

## PICTURE OF THE MONTH

## Mesoscale Vortices Embedded within a Lake-Effect Shoreline Band

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**1. Introduction**

Mesoscale vortices are one of the basic types of wintertime atmospheric circulations that occur in the Great Lakes region as a result of lake-to-atmosphere heat and moisture exchanges. Mesoscale vortices associated with the Great Lakes occur over a range of diameters from approximately 10 to 1000 km. On the largest scale, aggregate vortices with widths of 500–1000 km form over the Great Lakes region and often appear as weak low pressure centers or large-scale sea level pressure (SLP) and circulation perturbations (e.g., Sousounis 1997). This article presents a lake-effect event in which vortices developed with diameters of 15–35 km, which fall within large meso- $\gamma$  and small meso- $\beta$  scales (Orlanski 1975).

Meso- $\beta$ -scale vortices with size scales near that of a lake basin are often the most impressive and discernable in appearance on satellite and radar imagery. For example, Laird (1999) documented an unusual case with four meso- $\beta$ -scale vortices simultaneously occurring over Lakes Huron, Michigan, and Superior. These vortices are generally associated with weak winds and light snowfall (e.g., Forbes and Merritt 1984), although some can result in localized intense snowfall (Laird et al. 2001). Forbes and Merritt (1984) documented 14 vortex events over Lakes Huron, Michigan, and Superior during a 5-yr period. The vortices were accompanied by brief snow squalls, lower surface pressures, and weak

cyclonic low-level circulations with diameters of about 50–120 km. Similarly, Pease et al. (1988) reported a vortex over the southern basin of Lake Michigan that was accompanied by a weak cyclonic circulation and light snow.

Past observational and numerical studies (e.g., Hjelmfelt 1990; Pease et al. 1988) have indicated that meso- $\beta$ -scale lake-effect vortices tend to occur with large lake-air temperature differences ( $\Delta T$ ) and weak synoptic-scale winds. However, Laird et al. (2001) examined a mesoscale vortex that developed along an existing convergence zone under conditions of low  $\Delta T$  (6°–9°C). More recently, Laird et al. (2003a,b) used numerical simulations for a large range of lake-effect environments to determine that mesoscale vortex formation is related to small values of the ratio of wind speed ( $U$ ) to overlake fetch ( $L$ ) and is independent of  $\Delta T$  when  $\Delta T \geq 5^\circ\text{C}$ .

Meso- $\gamma$ -scale vortices are typically embedded within or develop in close proximity to lake-effect shoreline snowbands. A number of past studies have indicated significant variations in small-scale structure along shoreline snowbands (e.g., Sheffield 1964; Pitts et al. 1977; Braham 1983; Passarelli and Braham 1981; Forbes and Merritt 1984). However, the study of Schoenberger (1986) was the only one to provide detailed documentation of meso- $\gamma$ -scale vortices along a lake-effect snowband. He used dual-Doppler radar measurements to describe the structure and evolution of several cyclonic and anticyclonic 10-km-scale vortices. While meso- $\gamma$ -scale vortices can cause significant inhomogeneities in the structural coherence and snowfall distribution of shoreline bands, the mechanisms leading to their development are the least understood. Obtaining an understanding of the development of these cold-season vortices may also provide insight toward mechanisms responsible for analogous warm-season nonsupercell vortex formation.

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In this article, we provide detailed observations of a line of small-scale lake-effect vortices. These vortices developed along an intense lake-effect snowband over the eastern portions of Lake Michigan on 14 January 2003 (Fig. 1), had lifetimes of 2–5 h, and resulted in significant variations of the winds and snowfall rates along the band.

