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SIMULATIONS OF WINTER MESOSCALE CIRCULATIONS ASSOCIATED WITH AN ISOLATED HEAT AND MOISTURE SOURCE

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1. INTRODUCTION

Spatial heterogeneities in surface heat fluxes, such as land-water boundaries, surface vegetation and land use differences, sea surface temperature gradients, polar sea-ice openings, and soil wetness variations are often associated with the development of mesoscale circulations. Lake-effect (hereafter LE) winter storms are excellent examples of mesoscale circulations which develop in response to variations in surface heat fluxes. Meso-β scale (i.e., 20-200 km) circulations that develop during the late fall and winter in response to cold flow over open lake waters are often associated with a distinct morphological regime. The most commonly discussed regimes include: 1) widespread coverage, 2) shoreline bands, and 3) mesoscale vortices. The current article offers a comprehensive examination of the conditions that favor an individual LE morphological regime over another. The research presented in this article evaluates two primary hypotheses.

1. The *morphological regimes* of mesoscale LE circulations can be reasonably identified using basic parameters which characterize the response of stratified airflow over an isolated surface heat and moisture source.
2. The *intensity* of the response can be reasonably predicted using a function comprised of variables fundamental to describing a LE system.

These hypotheses are evaluated using an array of idealized mesoscale model simulations of stratified airflow over a relatively warm axisymmetric lake.

2. MESOSCALE MODEL

The Colorado State University Mesoscale Model used for this investigation is a three-dimensional, hydrostatic, incompressible, primitive-equation model (Mahrer and Pielke 1977, Mahrer and Pielke 1978). Near the lower boundary, surface layer similarity theory is used to parameterize fluxes based on heat, moisture, and momentum flux-profile relationships. The vertical turbulent exchange coefficients are derived from the predicted local turbulent kinetic energy and planetary boundary layer depth. Atmospheric water vapor was considered a passive scalar quantity that could be advected by the wind, diffused by turbulence, and exchanged at the surface. Precipitation processes and solar radiation were not included in the simulations.

Thirty-five model simulations were performed using varied geostrophic wind speed, lake-air temperature difference, atmospheric stability, and lake diameter. Flat topography was used with a single axisymmetric lake with a diameter of 100, 200, or 300 km located near the center of the domain. A constant, uniform lake surface water temperature of 273 K was prescribed. The idealized model simulations were preformed on a $76 \times 76 \times 20$ grid. The horizontal grid spacing was 10 km. The model requires input of vertical profiles of temperature, specific humidity, and geostrophic wind. Initial 10-m air temperatures ranged from 265.5 to 250.5 K. The stability was constant from the surface to 1.5 km ($d\theta/dz$ = 1.0, 3.0, or 6.0 K km^{-1}) with a stable layer above of $d\theta/dz$ = 8.0 K km^{-1}. Geostrophic wind speeds were varied from 0-18 m s^{-1}.

A 36 hr simulation was performed for each experiment using a time step of 40 s. This allowed the initially uniform conditions to respond to the positive heat and moisture fluxes associated with the relatively warm axisymmetric lake. By 24 hours simulation time (time of results presented), the mesoscale circulation had reached maximum intensity and a quasi-steady circulation was sustained in each experiment.

3. STRUCTURE OF MESOSCALE CIRCULATION

A fundamental outstanding issue in mesoscale and boundary layer research is how the atmosphere responds to, and interacts with, surface heat and moisture variations. Using an array of thirty-five idealized mesoscale model simulations, we have examined the atmospheric response and subsequent structure of mesoscale circulations that result from cold flow over an isolated body of water at mid-latitudes. Figure 1 presents the simulated 10-m wind, surface pressure, and 1500-m vertical motion fields for a mesoscale vortex, shoreline band, and widespread coverage event. Figure 1a-b shows a closed lake-scale cyclonic vortex centered over the downwind half of the lake, with a surface pressure perturbation of approximately -1.5 hPa, and weak vertical motions associated with the vortex circulation of 2.5-5.0 cm s^{-1}. Several characteristics of the simulated vortex are consistent with observations discussed by Forbes and Merritt (1984) and Laird (1999).

