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SIMULATIONS EXAMINING THE INFLUENCE OF WIND SHEAR ON THE COHERENT MESOSCALE STRUCTURE OF INTENSE LAKE-EFFECT SNOW BANDS

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1. INTRODUCTION

A fundamental outstanding issue in mesoscale and boundary layer research is understanding the processes by which the atmosphere responds to, and interacts with, surface heat and moisture variations. Spatial heterogeneities in surface heat fluxes, such as land-water boundaries, lake/sea-ice openings, sea surface temperature gradients, and soil wetness variations often lead to the initiation and maintenance of mesoscale circulations. Lake-effect (hereafter LE) winter storms are excellent examples of mesoscale circulations that develop in response to variations in surface heat fluxes. The morphology and intensity of meso-β-scale (i.e., 20-200 km) LE circulations during the late fall and winter are controlled by numerous environmental parameters (e.g., wind speed, fetch distance, lake-air temperature difference, stability, and shoreline configuration). Previous investigations have examined the influence of several of these parameters on the morphology and intensity of LE mesoscale circulations (e.g., Lavoie 1973, Hjelmfelt 1990, Sousounis 1993, Laird et al. 2003a, Laird et al. 2003b). However, the influence of vertical wind shear on LE meso-β scale circulations has not been examined using observations or numerical models.

Over many years of operational forecasting, Great Lakes National Weather Service forecast offices have observed that a significant change in wind direction with height is often detrimental to the development and maintenance of intense LE snow bands (Niziol 1987, Niziol et al. 1995). An operational forecast decision tree used to predict LE snow band coherence and the possibility of band development incorporates three categorical criteria of the vertical directional wind shear between the surface and 700 hPa. The three criteria include: (1) a wind direction change within this layer between 0°-30° leads to forecasts of a strong, well-organized band; (2) weaker, less-coherent bands are predicted for a 30°-60° change; and (3) conditions with wind direction changes of greater than 60° produce forecasts that indicate snow band development will be inhibited.

To date the influence of vertical directional wind shear on the structural coherence of LE snow bands has not been quantified and the dynamical / physical basis behind the operational criteria has not been investigated. A series of idealized mesoscale model simulations was used for an examination and comparison of the structure and intensity of the mesoscale circulations resulting from LE conditions with different values of vertical directional wind shear and wind speed.

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2. MESOSCALE MODEL

The Colorado State University Mesoscale Model used for this investigation is a three-dimensional, hydrostatic, incompressible, primitive-equation model. Flat topography was used with a single elliptical lake with a 4:1 axis ratio and surface area of 20106 km^2. For comparison, the lake axis ratios of Lakes Superior, Huron, Michigan, Erie, and Ontario are approximately 2:1, 1:1, 3:1, 4:1, and 4:1 with surface areas of 82200, 59600, 57800, 25700, and 19000 km^2, respectively. The idealized model simulations were performed using 20 vertical levels with vertical grid spacing expanded with height and a horizontal grid spacing of 5 km. A constant, uniform lake surface temperature of 0°C was prescribed and each simulation was initialized with a domain-uniform vertical profile of temperature, specific humidity, and wind. Fifteen model simulations were performed using varied ambient wind speed and vertical directional wind shear. The array of simulated ambient conditions included wind direction changes of 0°, ±45°, and ±90° from the surface to 3.0 km, with surface winds parallel to the long axis of the elliptical lake, wind speeds of 5, 10, and 15 m s^{-1}, and a temperature difference of 15 °C between the lake surface and upwind air temperature at 10-m.

A 36-hour simulation was performed for each of the 15 cases using a time step of 20 s. This allowed the initially uniform conditions to respond to the positive heat and moisture fluxes associated with the open water of the elliptical lake. By 24 hours simulation time (time of results presented), the mesoscale circulation had reached maximum intensity and a quasi-steady LE circulation was sustained in each cases.

3. WIND SHEAR SIMULATION RESULTS

Results showed that coherent meso-β-scale LE bands developed under all shear conditions for wind speeds of 5, 10, and 15 m s^{-1} when the surface wind direction was parallel to the long axis of the elliptical lake and vertical directional shear was 0°, ±45°, or ±90°. Figure 1 shows that large variability existed in the vertical motions, snowfall rates, and location and presence of significant weather impacts.

