PICTURE OF THE MONTH

Observation of Coexisting Mesoscale Lake-Effect Vortices over the Western Great Lakes

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1. Introduction

Mesoscale vortices are one of several types of wintertime lake-effect structures that are observed over the Great Lakes region as cold arctic air is rapidly modified from below by warm lake waters. These vortices are thought to occur less frequently than other lake-effect structures, such as wind-parallel snowbands (e.g., Kristovich 1993), which are responsible for greater than half of the yearly snowfall downwind of the western Great Lakes (Kelly 1986), and more intense shore-parallel snowbands, which can produce localized heavy snowfalls (e.g., Braham 1983).

Through the examination of visible satellite imagery, Forbes and Merritt (1984) found 14 cases of mesoscale vortex formation over the Great Lakes in the years 1978–82. This suggests that, on average, a mesoscale vortex will occur within the Great Lakes region less than four times a winter. During an early winter lake-effect event on 13 November 1995, intense land-breeze circulations and four mesoscale vortices (>50-km diameter) developed over Lakes Superior, Huron, and Michigan simultaneously (Fig. 1). This unique observation of coexisting lake-effect vortices over the western Great Lakes has not previously been reported in the literature and suggests that atmospheric conditions favorable for vortex development were widespread throughout the region. Previous cases have typically observed a single vortex, suggesting that favorable meteorological conditions were localized. The author is aware of only two other reported observations of simultaneous mesoscale vortices within the Great Lakes region (Schoenberger 1986; Pitts et al. 1977). However, the lake-effect vortices that Schoenberger (1986) and Pitts et al. (1977) observed were smaller scale (<20-km diameter) and were embedded within single land-breeze convergence zones over Lakes Michigan and Superior, respectively.

Most studies of lake-effect mesoscale vortices have discussed events over the western Great Lakes, in particular Lake Michigan. For example, the 14 cases found by Forbes and Merritt (1984) all occurred over the western Great Lakes. Fewer observations of mesoscale vortices have occurred over Lakes Erie and Ontario. Peace (1966) and others observed mesoscale vortices embedded within midlake snowbands over Lakes Erie and Ontario using WSR-57 radars. More recently, a lake scale vortex (approximately 100-km diameter) was reported over central Lake Ontario during the 1995–1996 season of the National Weather Service Lake-Effect Snow project on 15 February 1996 (J. Waldstreicher 1996, personal communication). In addition, similar wintertime vortices have been observed over the Japan Sea (e.g., Asai and Miura 1981) and the Antarctic Weddell Sea (e.g., Heinemann 1990).

The purpose of this note is to document the occurrence of coexisting mesoscale lake-effect vortices over the western Great Lakes (i.e., Superior, Michigan, and Huron), describe the conditions that led to their development, and compare these conditions with those from previous studies.

2. Synoptic and mesoscale environments

Previous investigations of wintertime mesoscale vortices in the western Great Lakes region (e.g., Forbes and Merritt 1984; Hjelmfelt 1990) have described the synoptic-scale conditions favorable for their development. These include 1) low surface wind speeds (i.e., weak synoptic-scale horizontal pressure gradients), 2) large air–lake temperature differences, 3) low atmospheric stability, and 4) organized convergence over the lake. The synoptic and mesoscale environments leading to the development of coexisting vortices over the west-

