**11.3** # MULTISCALE INTERACTIONS IN A LAKE-EFFECT SNOWSTORM

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## 1. INTRODUCTION

Research over the past 30 years has classified lake-effect systems into several distinct morphological types, based upon band characteristics visible in satellite imagery. These band types are: (1) Widespread, wind-parallel bands or cells (WPB e.g., Young et al., 2002; Kristovich 1993; Kelly 1982), (2) Shoreline or midlake bands (SPB, e.g., Ballentine et al. 1998; Passarelli and Braham 1981; Peace and Sykes 1966), and (3) Mesoscale Vortices (MV, e.g., Grim et al., 2004; Laird et al., 2001; Laird 1999; Forbes and Merritt 1984). Multiple morphologies and spatial scales of lake-effect convection can exist at the same time (e.g., Schoenberger 1986), sometimes leading to unusual snowfall distributions, as in a snowstorm which occurred downwind of Lake Ontario in mid-January 2005.

In this event, mesoscale vortices were present for a period of over six hours. Such vortices have historically been regarded as weak snowfall producers (Niziol et al., 1995), although there have been cases (e.g., Laird et al., 2001) of enhanced snowfall occurring. A review of past research on the topic, including Kawashima and Fujiyoshi (2005), Grim et al. (2004), and Laird (1999), suggests that lake-effect mesovortices fall into two subtypes: meso-$\gamma$ vortex chains and meso-$\beta$ lake-scale vortices. Although the latter is formed through the interaction between weak synoptic-scale windfields and strong sensible heating from the lake (Hjelmfelt 1990; Pease et al. 1988), formation mechanisms for the former have not been well-established.

## 2. LAKE-EFFECT STORM "DATE"

Lake-effect vortex chains played a key role in organizing convective bands in snowstorm "Date", which occurred from 16-18 January 2005. The system was rated the most noteworthy of nine named storms during the 2004-2005 season by the National Weather Service Forecast Office in Buffalo, NY, for producing "almost unprecedented snowfall amounts" over portions of the southern Lake Ontario shore. In fact, the storm resulted in over 30 cm of snowfall across a region from Niagara to Rochester, New York, a region climatologically unfavorable for heavy lake-effect storms (NWS, 2007). Snowfall rates of 1-3 cm $hr^{-1}$ were reported by Weather Service cooperative "snow spotters" for three to six hours on 16 January, in lake-effect bands modulated by mesovortices.

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The storm began as the most intense arctic airmass of the season dominated much of the United States east of the continental divide. Unusually warm temperatures during the first half of January 2005 had led to warm lake-surface temperatures of approximately 3-6°C on Lake Ontario. Thus, lake-air temperature differences were very large, approximately 21°C.

At 1200 UTC 15 Jan 2005, an upper-level shortwave trough was located in northeastern Montana. Over the next day and a half, this system moved through the Ohio River Valley, bringing light snowshowers to portions of the Great Lakes states. Meanwhile, a surface trough formed in West Virginia. As the upper level wave approached the Great Lakes region, surface pressure falls of 0.2-0.5 hPa $hr^{-1}$ occurred on the north side of the developing surface trough. As the trough developed north toward the Great Lakes, it split the surface ridge of high pressure, causing surface winds along the eastern shore of Lake Ontario to back toward the northeast. Surface observations, the rawinsonde from KBUF, and the wind profiler at Syracuse (Figure 1) show that this layer of northeasterly winds deepened and spread westward across the lake with time. A directional shear zone lifting from about 1.0 km above sea level at 1200 UTC to 1.9 km by 0000 UTC 16 Jan 2005. Most of this deepening occurred during a few hours, from 1500 to 1800 UTC. After the passage of the upper-level trough axis between 0000 and 0300 UTC 17 Jan 2005, boundary layer winds shifted to the northwest across the lake and increased in velocity.

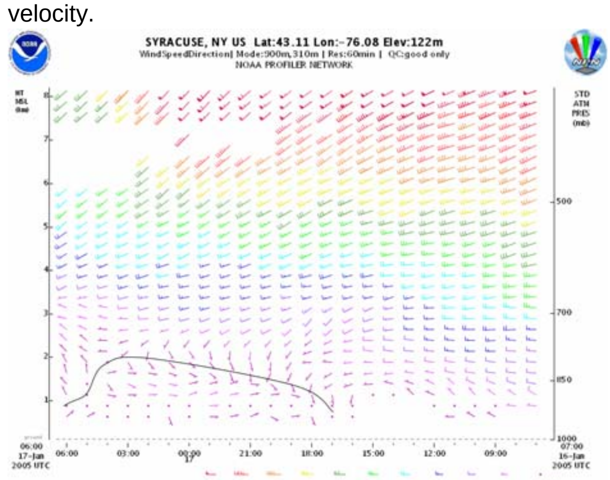


Figure 1. A time-height plot of wind speed and direction from the Syracuse, NY wind profiler. Wind barbs are color-coded by speed in m $s^{-1}$, the abscissa runs from 0700 UTC 16 January to 0600 UTC 17 January, and the ordinate is labeled in kilometers above sea level. The black solid line represents the approximate altitude of the directional wind shear zone. The profiler image is courtesy of NOAA, available at http://www.profiler.noaa.gov/npn/profiler.jsp.

