess of 7°C, the result of diabatic heating from the underlying warm lake water.

On the whole, there is striking similarity between this model-simulated, low-level circulation and the ob-

[1] Sublimation in the subcloud layer is not considered, and may modify the strength of the simulated response.

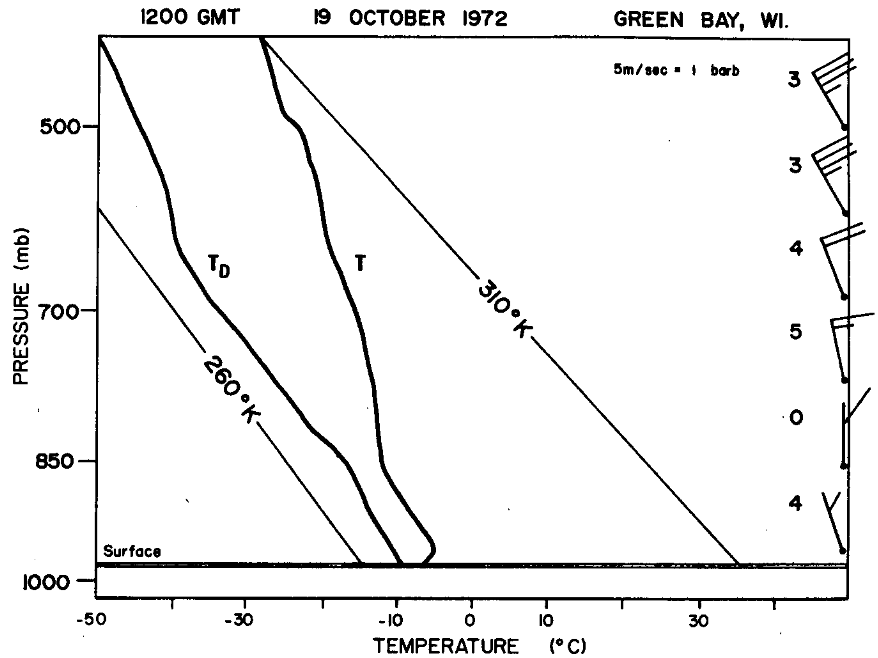

FIG. 4. Sounding used to initialize the P3DM Model, based upon the 1200 UTC 19 October 1972 radiosonde ascent from Green Bay, Wisconsin. One wind barb equals 5 m s^{-1}.