## 2. Synoptic and mesoscale environment

Environmental conditions on 14 January 2003 were conducive to the development of a strong land breeze over western lower Michigan, leading to the formation of a snowband oriented nearly parallel to the long axis of Lake Michigan (i.e., shoreline band). At 0000 UTC, a low pressure center was positioned near Maine with a cold front along the northeastern Atlantic coast and extending westward through Virginia and Kentucky. As the center of low pressure moved eastward, a weak trough swung southward through the Great Lakes, providing a region of large-scale convergence over Lakes Huron and Michigan (Fig. 2). A weak pressure gradient over the western Great Lakes resulted in northwest surface winds generally less than  $8 \text{ m s}^{-1}$ . The increasingly cold air combined with Lake Michigan water surface temperatures of  $0^{\circ}$ – $5^{\circ}\text{C}$  to cause  $\Delta T$  to increase to  $14^{\circ}$ – $22^{\circ}\text{C}$ . At 850 hPa, temperatures in the vicinity of Lake Michigan ranged from about  $-16.0^{\circ}$  to  $-20.0^{\circ}\text{C}$ , with little evidence of the shallow, westward-extending surface trough (Fig. 3). The temperature difference between the lake surface and 850 hPa exceeded the  $13^{\circ}\text{C}$  criterion often cited for the development of lake-effect snows (e.g., Rothrock 1969; Niziol 1987).

As both surface wind speeds in the vicinity of Lake Michigan and surface temperatures over central lower Michigan began to decrease around 0000 UTC on 14 January, a land breeze formed inland of the eastern shore of Lake Michigan from Manistee, Michigan, southward to Benton Harbor, Michigan. Surface and radar observations showed that by 0200 UTC the land-breeze front had moved westward to the shoreline, with the most coherent portion positioned offshore from Muskegon, Michigan, southward. As detailed in section 3, it is along the land-breeze front that an intense lake-effect shoreline band formed and subsequently a line of small-scale vortices developed within the band.

## 3. Radar observations

### a. Shoreline band formation

Prior to the development of the shoreline snowband, the National Weather Service (NWS) Grand Rapids Doppler radar (KGRR) observed an area of wind-parallel bands over Lake Michigan. At 0000 UTC 14 January 2003, an area of widespread snow with embedded banded structure was located just west of Grand Rapids, Michigan (Fig. 1b). The bands had a spacing of about

5–8 km and a west-northwest to east-southeast orientation. Peak effective reflectivity factors (reflectivities) within each band ranged from 10 to 27 dBZ. Radial velocities showed that the environment was characterized by nearly unidirectional flow from  $300^{\circ}$  with an increase in wind speed from  $3 \text{ m s}^{-1}$  at about 100 m above the surface to  $13 \text{ m s}^{-1}$  near the tops of the bands (approximately 1800 m). The orientation and spacing of the bands, as well as the environmental conditions, were similar to those reported in past studies of boundary layer roll convection (i.e., wind-parallel bands) over Lake Michigan (e.g., Kelly 1986; Kristovich 1993).

The land breeze that had developed over western lower Michigan was initially observed by KGRR at around 0200 UTC. At the leading edge of the land breeze a narrow region of weak divergence at 1500-m altitude could be seen in the radial velocity field stretching along the shore from 40 km north-northwest of Muskegon to about 85 km southwest of Grand Rapids. North-northeasterly near-surface winds were observed within the land breeze by KGRR, while northwesterly winds consistent with the synoptic pressure field were observed at higher levels.

The land-breeze front became more distinct in the radar reflectivity and radial velocity fields and moved slowly westward over the lake during the next several hours (Fig. 1f), while the radar observations suggested the wind-parallel bands became weaker and less coherent. Reflectivities increased along and just to the east of the land-breeze front as a shoreline snowband developed and strengthened. By 1200 UTC the 20–30-km-wide, north-south-oriented, shoreline band had become stationary over the eastern portion of the lake (Fig. 1c). The band intersected the shoreline both north of Muskegon and near the Indiana–Michigan border. Reflectivities within the band were as high as 32 dBZ, while divergence near the upper levels of the snowband (calculated from the radial velocities) was about  $6.7 \times 10^{-4} \text{ s}^{-1}$ .