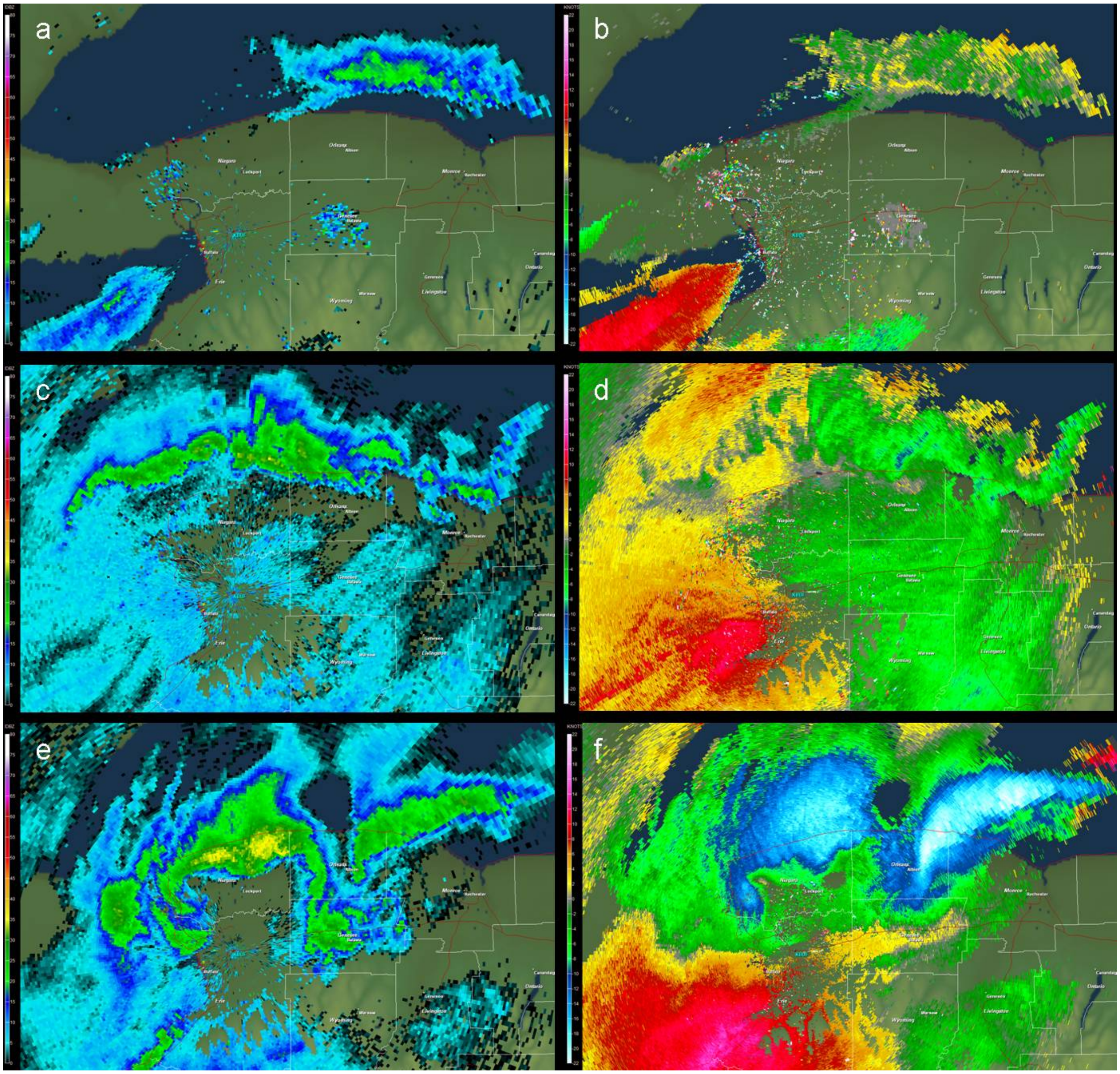


Figure 2. Level II WSR-88D radar images from the 0.4 degree tilt at Buffalo, New York. Images (a) and (b) are radar reflectivity and base velocity, respectively, from 1349 UTC. Images (c) and (d) are from 1801 UTC, and (e) and (f) are from 2222 UTC. Note that radial velocities receding from the radar are colored red or yellow, while those approaching are green or blue.