Figure 1c-d presents results of a shoreline band over the downwind lakeshore. A surface pressure

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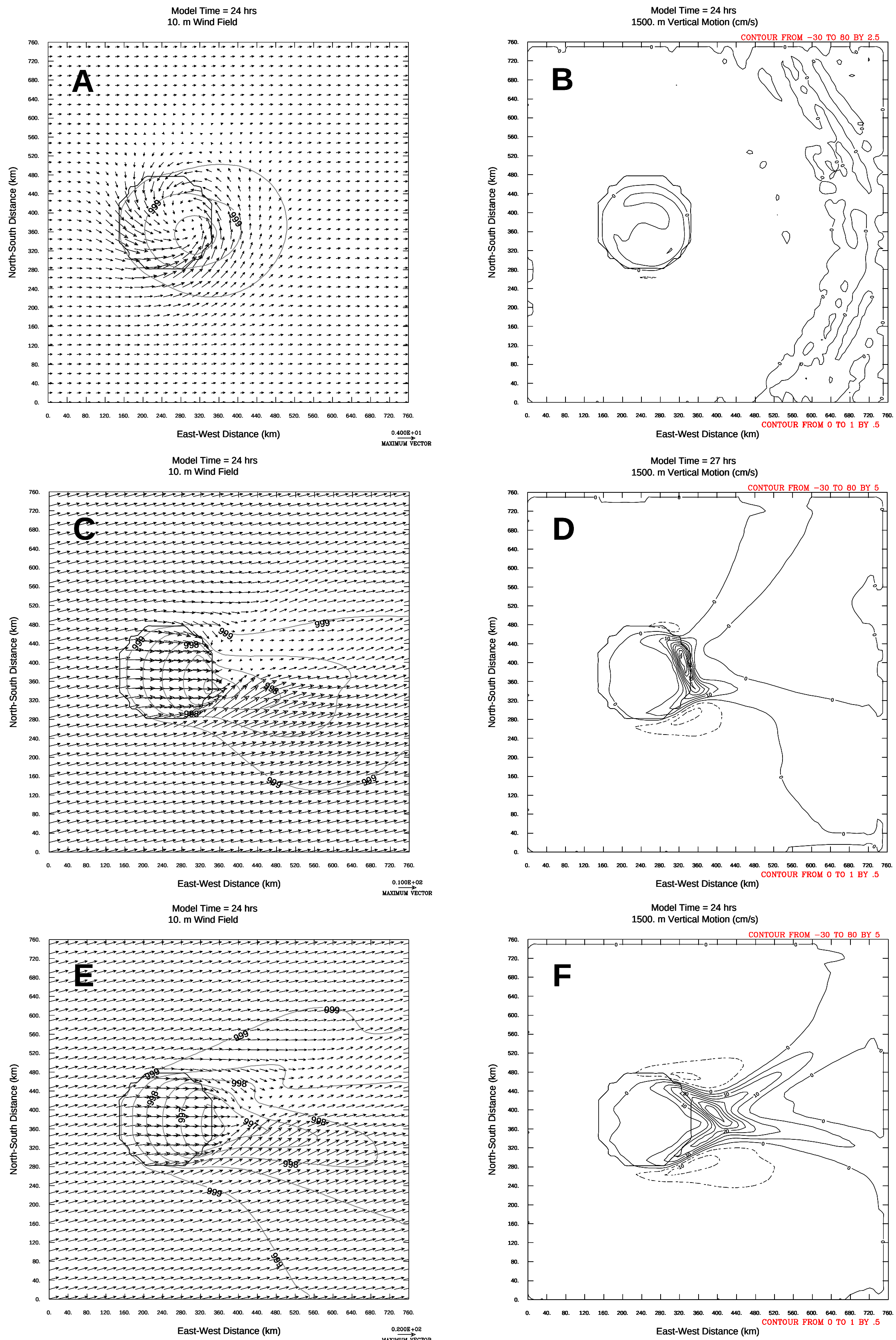


Fig 1. Examples of the 10-m wind and 1500-m vertical motion fields for the three organizations of winter mesoscale circulations. (a - b) Vortex with initial condition of U = 2.5 m s^{-1}. (c – d) Wind perpendicular band with initial condition of U = 10.0 m s^{-1}. (e – f) Widespread downwind convergent region with initial condition of U = 18.18 m s^{-1}. All simulations had L = 200 km, ΔT = 22.5C, and N = 0.006 s^{-1}. Solid (dashed) contours represent positive (negative) values.