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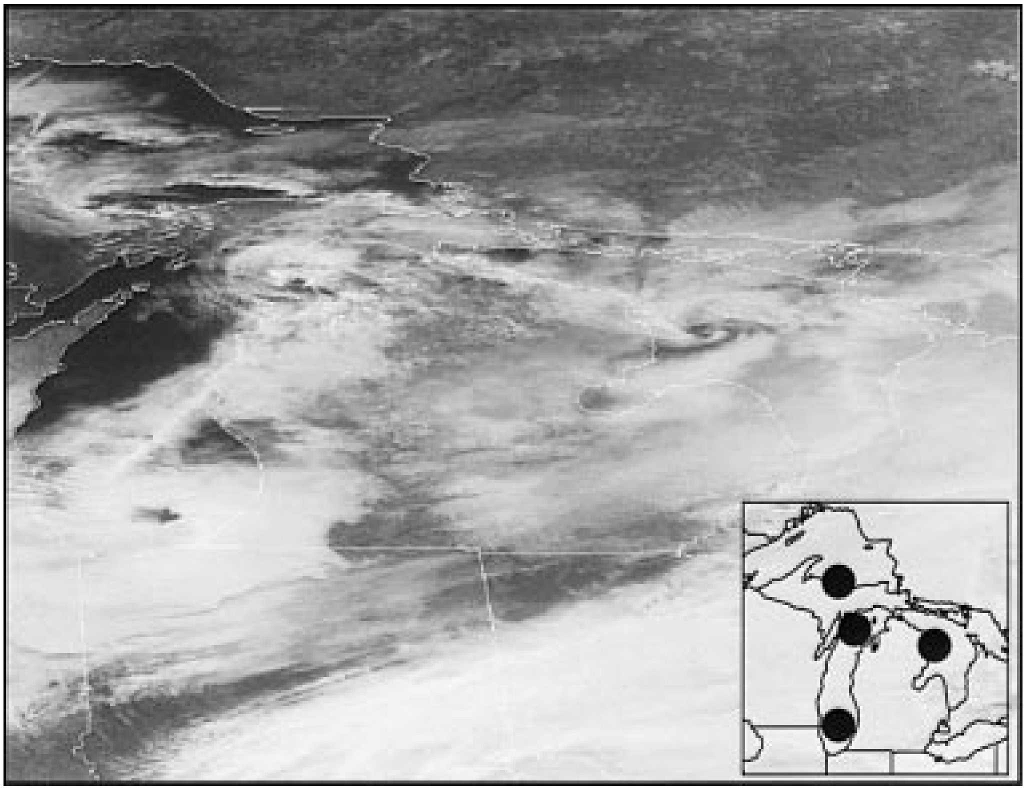

FIG. 1. *GOES-9* visible satellite image of coexisting lake-effect mesoscale vortices over southern Lake Superior, southern and northern Lake Michigan, and central Lake Huron on 13 Nov 1995 at 1815 UTC. (Image courtesy of Cooperative Institute for Research in the Atmosphere, Fort Collins, Colorado.)

ern Great Lakes on 13 November 1995 included each of the conditions previously found to be favorable for lake-effect vortex development.

On 13 November, a cold frontal system had pushed through the western Great Lakes region by 1800 UTC and extended southward from the center of low pressure situated over Lake Erie through southern Indiana (Fig. 2). The cloud band associated with the cold front is also evident in Fig. 1 at 1800 UTC. At the surface, a weak pressure gradient and an inverted trough associated with the region of low pressure over Lake Erie resulted in northerly winds (generally less than 6 m s^{-1} below 850 hPa) throughout much of the western Great Lakes region. At 850 hPa, a weak trough was situated over the region (see Figs. 3a,b) with 850-hPa temperatures ranging from about $-8.0°$ to $-16.0°C$. The synoptic-scale cyclonic vorticity and convergence over the region likely provided a favorable environment for cyclonic mesoscale vortices. Forbes and Lottes (1985) found that multiple polar vortices often formed in a similar synoptic environment near occluded synoptic lows over the North Atlantic Ocean.

During the development of the coexisting vortices on 13 November, the atmospheric stability decreased over the western Great Lakes region. A comparison of the 1200 UTC 13 November and 0000 UTC 14 November soundings from Green Bay, Wisconsin, shows an increase in the atmospheric lapse rate with time below 2 km of roughly 4.5°C km^{-1}, bringing the atmosphere to nearly neutral stability (Fig. 4). This change in the low-level stability was also apparent in the Sault Ste. Marie and Detroit, Michigan, soundings during the same period. The lapse rates within the layer below 1 km at Sault Ste. Marie and Detroit increased from 3.2° to 8.3°C km^{-1} and from 4.0° to 5.7°C km^{-1}, respectively.

The increasingly cold air following the low pressure system into the Great Lakes and water temperatures of Lakes Michigan, Superior, and Huron of about 5°–10°C caused the surface air–lake temperature difference to increase to roughly 10°–15°C. Pease et al. (1988) found that diabatic heating due solely to surface sensible heat flux over southern Lake Michigan from air–lake temperature differences of 12°–14°C on 19 October 1972 was sufficient to develop a mesoscale vortex. In a numerical modeling sensitivity study, Hjelmfelt (1990) found that as the air–lake temperature difference increases, the tendency for a vortex to develop at the southern end of Lake Michigan increases.