The deepening layer of northeasterly winds caused convective elements comprising the midlake band over Lake Ontario to reverse direction near 1300 UTC. Shortly after this occurred, radar (Figures 2 a and b) and surface observations suggest a shear zone was found on the southern side of the lake-effect band. The band assumed a more cellular appearance by about 1450 UTC, and then an undular appearance. Individual convective cells developed weak vortex-chain circulations by 1600 UTC. As the circulations became more developed, from about 1650 to 1830 UTC, they tended to form nearly solid reflectivity rings of 25-35 dBZ, with nearly precipitation-free “eyes” (Figures 2 c and d). After 1930 UTC, individual vortices within the chain began to move toward shore and develop upscale. As this occurred, the radar reflectivity rings developed into larger asymmetric bands oriented perpendicular to the shoreline (Figures 2 e and f). At this point, heavy snowfall of greater than 2.5 cm $hr^{-1}$ was reported across portions of Niagara and Orleans Counties. Eventually, by 0045 UTC, only one large vortex was evident over Genesee County, drifting to the south-southeast. Between 2300 and 0400 UTC, another small vortex chain formed and moved inland along the band into Wayne and Monroe Counties, but rapidly dissipated. Finally, by 0600 UTC, the last evidence of circulation centers had dissipated and wind-parallel bands were present over the lake.

## 3. SYNOPTIC-MESOSCALE INTERACTIONS

The mesoscale vortex chain described above formed within a few hours from a single lake-effect band. Two mechanisms have been posited in the scientific literature to explain the origin of such features: (1) development of vertical vorticity through a shearing instability (e.g., Kawashima and Fujiyoshi 2005; Lee and Wilhelmson 1997) and (2) the tilting of horizontal rolls along a pre-existing convergence zone (e.g., Dailey and Fovell 1999; Atkins et al., 1995). The question of which mechanism plays the chief role in the formation of lake-effect vortex chains has yet to be decided. In previous studies of vortex chains over Lake Michigan, Grim et al. (2004) and Shoenberger (1986) examined the development of vortex chains within a single lake-effect band, concluding that shear along the band likely played a significant role.

In this case, an overlying synoptic-scale cloud deck obscured the band during the time of mesovortex chain formation, so it was not possible to use satellite imagery to investigate the presence of wind-parallel rolls or cells over Lake Ontario. However, several other types of measurements, including automated surface observations, high-vertical-resolution (six-second) rawinsonde soundings, and Level II WSR 88-D data, were available. An examination of radar imagery showed no evidence of boundary layer rolls before 1930 UTC, although the radar may have failed to detect them due to beam overshooting or a lack of suitable scatterers.

In addition to radar evidence, various environmental metrics found in previous studies to discriminate between rolls and cellular convection over the Great Lakes were examined. For each index, values encompassing the range of uncertainty of over-lake conditions were estimated. Bulk values of $-Z_i/L$ computed in this case after Kristovich et al. (1999) were found to be at least twice as large as any such values calculated by Kristovich (1993) for observed roll vortices, and 6 times larger than the criteria suggested by Grossman (1982) to distinguish rolls from cellular convection. Values of $U\Delta T$ were also computed after Weckwerth et al. (1997). The minimum value of $U\Delta T$ in this case was marginally larger (28.73 K m $s^{-1}$) than the maximum value found for observed roll convection (21 K m $s^{-1}$) in that study. Finally, an analysis of $u_*(w_*)^{-1}$, indicated slightly more mixed results, being well below the 0.35 criteria for cases exhibiting roll development set by Sykes and Henn (1989), but within the range of values found for roll convection in Kristovich (1993). Based on these results, it appears unlikely that roll convection was present during the early vortex formation. Therefore, the authors postulate that shear-generated vertical vorticity along the band led to the initial development of the vortices in this case, rather than the roll-tilting mechanism described by Dailey and Fovell (1999) and Atkins et al. (1995).

Several mechanisms for the development or upscale growth of meso-β vortices have been explored in the literature, including stretching of vorticity due to broad low-level convergence, differential diabatic heating associated with the lake shoreline, and synoptic-scale vorticity and thermal advection (e.g., Pease et al. 1988; Forbes and Merritt 1984). In addition, a mechanism of subharmonic vortex interactions has been proposed to explain misocyclone development in non-supercell tornadoes (e.g., Lee and Wilhelmson 1997) and discussed in vortex chains over the Sea of Japan (Kawashima Fujiyoshi 2005). In such interactions, a vortical disturbance interacts with one of its subharmonics through coalescence or extrusion. A comparison of Figure 9 from Lee and Wilhelmson (1997) with radar data from this case shows a compelling amount of similarity. In both cases, coalescing vortices were typically of the same spatial scale and larger vortices often developed increasingly elliptical circulations, with one rotating around the other prior to the mergers.

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