perturbation of nearly -2.5 hPa is located at the southern end of the shoreline band. A reduction in surface pressure extends several hundred kilometers downwind of the lake and intense vertical motions of 10-45 cm s^{-1} exist along the band. The reduced surface pressure and strong vertical motions associated with the simulated shoreline band are reasonably consistent with observations presented by Braham (1983) of 1.0-4.0 hPa pressure decreases and 0.5-1.0 m s^{-1} vertical motions associated with a narrow Lake Michigan snow band. The 10-m winds in the northeastern region downwind of the lake clearly contain a lake-ward component that is indicative of a land breeze. The presence of this land-breeze wind component is used to identify shoreline band events. This definition is consistent with both observations of intense LE bands (e.g., Passarelli and Braham 1981) and a definition used by Hjelmfelt (1990).

Figure 1e-f shows a simulated widespread coverage event. It is important to note that although there are regions of low wind speeds and weak convergence downwind of the lake, a land-breeze component is not present. The mesolow is slightly deeper (i.e., pressure perturbation of -3.0 hPa) and the magnitude of the maximum vertical motions is lower (i.e., w_{max} (1500m) = 30 cm s^{-1}) compared with the shoreline band event (Fig. 1c-d). These vertical motions are similar to values of 20-50 cm s^{-1} derived from observations of several widespread wind-parallel band events (Kristovich 1993).

Past investigations of LE storms (e.g., Hjelmfelt 1990), boundary layer convection (e.g., Grossman 1982), and thermally driven mesoscale circulations (e.g., Walsh 1974), have used the two-dimensional parameter space of wind speed, U, versus water-air temperature difference, ΔT, to identify favorable conditions suitable for a particular type of mesoscale structure. For example, widespread coverage events most often occur with $U > 5$ m s^{-1} and $\Delta T > 6$ °C. Shoreline bands generally occur with $U < 6$ m s^{-1} and ΔT ranging from small to large positive values (e.g., 5-25 °C). Lastly, LE vortex events have been most frequently observed with $U < 5$ m s^{-1} and $\Delta T > 10$ °C. A disadvantage to using the U versus ΔT parameter space is that it only offers an indication of the mesoscale structure of the circulation and does not provide information about the circulations intensity. In addition, different LE mesoscale structures (e.g., vortex, shoreline band) can occur under identical U and ΔT conditions. Therefore, a parameter(s) that can better predict the mesoscale structure is desirable.

Linear theory investigations have examined uniform stratified airflow over a two-dimensional near-surface mesoscale heat source (e.g., Lin and Smith 1986, Hsu 1987) and found the phase relationship between the heat source and the induced vertical motion depends on the Froude number. When $Fr << 1$, the region of ascent occurs over the heat source. As the Froude number increases, the center of the ascending region moves downstream, while a region of descent shifts toward the heat source from upstream. When $Fr > 1$, a negative phase relationship is reached and the center of descending region is located over the heat source.

Sousounis and Shirer (1992) and Sousounis (1993) used two-dimensional numerical model investigations to examine the atmospheric response to prescribed theoretical LE conditions. Similar to earlier linear theory studies, Sousounis and Shirer (1992) found that the mesoscale LE response was dependent on Froude number. Sousounis (1993) found that the wind speed for maximum LE snowfall near the downwind lakeshore of a 200 km lake yielded a Froude number very close to unity and suggested that the Froude number might be a useful parameter for the forecasting of LE storms. More recently, Xie and Lin (1996) presented results from a study of Carolina coastal frontogenesis that suggested the intensity of the mesoscale response decreases as the Rossby number increases and the horizontal structure of the response is largely determined by the Froude number.

Two non-dimensional parameters (i.e., Froude and Rossby numbers) were examined that have been suggested as useful to characterize the response of stratified airflow over an isolated surface heat source. Figure 2a shows the relationship of the Froude number to maximum vertical motion and the mesoscale structure of each of our 35 model simulations. For this study, the Froude number was defined as $Fr = U/N \cdot H$, where U is the geostrophic wind speed, N is the maximum buoyancy frequency, and H is the upwind boundary layer depth (2.0 km). The Froude number is able to reasonably stratify the mesoscale structure of the circulations that developed. Mesoscale vortex and widespread coverage events are confined to lower (< 0.4) and higher (> 0.8) Froude numbers, respectively. However, shoreline band events span the entire range of Froude numbers in addition to being uniquely defined at intermediate Froude numbers ($0.4 < Fr < 0.8$). These results suggest that the Froude number may be of limited use as an aid to forecast the structure of LE circulations.

