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

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1. INTRODUCTION

A fundamental outstanding issue in mesoscale and boundary layer research is how the atmosphere responds to, and interacts with, surface heat and moisture variations. Spatial heterogeneities in surface heat fluxes, such as land-water boundaries, surface vegetation and land use variations, 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 distinct morphological regimes. The most commonly discussed LE regimes include: 1) widespread coverage, 2) shoreline bands, and 3) mesoscale vortices.

Two overarching goals of the current investigation are: 1) the determination of the environmental conditions that favor an individual meso-β scale LE morphological regime over another and 2) the influence that changes in environmental conditions have on both the structure and strength of meso-β scale LE circulations. To address the goals we use an array of idealized mesoscale model simulations of stratified airflow over a relatively warm axisymmetric lake. The results of this investigation provide practical information to predict the 1) morphological regime of a mesoscale LE circulation, 2) periods of transition across regimes, and 3) intensity of the mesoscale response based on knowledge of wind, temperature, and stability conditions.

2. MESOSCALE MODEL

The Colorado State University Mesoscale Model used for this investigation is a three-dimensional, hydrostatic, incompressible, primitive-equation model (e.g., Mahrer and Pielke 1977). 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 ambient 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 performed on a 76 × 76 × 20 grid. The horizontal grid spacing was 10 km. The model requires input of vertical profiles of temperature, specific humidity, and 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 (dθ/dz = 1, 3, or 6 K km^{-1}) with a stable layer above of dθ/dz = 8 K km^{-1}. 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 LE circulation was sustained in each experiment.

3. DIMENSIONAL ANALYSIS

Previous studies of LE conditions (e.g., Sousounis 1993) and stratified flow over an isolated surface heat source (e.g., Hsu 1987) have demonstrated the significance of individual variables to the development of a mesoscale response circulation. Consider that the following function of fundamental variables describes a LE system

$$f\,(U, L, H, \rho, T, \Delta T, p, N, f) = 0$$

where U is the ambient wind speed above the planetary boundary layer, L is axisymmetric lake diameter, H is the 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, N is maximum buoyancy frequency, and f is the Coriolis parameter. From these nine variables, the following dimensionless quantities are determined using dimensional analysis and the Buckingham Pi theorem,

$$f\left[\frac{H}{L},\frac{\Delta T}{T},\frac{p}{U^2\rho},\frac{U}{NL},\frac{U}{fL}\right] = 0$$

Since the Euler number, $p/(\rho U^2)$, is typically associated with externally forced motions, it can be considered independent of fluid motions that are primarily thermally induced, such as lake-effect circulations. The remaining four quantities, which include the Rossby number (Ro = U/(f·L)) and Froude

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number (Fr = U/(N·H)), will be used to examine the mesoscale structure and intensity of LE circulations.

4. STRUCTURE OF MESOSCALE CIRCULATIONS

Using an array of thirty-five idealized mesoscale model simulations, we have examined two non-dimensional parameters (i.e., Fr and Ro) that have been suggested as useful to characterize the response of stratified airflow over an isolated surface heat source and designated by our dimensional analysis.

Figure 1a shows the relationships of Fr to the mesoscale structure of the LE circulation from each of the 35 model simulations and maximum vertical motion. For this study, Fr was defined using model initial conditions of the ambient wind speed (U), lower tropospheric maximum buoyancy frequency (N), and boundary layer depth upwind of the lake (H = 1.5 km). Fr is clearly related to the mesoscale structure of the response circulation. Mesoscale vortex and widespread coverage events are confined to lower (< 0.3) and higher (> 0.8) Froude numbers, respectively. However, shoreline band events span the entire range of Froude numbers in addition to being uniquely identified at intermediate Froude numbers. For example, a Fr of approximately 0.25 would indicate the possible development of both a mesoscale vortex and shoreline band. These results suggest that Fr may be of limited use to forecast the mesoscale structure of LE circulations.

Figure 1b shows the relationships of Ro to the mesoscale structure of the LE circulation from each of the 35 model simulations and maximum vertical motion. For this study, Ro was defined using the ambient wind speed (U), Coriolis parameter ($f = 1.0 \times 10^{-4}\ s^{-1}$), and axisymmetric lake diameter (L). Figure 6 shows that Ro was effective in differentiating the three basic LE morphological regimes. Simulated LE conditions with low Rossby numbers (i.e., approximately < 0.2) resulted in a mesoscale vortex circulation. Simulations having 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 with values greater than about 0.9 produced widespread coverage events. It should be noted that the transitions between LE morphological regimes in Ro space are not discrete, but rather where gradual transformations of the lake-effect circulation occurs.

5. INTENSITY OF MESOSCALE CIRCULATIONS

A relationship was empirically determined that can be used to simplify the complex LE system and predict the strength of LE circulations from first order fundamental variables that are easily measured. Each of the dimensionless numbers and numerous combinations of the dimensionless numbers were evaluated using the output from our model simulations. A simple combination of dimensionless quantities produced an exceptional match to the model data and resulted in the development of the LE intensity index. The LE intensity index, Φ, is defined as:

$$\Phi = \frac{U \cdot \Delta T \cdot L}{N \cdot T \cdot H^2}$$

The index is highly correlated with the model-estimated surface sensible heat flux integrated over the entire lake surface area. This can be attributed to the dominance of U and ΔT in the numerator of Φ. 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 (the dominant variable in the denominator of Φ). Model results will be used during our presentation to demonstrate the capability and utility of the lake-effect intensity index.

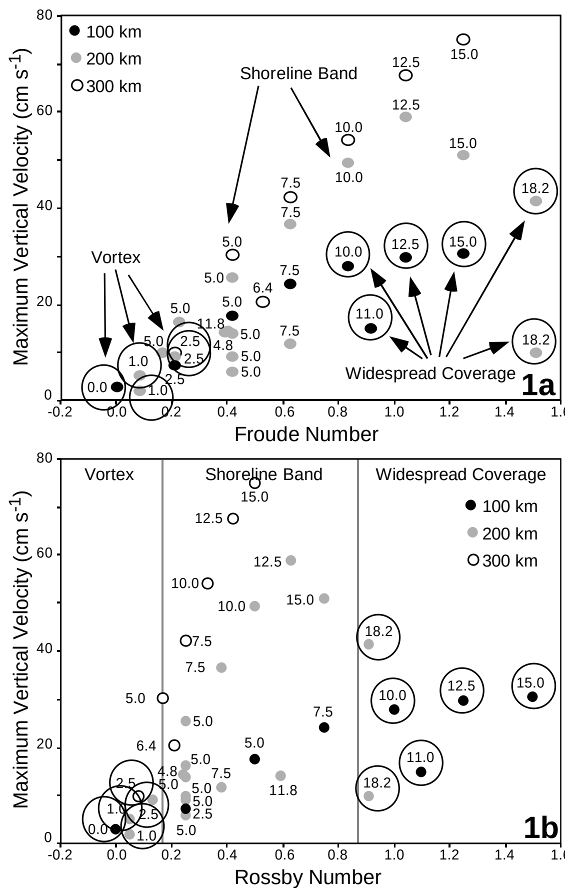

Fig. 1. Labels represent wind speed. Lake diameter denoted. Shoreline band events are not circled.

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