P 9.7 WRF SIMULATIONS OF ENVIRONMENTAL CONDITIONS CONDUCIVE TO THE FORMATION OF LAKE-TO-LAKE BANDS

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1. INTRODUCTION

Lake-effect snow storms occur frequently over the Great Lakes region during the winter season as cold air outbreaks modify boundary layer air. Cloud bands are defined as lake-to-lake (L2L) bands when the bands extend over two or more lakes at one time. While considerable knowledge about lake-effect snow storms exists, little is known about L2L bands. Past studies of upwind lake influences on downwind lake-effect convection have led to a research goal of determining the processes involved in sustaining convective boundary layer circulations over intervening land between lakes.

Numerical simulations of a L2L case from 02 December 2003 are presented. Sensitivity studies consisting of a change to the snow roughness and an increase or decrease of lake surface temperatures were compared against a base simulation and some initial results are described. Also included is a description of techniques and limitations in using the Weather Research and Forecasting (WRF) model for research of Great Lakes cloud bands.

2. BACKGROUND

Numerical simulations of L2L bands have been few to date. Despite this, research of upwind lake influences has led to the identification of processes that may be important to L2L band formation. Four processes are summarized in Hjelmfelt et al. (2004): (1) propagation of heat and moisture plumes downwind, (2) Lake-induced circulation growth to a downwind lake, (3) Gravity wave initiation by an upwind lake, and (4) Band microphysical and radiational processes able to sustain propagation of the band. Each of these has a profound effect on boundary layer evolution, and several studies in the past have noted that the upwind Great Lakes cause rapid warming and increasing moistening of near-surface air in the boundary layer (e.g., Chang and Braham 1991, Kristovich et al. 2003). A sensitivity study by Hjelmfelt et al. (2004) revealed that removing Lake Superior from simulations led to a boundary layer over Lake Michigan half the size of a boundary layer with Lake Superior present. A more recent observational study by Rodriguez et al. (2007) determined the frequencies of L2L bands over the Great Lakes. The majority of cases were found to originate over Lake Superior, which is consistent with the northwest direction of cold air outbreaks and large fetch of the lake. This study also provided a database of L2L cases for future research, including this current study.

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3. 02 DECEMBER 2003 CASE DAY

The case day of 02 December 2003 was chosen for simulations due to its well-represented L2L bands. Cloud band formation began following the passage of a surface low pressure system, which evolved over the Great Lakes and continued beyond to the East Coast. Northwest winds existed in the wake of the low that allowed flow over the long fetch of Lake Superior towards Lakes Michigan and Huron. Northwesterly wind extended vertically through the boundary layer up to 850 mb. Figure 1 shows a surface analysis for 12Z on 02 December. By the beginning of the day on 03 De-

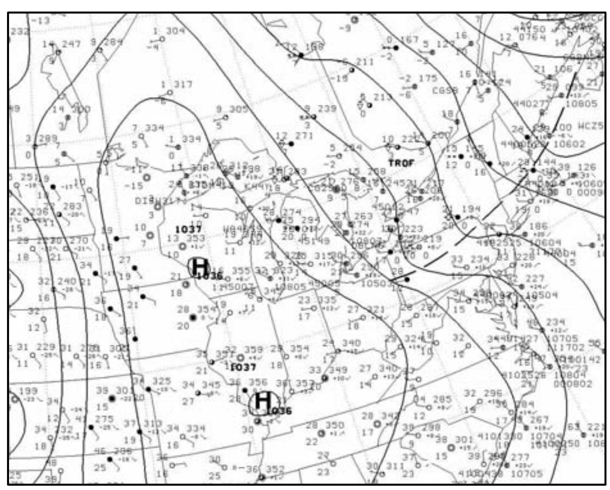

Figure 1: NCEP surface analysis for 02 December 2003 valid at 12Z.

cember 2003, the high pressure system was located over the Lake Michigan region and the L2L bands ceased. An analysis of lake surface temperatures and ice cover is also provided in Figure 2.

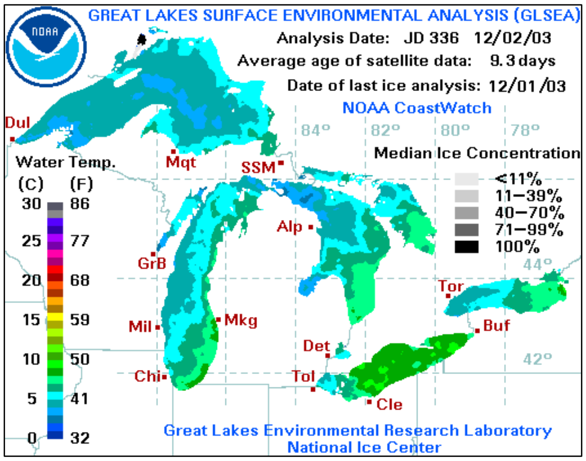

Figure 2: GLERL lake temperature and ice concentration for the Great Lakes on 02 December 2003.