Prior to the development of each of the mesoscale vortices on 13 November, intense land-breeze circulations resulted in shoreline or midlake convergence

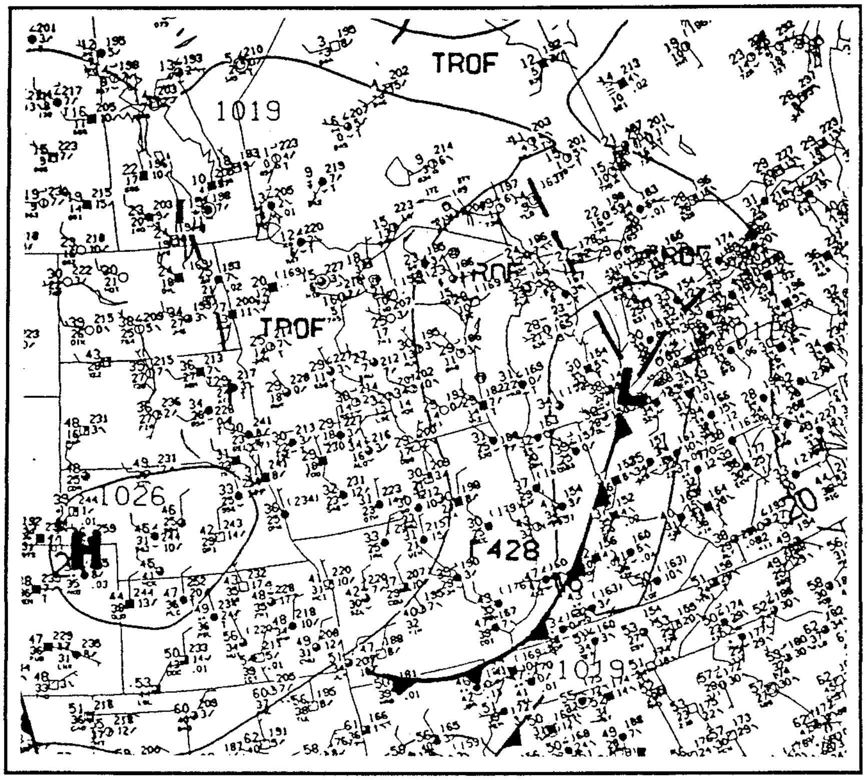

FIG. 2. Surface analysis at 1800 UTC on 13 Nov 1995.

zones. Mesoscale vortices later developed in the vicinity of the convergence zones located over southern Lake Superior, eastern Lake Michigan, and central Lake Huron. Several previously observed cases of lake-effect vortices have noted the coexistence and interaction of a vortex with shore-parallel or midlake snowbands (e.g., Pease et al. 1988). Using observations of surface winds, Forbes and Merritt (1984) found that 11 of their 14 cases showed convergence over the lake prior to vortex development.

3. Mechanisms leading to the formation of lake-effect vortices

Previous researchers have for the most part only qualitatively discussed the mechanisms responsible for the development and evolution of lake-effect vortices. The exception was the study by Pease et al. (1988), which focused on the role of surface heating over the lake. The diameter of lake-effect vortices has been observed to range from 10 km (Schoenberger 1986), the width of shore-parallel snowbands, to over 100 km (Forbes and Merritt 1984), the width of an individual lake. The small-scale vortices embedded within a land-breeze convergence zone observed by Schoenberger (1986) are similar in appearance and suggestive of misocyclones observed by Wilson et al. (1992) and simulated by Lee and Wilhelmson (1997) and are likely initiated by similar mechanisms (e.g., vertical and horizontal shear). The larger lake-effect vortices have been compared to weak polar lows, which result from cyclogenesis within polar airstreams and sensible and latent heating (Forbes and Merritt 1984). The differences in size of lake-effect vortices suggest that the forcing mechanisms responsible for their development may vary. The mechanisms proposed by previous investigations (e.g., Forbes and Merritt 1984; Pease et al. 1988) for cyclogenesis leading to lake-effect vortex development include 1) stretching and tilting of vorticity due to low-level convergence and vertical wind shear, 2) differential diabatic heating associated with the lake shoreline, and 3) synoptic-scale vorticity and thermal advection. The first and second mechanisms have been suggested to be the primary factors that initiate lake-effect vortices, with the third being unimportant to vortex development, but perhaps contributing to their evolution and propagation following formation. Comprehensive observational and numerical modeling studies are necessary to investigate the structure and evolution of lake-effect mesoscale vortices. In addition, the mechanisms responsible for their development should be quantitatively examined during several events where vortex diameter varies from roughly 10 km to over 100 km.