### b. Small-scale vortices

Shortly after the shoreline band became stationary, wavelike perturbations developed along the band with spacings of about 20 km. By 1330 UTC the band began propagating eastward while several of the wavelike perturbations developed into cyclonic vortices. Weak anticyclonic vertical vorticity was observed in some locations, but anticyclonic vortices were not evident. Three cyclonic vortices developed along the southern portion of the shoreline band (south of KGRR) with radar reflectivity showing diameters ranging from 15 to 25 km. Initial values of vertical vorticity<sup>1</sup> were about  $2.0 \times 10^{-3} \text{ s}^{-1}$ , estimated from radial velocities. Shortly after 1330 UTC, the vortices propagated nearly due

<sup>1</sup> Vertical vorticity for each vortex was estimated using peak inbound and outbound radial velocities along a line oriented perpendicular to the radar beam through the vortex center.

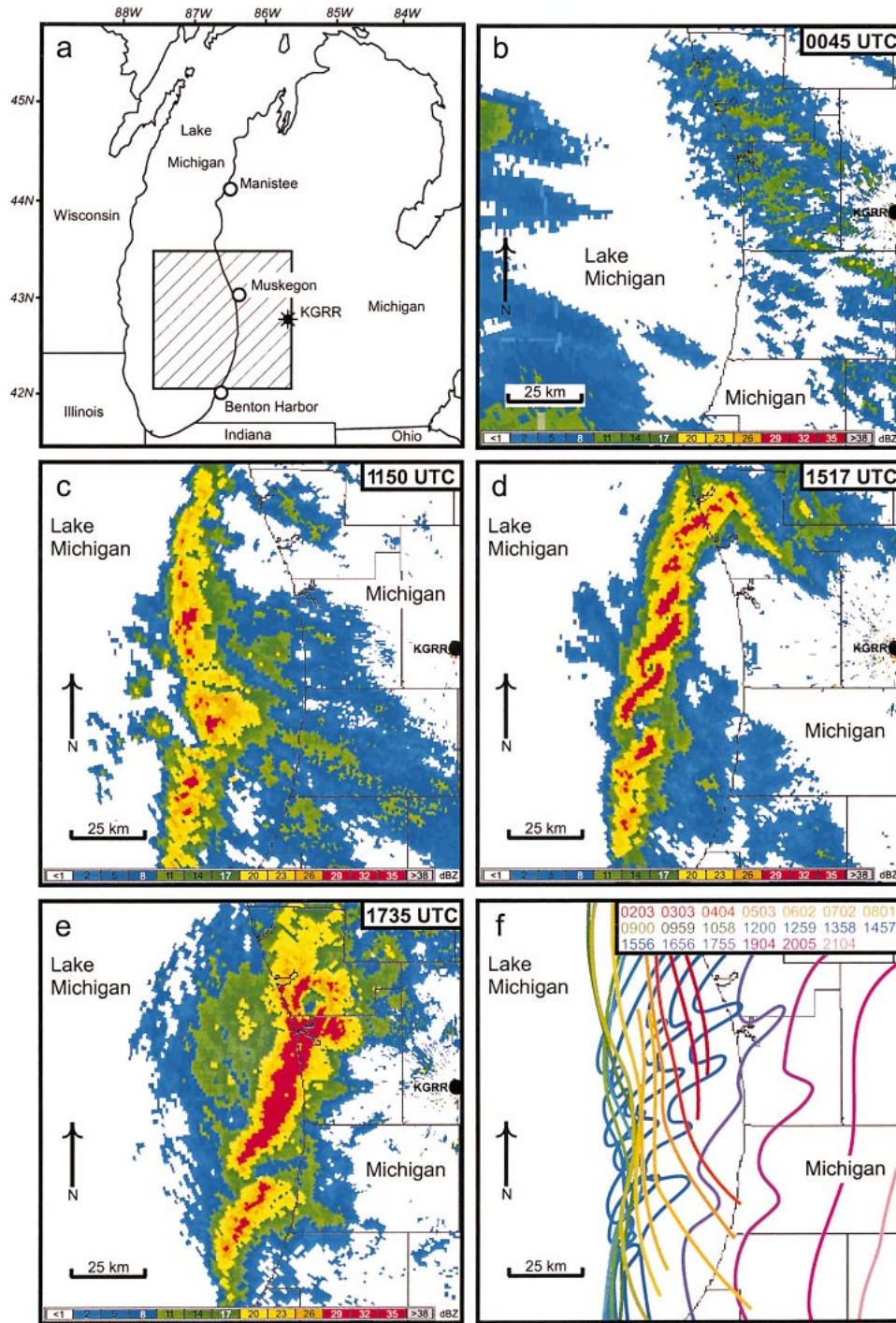