Simulations with wind speeds of 5 m s^{-1} and wind direction changes of 0°, ±45°, and ±90° from the surface to 3.0 km resulted in very weak snow bands. Maximum vertical motions ranged from about 22 to 25 cm s^{-1} across the cases. The snowfall was primarily restricted to over-lake regions except in the +90° shear case (Fig. 1a) where the snow band extended along the western shoreline and the 0° shear case (Fig. 1d) where the band came on shore over a small region of the downwind shoreline. In each of the 5 m s^{-1} cases the snow band was primarily controlled by the merging of the thermally-driven land breeze circulations. Figure 2 shows the horizontal wind field at the 10-m height (lowest model atmospheric level). The land breeze in the direction of the vertical shear vector dominates over the opposite-shore land breeze (Figs. 2a, 2g). In each of these cases, the reduced stability over the lake provides a favorable environment to transport the winds above the boundary layer downward toward the lake surface to strengthen the land breeze flow over the lake.

Simulations with wind speeds of 10 m s^{-1} and wind direction changes of 0°, ±45°, and ±90° from the surface to 3.0 km produced stronger snow bands that often impacted a greater extent of shoreline (Figs. 1b, 1e, 1h). The strongest snow band developed with winds from the surface to 3.0 km aligned along the long axis of the lake. This is consistent with observational experience of forecasters for the eastern Great Lakes (Niziol 1987). A comparison of the band intensity for the 5 and 10 m s^{-1} wind speed cases with 0° shear showed the maximum vertical motions were more than 3 times greater for the 10 m s^{-1} wind speed case. This resulted from a substantial increase in sensible and latent heat fluxes from the lake surface. Figures 1b and 1h show a distinct asymmetry in the strength of LE snow bands associated with the sign of the vertical directional wind shear. The case with +90° vertical shear (Fig. 1b) is substantially weaker than the −90° cases (Fig. 1h). The greater intensity of the −90° case may be due to an enhancement of the vertical momentum transport (i.e., stronger winds transported downward toward the lake surface), increased surface fluxes, decreased boundary layer stability, and increased convergence along the shoreline due to an interaction of the over-lake and land-breeze flows.

Simulations with wind speeds of 15 m s^{-1} and wind direction changes of 0°, ±45°, and ±90° from the surface to 3.0 km produced the largest variability in snow band intensity across the shear cases. Maximum vertical motions ranged from about 37 cm s^{-1} (Fig. 1i) to nearly 130 cm s^{-1} (Fig. 1f). The most intense snow band of the 15 idealized simulations developed for the 0° shear case. Although the band that develops under these conditions impacts a very localized region of the downwind shoreline, it is this type of LE case often produces snowfall amounts approaching 1 m for a single storm. Snow bands for the ±45°, and ±90° cases were significantly weaker, although a larger region in the vicinity of the lake was impacted with lighter snow fall. Again, a distinct asymmetry in the strength of LE snow bands associated with the sign of the vertical directional wind shear is shown in figures 1c and 1i. Interestingly, this asymmetry is opposite to that found for the two corresponding 10 m s^{-1} cases, with the stronger band developing in the +90° case.

This series of idealized simulations was used to quantify the influence of vertical directional wind shear on the structural coherence of LE snow bands and examine the dynamical / physical basis behind the differences in snow band structure. Further details of each of the simulations will be presented during the conference. Lastly, the results of this study suggest that when only vertical directional shear between the surface and 3.0 km (~ 700 hPa) is changed the morphology of the LE circulation continues to be a meso-β-scale band, but with significantly varied intensity. This seems to suggest that the operational wind shear criteria used to aid forecasting of intense LE snow bands may indirectly incorporate additional atmospheric processes not included in the model simulations, such as vertical differences in thermal advection by the ambient flow.

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4. REFERENCES

Hjelmfelt, M., 1990: Numerical study of the influence of environmental conditions on lake-effect snowstorms on Lake Michigan. *Mon. Wea. Rev.*, **118**, 138-150.

Laird, N., D. Kristovich, and J. Walsh, 2003a: Idealized model simulations examining the mesoscale structure of winter lake-effect circulations. *Mon. Wea. Rev.*, **131**, 206–221.

—, J. Walsh, and D. Kristovich, 2003b: Model simulations examining the relationship of lake-effect morphology to lake shape, wind direction, and wind speed. *Mon. Wea. Rev.*, in press.

Lavoie, R., 1972: A mesoscale numerical model of lake-effect storms. *J. Atmos. Sci.*, **29**, 1025–1040.

Niziol, T., 1987: Operational forecasting of lake effect snowfall in Western and Central New York. *Wea. Forecasting*, **2**, 310-321.

—, W. Snyder and J. Waldstreicher, 1995: Winter Weather Forecasting throughout the Eastern United States. Part IV: Lake Effect Snow. *Wea. Forecasting*, **10**, 61-77.