Figure 2b shows the relationship of the Rossby number to maximum vertical motion and the structure of each of our 35 model simulations. For this study, the Rossby number was defined as $Ro = U/f \cdot L$, where U is the geostrophic wind speed, f is the Coriolis parameter, and L is the lake diameter. The results show that the structure of a LE circulation is directly dependent on the magnitude of the Rossby number and that its use may be benefical for predicting the structure of LE circulations.

4. INTENSITY OF MESOSCALE CIRCULATION

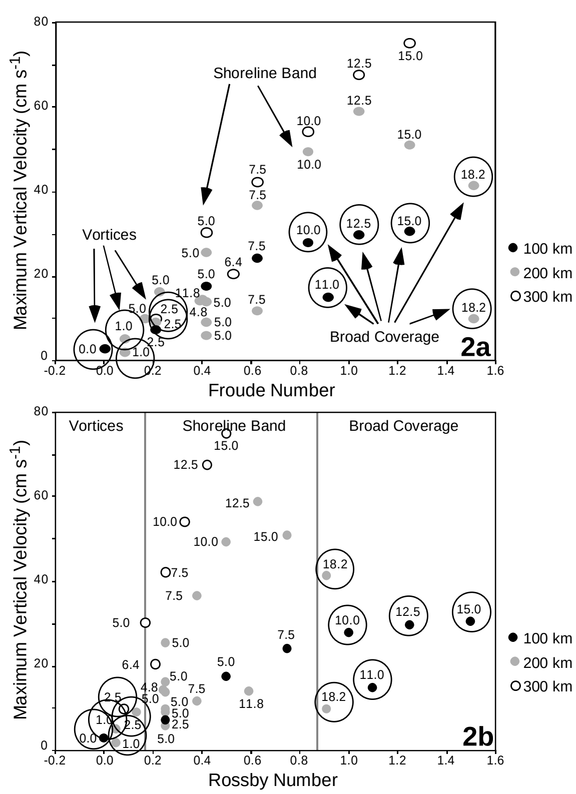
The Buckingham Pi technique of dimensional analysis and similarity theory is used to identify a functional relationship for the prediction of the mesoscale circulation intensity regardless of the associated LE morphological regime. Consider that the following function of fundamental parameters describes a LE system

$$\Phi = f\,(U, L, h, \rho, T, \Delta T, p, g, N, f)$$

where U is near-surface geostrophic wind speed, L is axisymmetric lake diameter, h is mechanical boundary layer depth upwind of the lake, ρ is air density, T is 10-m air temperature upwind of the lake, ΔT is the temperature difference between the lake surface and T, p is pressure, g is gravitational acceleration, N is Brunt Viasala frequency, and f is the Coriolis parameter. From these fundamental parameters, several dimensionless quantities are determined and combined to develop the "intensity index", Φ. The intensity index is defined as:

$$\Phi = C \cdot \frac{U \cdot \Delta T \cdot f^2 \cdot L}{N \cdot T \cdot g \cdot h}$$

The index makes use of physical constants and measurable parameters to predict the intensity of a LE mesoscale circulation. A constant, C, with a value of 5×10^4 is used to scale Φ. Changes in wind speed represent the largest contribution to variations of Φ followed by changes in lake-air temperature difference and boundary layer stability. Given that U and ΔT are important variables used to calculate bulk estimates of surface heat flux, Φ can be interpreted as the ratio of the lake surface heat flux to the maximum buoyancy frequency. Discussion and results examining the utility of Φ will be presented at the conference.



Labels represent geostrophic wind speed. Lake diameter denoted to right. Shoreline band events are not circled.

6. CONCLUSIONS

The results from our array of axisymmetric lake simulations show that the structure of a LE circulation is strongly dependent on the magnitude of the Rossby number. Low Rossby numbers (i.e., approximately < 0.2) resulted in a mesoscale vortex circulation. Rossby numbers between about 0.2 and 0.9 resulted in the development of a shoreline band (e.g., land-breeze convergence zone) and Rossby numbers having a value greater than approximately 0.9 produced a widespread coverage event over and downwind of the lake. Our results also demonstrate that the intensity of the mesoscale response (e.g., maximum vertical motions) can be predicted using a dimensionless function comprised of fundamental variables (e.g., wind speed, water-air temperature difference, ambient stability).

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