FIG. 1. Radar reflectivity (dBZ) fields measured by the NWS Grand Rapids Doppler radar (KGRR) on 14 Jan 2003. (a) The area used for displaying the radar reflectivity field. (b)–(e) The 0.5° elevation scans at 0045, 1150, 1517, and 1735 UTC. (f) The shoreline band location each hour between 0203 and 2104 UTC.

south at  $2 \text{ m s}^{-1}$  along the snowband as it moved slowly eastward.

Over the next 4 h, at least two additional cyclonic vortices were observed along the shoreline band north of the earlier three vortices. The line of vortices de-

veloped a “braidlike” reflectivity structure (Fig. 1d). Reflectivities reached values as high as 35 dBZ in the “braid” around each vortex and as low as 5 dBZ in the “eye” regions. The vortices had diameters of 15–35 km and an average spacing of about 20 km. The maximum

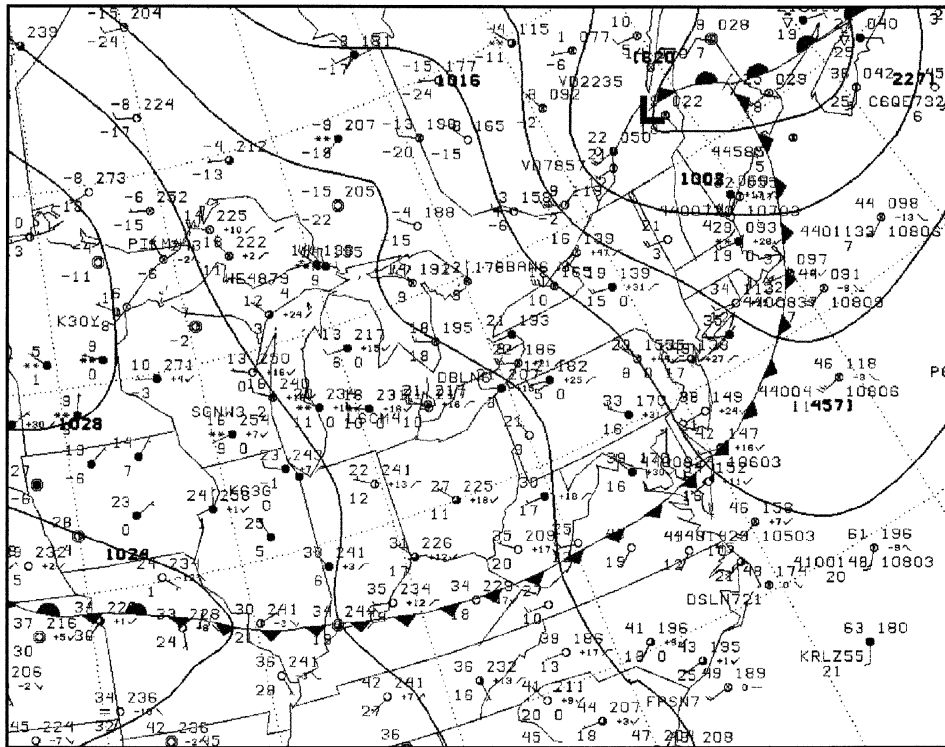


FIG. 2. Surface analysis on 14 Jan 2003 at 0000 UTC. (Map courtesy of the National Weather Service.)