Sousounis, P. J., 1993: A numerical investigation of wind speed effects on lake-effect storms. *Bound.-Layer Meteor.*, **64**, 261-290.

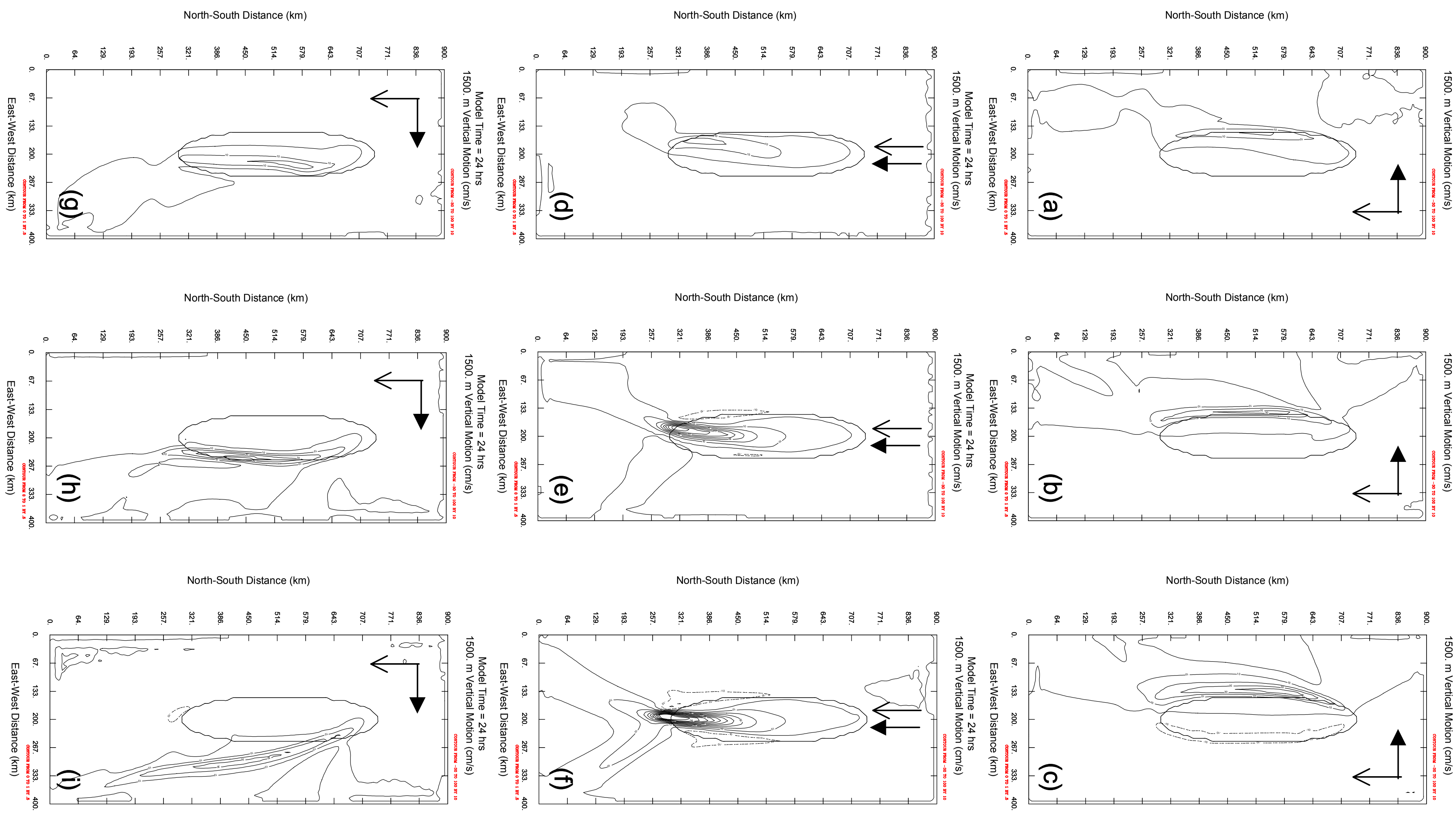

Figure 1. Vertical motion field at 1.5 km height. The large arrows on each panel represent the approximate surface (open arrow) and 3.0 km (solid arrow) wind directions. Simulations with wind directions of 45 deg are not shown. Results are presented for free-atmosphere wind speeds of 5 m s^{-1} (panels a, d, g), 10 m s $^{-1}$ (panels b, e, h) and 15 m s $^{-1}$ (panels c, f, i). Vertical motion is contoured at intervals of 10 cm s-1 with solid and dashed contours representing upward and downward motions, respectively. The elliptical lake coastline is also shown with a solid contour