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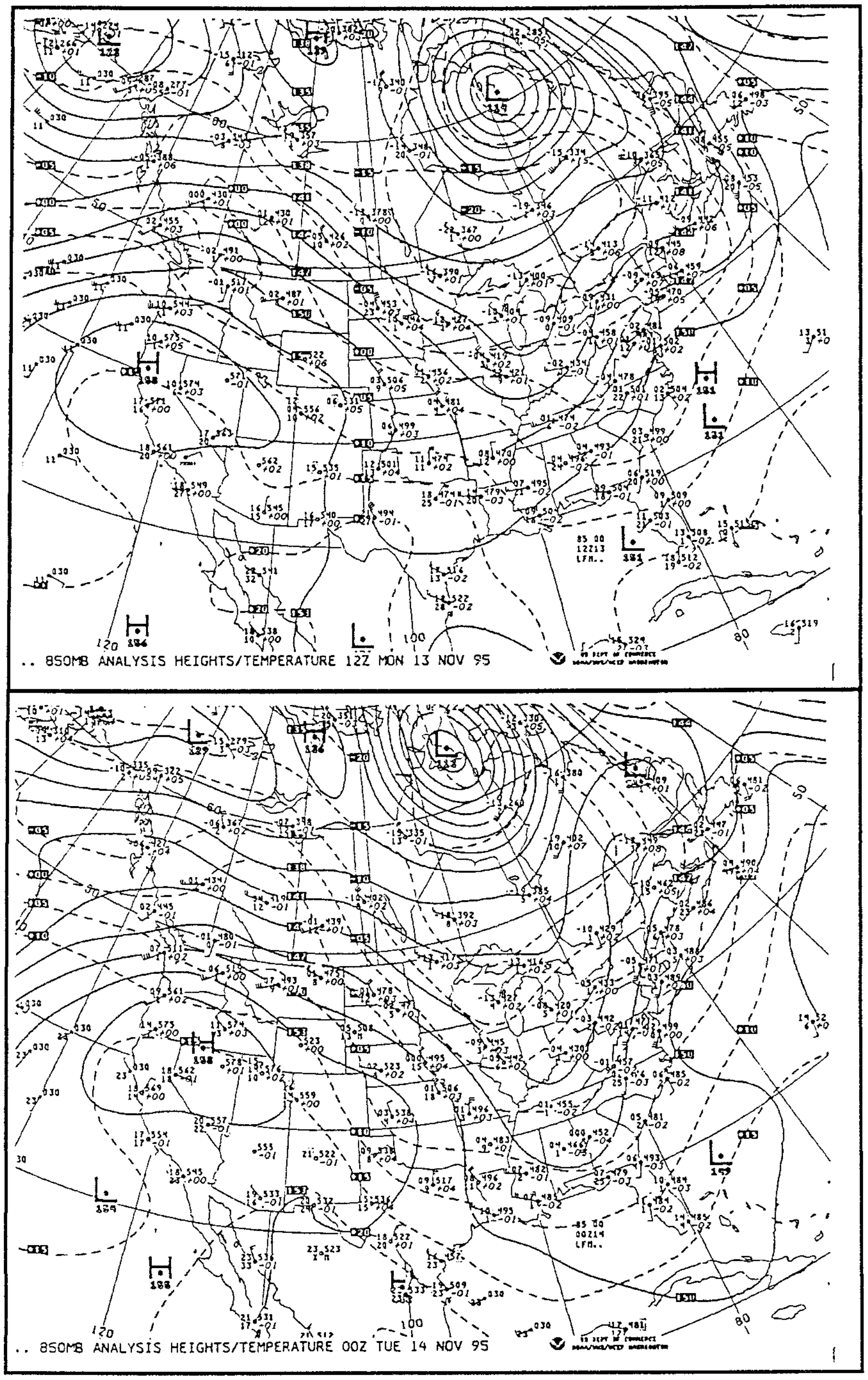

FIG. 3. 850-hPa maps at (a) 1200 UTC on 13 Nov 1995 and (b) 0000 UTC on 14 Nov 1995.

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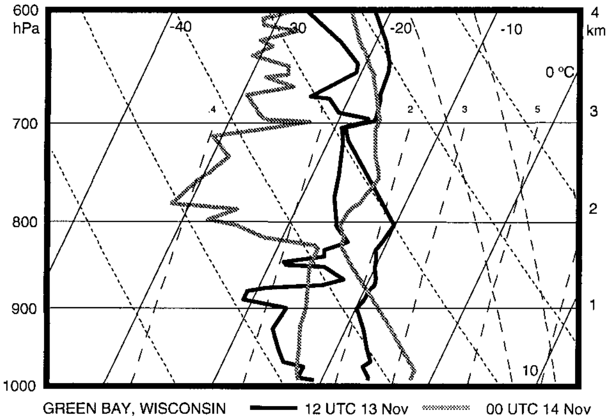

FIG. 4. Green Bay, Wisconsin, atmospheric soundings at 1200 UTC 13 Nov 1995 and 0000 UTC 14 Nov 1995.

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