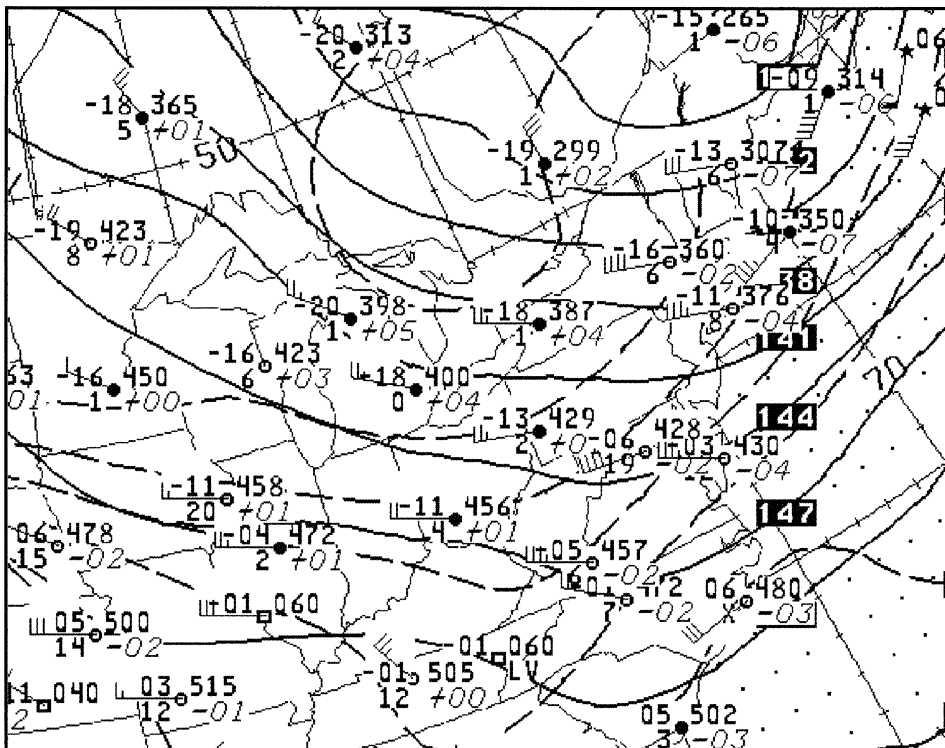


FIG. 3. The 850-hPa analysis on 14 Jan 2003 at 0000 UTC. (Map courtesy of the National Weather Service.)

vertical vorticity was  $4.6 \times 10^{-3} \text{ s}^{-1}$ , observed at 1703 UTC.

By 1730 UTC the eastward motion of the snowband increased, and three of the five vortices had dissipated (Fig. 1e). The two remaining vortices increased in diameter and their vertical vorticity slowly decreased. After the entire shoreline band moved onshore around 1800 UTC, the remaining two vortices dissipated, the snowband increased in width, and widespread regions of snowfall developed to the east and west of the band. West of the band, wind-parallel bands were again apparent from radar and satellite observations with northwest-southeast orientations and spacings of about 7 km. By 2100 UTC, the winds within the wind-parallel band region were nearly unidirectional ( $280^\circ$ ), with wind speeds of about  $5 \text{ m s}^{-1}$  near the surface increasing to around  $10 \text{ m s}^{-1}$  at 1200-m altitude.

#### 4. Discussion

Detailed observations of the structure, circulation, and evolution of small-scale vortices (e.g., landspouts, waterspouts, misocyclones) are infrequent and most often obtained during major field projects. The current study uses operational measurements collected by the NWS Grand Rapids, Michigan, Doppler radar to provide a detailed description of the development and evolution of small-scale vortices that formed along a lake-effect shoreline snowband. The characteristics of the vortices and the environmental conditions in which they developed were similar between the current case and those reported by Schoenberger (1986). In both cases, multiple small-scale vortices developed along a shoreline snowband associated with a land-breeze front as it moved westward into an area of horizontal convective rolls over Lake Michigan. Similarities between these two cases allow for speculation about the processes responsible for the development of small-scale vortices along lake-effect snowbands.