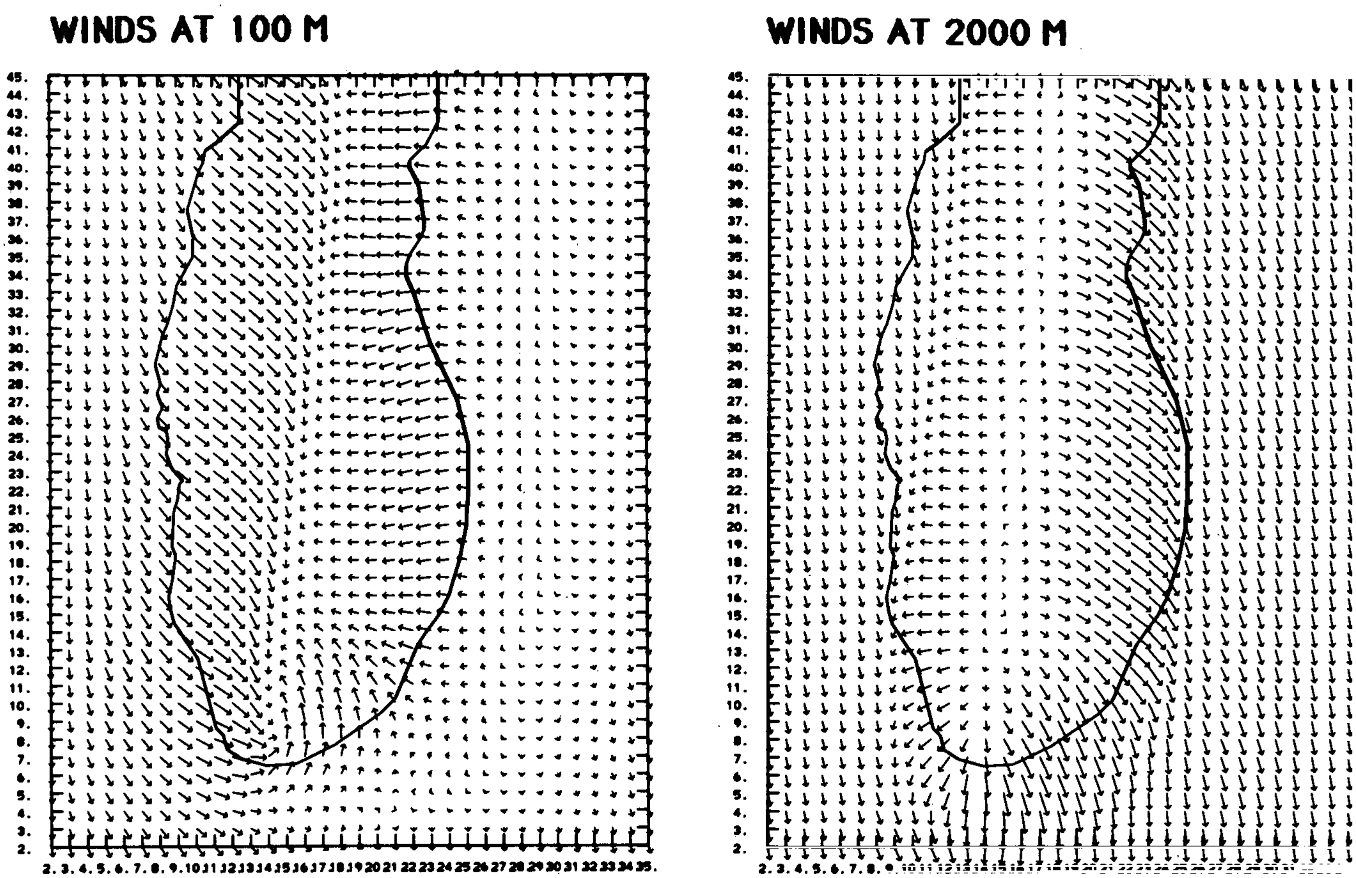

FIG. 5. (a) Computed wind vectors (scale: 8 m s^{-1} per grid interval) at the 100 m level, for hour 20 of the model run. (b) Same as (a) except for the 2000 m level.