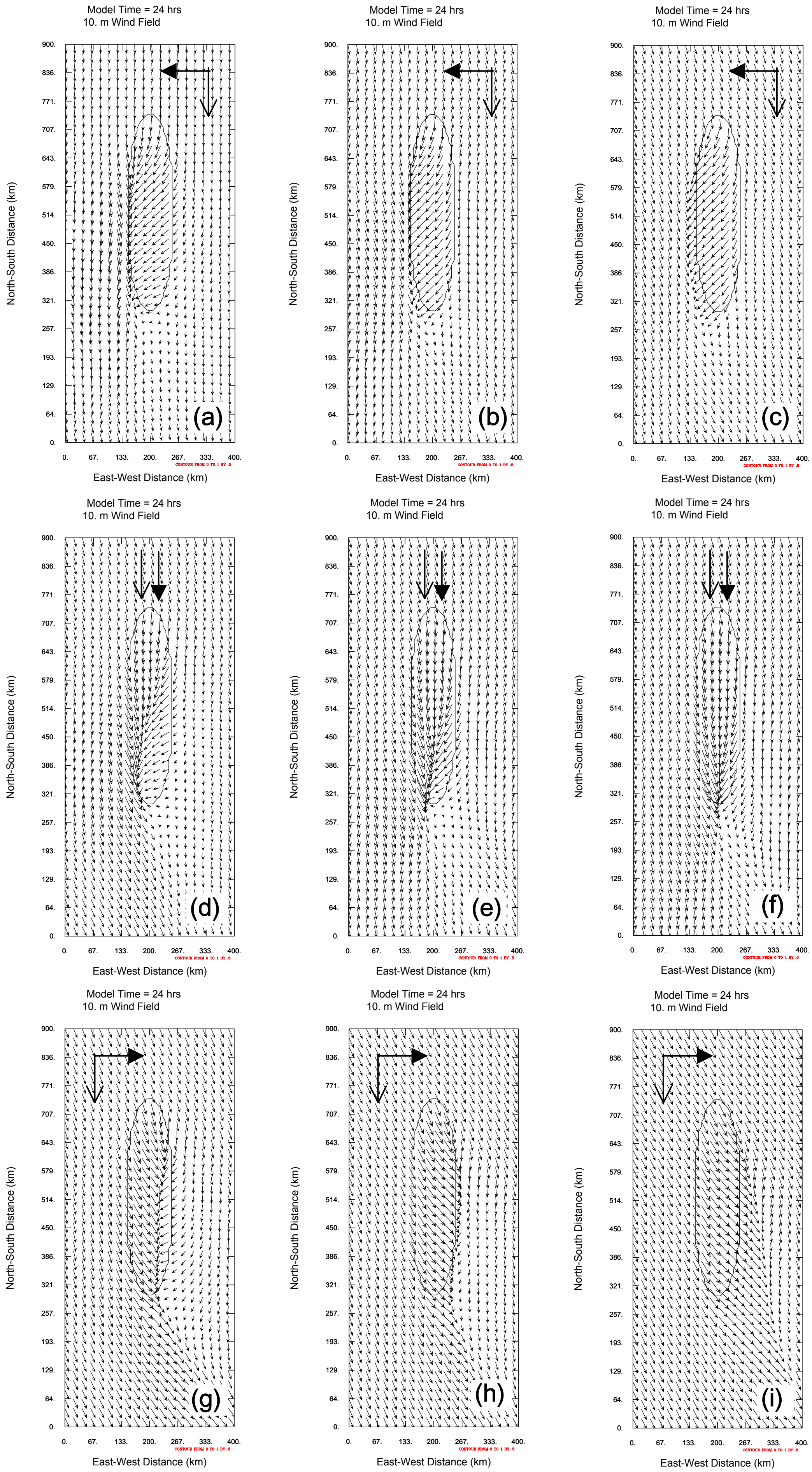

Figure 2. Horizontal wind field at 10-m height. The large arrows on each panel represent the approximate surface (open arrow) and 3.0 km (solid arrow) wind directions. Simulations with wind directions of 45 deg are not shown. Results are presented for free-atmosphere wind speeds of 5 m s^{-1} (panels a, d, g), 10 m s^{-1} (panels b, e, h) and 15 m s^{-1} (panels c, f, i). Wind vectors are scaled to a standard of 7.5 m s^{-1} for panels a, d, and g, 12.5 m s^{-1} for panels b, e, and h, and 17.5 m s^{-1} for panels c, f, and i. The lake coastline is shown by the solid contour.