Although not typically thought of as being active along lake-effect snowbands, several warm-season convective processes have been shown to generate small-scale vortices along boundaries. Such processes have been explored in studies of nonsupercell tornadoes along thunderstorm gust fronts (e.g., Wakimoto and Wilson 1989; Lee and Wilhelmson 1997), landspouts or tornadoes along cold fronts (e.g., Carbone 1983), and misocyclones (Wilson et al. 1992) or enhanced convection (e.g., Atkins et al. 1994; Dailey and Fovell 1999) at the intersection of rolls and mesoscale convergence zones. There are two primary processes that have been shown to be responsible for the development of warm-season small-scale vortices. The first is the development of instabilities at discrete locations as a result of strong horizontal shear across a lower-tropospheric boundary (e.g., thunderstorm gust front, cold front) with horizontal gradients in vertical velocity. The second process involves the interaction of rolls with a lower-tropospheric bound-

ary (e.g., gust front, sea-breeze front). As the rolls are tilted and lifted ahead of the boundary, regions of vertical vorticity are generated. For both processes, stretching by convective updrafts can then result in enhanced vertical vorticity at discrete locations and the development of small-scale vortices (e.g., Crook et al. 1991; Wilson et al. 1992; Lee and Wilhelmson 1997).

It is unclear whether one of the two processes, both, or neither, may have been responsible for the development of the line of small-scale lake-effect vortices in the present case and that discussed by Schoenberger (1986). In both cases, a line of discrete vortices developed as environmental conditions over Lake Michigan were changing and an intense shoreline snowband along a land-breeze front was undergoing continual evolution. In order to examine the possibility that strong horizontal shear led to the development of small-scale cyclonic vortices in the present case, radar-estimated winds were determined on either side of the shoreline snowband. Prior to the time of vortex development, winds were  $290^\circ$  at  $10 \text{ m s}^{-1}$  and  $30^\circ$  at  $10 \text{ m s}^{-1}$  on the west and east sides of the band, respectively. These winds produced band-parallel shear of  $5 \text{ m s}^{-1}$  across the band at an estimated height of 700 m. However, the change in winds across the band resulted in anticyclonic vertical vorticity, opposite the observed rotation of the vortices.

In both this case and Schoenberger (1986), a land-breeze front propagated westward into an area of horizontal convective rolls. Wakimoto and Wilson (1989) showed that the production of vertical vorticity by upward tilting of rolls may lead to the development of vortices. This is consistent with the observation by Schoenberger (1986) of several adjacent cyclonic and anticyclonic vortices along a shoreline band. He suggested that high (low) reflectivities in the region of the cyclonic (anticyclonic) vortices were associated with updrafts (downdrafts). In the present case, the spacing of the intersection points of the rolls with the shoreline band was 7–15 km. Since the roll spacing was roughly half the spacing of the observed vortices along the snowband (15–25 km) and anticyclonic vortices were not observed, roll tilting may not have been responsible for the lake-effect vortices.

Despite the observations suggesting that roll tilting may not have been responsible for the vortices in the present case, it is still possible roll tilting may have occurred. If anticyclonic vortices occurred in downdraft regions to the side of the high-reflectivity snowband, as suggested by Schoenberger (1986), then it would have been difficult to observe them in the radar reflectivity and radial velocity fields. The inconsistency between the roll spacing and the spacing of the vortices may have resulted from a merger of vortices. If vortices developed at each location where roll updrafts intersected the shoreline band, then mergers could have produced fewer larger-diameter vortices with a larger spacing than the existing rolls. Simulations of thunderstorm outflow boundaries (Lee and Wilhelmson 1997), squall lines,

and bow echoes (Weisman and Trapp 2003) have shown that vortex merger can result in upscale growth of mesovortices. For example, Fig. 9 of Lee and Wilhelmson (1997) shows that merging of vortices, with an initial spacing of 2–3 km along the leading edge of a vortex sheet, can lead to an increase in the size and spacing of the cyclonic circulations.

Because of a lack of observations of environmental conditions over the lake and the shallow nature of the interaction of rolls with the shoreline snowband, it is not possible to determine the mechanism(s) responsible for vortex formation in these lake-effect cases. Given that the formation and evolution of small-scale lake-effect vortices can result in significant variations of winds and snowfall rates along a shoreline band (Figs. 1c–e), the finescale structure of mesoscale lake-effect vortices and shoreline bands should be investigated further. Additionally, investigations of these cold-season vortices may provide further insight toward mechanisms responsible for warm-season nonsupercell vortex formation.

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