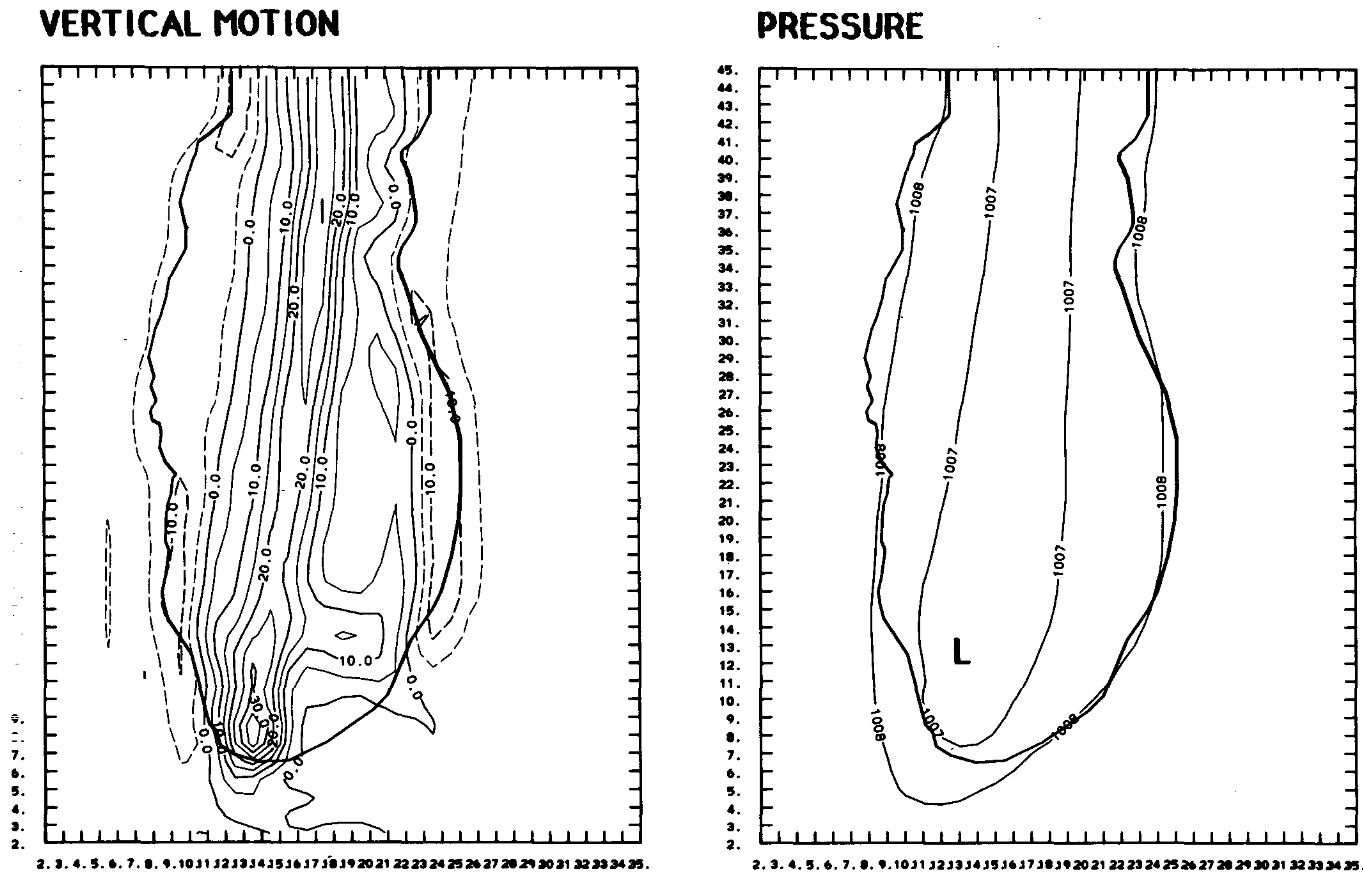

FIG. 6. (a) Computed vertical motion field (solid lines upward, 5 cm s^{-1} intervals) at 1000 m, for hour 20 of the model run. (b) Computed pressure field at 55 m above the surface, 1.0 mb isobars, at hour 20 of the model run.

served (and inferred) surface winds, although the actual spiral banded structure of the mesoscale cloud vortex can not be resolved by the P3DM. Due to the unavailability of other high resolution satellite images, it is unknown whether or not the actual cloud vortex propagated along the axis of the main cloud band or, in fact, was a quasi-stationary feature of the mesoscale flow. Given the nature of the quasi-circular heat source (the southern basin of Lake Michigan), it is plausible that the vortex was nearly stationary, with topographically induced forcing dominating advective effects in the very light regional flow field.

5. Summary and conclusions

The extremely high resolution afforded by Landsat imagery reveals the detailed structure of a lake effect snow event in which an embedded cyclonic circulation was plainly evident over southern Lake Michigan. Landsat imagery should be recognized as a significant data resource for mesoscale researchers. Forbes and Merritt (1984) suggested that most such observed mesoscale vortices are associated with relatively light precipitation. In this case, the snow band in which the vortex was present resulted in up to 12 cm of snow, a record early accumulation for the northwest Indiana "snow belt."

A three-dimensional primitive equation mesoscale numerical model, in which an initially uniform wind field is perturbed by warm underlying lake water, produces an excellent analog of the observed low-level circulation. The model simulation suggests that the development of such mesoscale vortices does not necessarily require support from atmospheric dynamic features aloft, but may develop as a natural response to the topographic forcing under weak wind conditions. Zhang and Fritsch (1985) suggest that there appears to be a common process responsible for the rapid cyclonic spinup of several different types of mesoscale vortices, including Polar lows, tropical cyclones, lake vortices, etc. A major factor in the development of these circulations is the intense air mass modification induced by the low-level sensible and latent heat flux from the water surface to the overlying colder air mass.

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