4. DATA AND METHODS

WRF-ARW version 2 (Skamarock et al. 2005) was utilized for simulations of the 02 December case. A nested grid was created (Fig. 3), with grid spacing of 15-km for the outermost grid, 5-km for the regional grid, and 1.67-km for the innermost domain. For vertical spacing, 35 levels were chosen, with 13 of those levels designated to the boundary layer for clear resolution of the shallow lake-effect convection. Specific physics options selected include the Thompson et al. (2004) graupel scheme, the Noah land surface model (Noah LSM, Skamarock et al. 2005), the YSU boundary layer scheme (Hong et al. 2006), and the Kain-Fritsch cumulus parameterization (Kain and Fritsch 1993) for the two outermost domains. With the high resolution innermost grid, only the explicit precipitation scheme was included. Data for the simulations were provided from the North American Regional Reanalysis (NARR) from NCEP (Mesinger et al. 2006) with additional lake temperature and ice data provided from the Great Lakes Surface Environmental Analysis (GLSEA) from GLERL (see Fig. 2). Initialization began at 18Z on 01 December 2003 and each run was completed at 06Z on 03 December 2003.

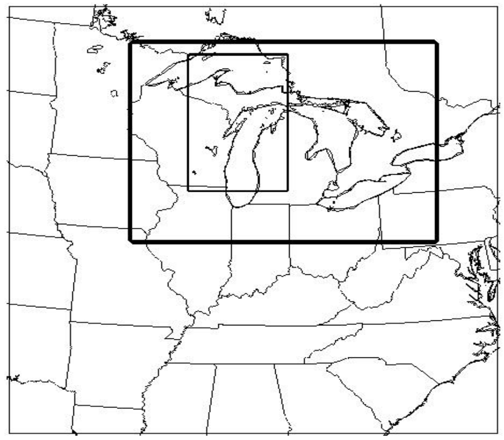

Figure 3: Model domains. Outermost grid is 130x135 with 15-km spacing, regional grid is 250x196 with 5-km spacing, and innermost grid is 244x391 with 1.67-km grid spacing.

An initial problem arose in location selection of the domains. In the Hudson Bay region, there was an inconsistency between the NARR grib landmask and land-surface fields. Specifically, large values were being substituted in the missing value component of the metgrid table, which in turn did not allow the case to be correctly simulated. The problem was fixed by modifying the number in the missing value variable and by moving the domains to avoid Hudson Bay. A similar issue arose when incorporating the GLERL data into the model run. The GLERL data was only used in the innermost domain, and to bring this data into the run required metgrid.exe to be executed twice. After the data was incorporated, the land-sea datamask was at different spatial scales than the concurring domain, so the missing value variable adopted large values and a landmask error occurred. Like the previous problem, the value in the missing value variable was changed.

In addition to the base run, several sensitivity simulations were completed to investigate L2L band and boundary layer behavior. Often the lake-effect clouds are unable to continue across the intervening land, and the sensitivity studies are designed to investigate some of the hypotheses concerning conditions that allow L2L bands. First, lake surface temperatures in the innermost domain were increased by 5 degrees. The second simulation involved lowering lake surface temperatures by 5 degrees from the base run. Both of these changes involved modification of the original GLERL data. Lastly, the roughness length over snow was changed; snow dependent roughness length was replaced with background land-surface roughness length. This was executed by editing the subroutine SNOWZ0 in the Noah LSM, followed by rebuilding Noah. The roughness length was modified in hopes of determining what happens when no snow is present to flatten out the land surface, since in the Noah scheme the presence of snow cover reduces the surface roughness to a very low value.

5. RESULTS

Figure 4 shows results of the base simulation cloud water in comparison with the observed satellite clouds, and appears to confirm that the base simulation reproduced L2L bands fairly accurately. Band location and width fit well with observations, given that the Terra MODIS visible satellite image is of 250-m resolution compared to the 1.67-km resolution of the inner grid in the output.

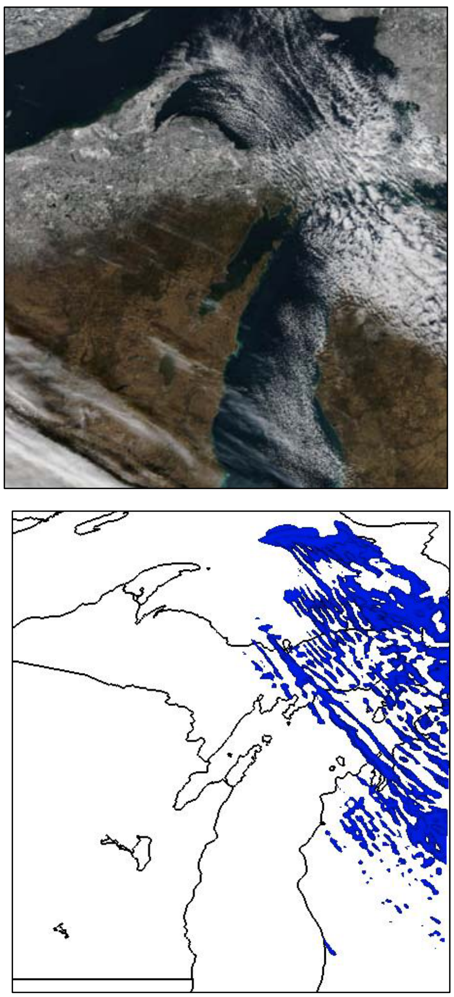

Figure 4: Comparison of Terra MODIS visible satellite at 1715Z (above) with an isosurface of cloud water mixing ratio of 5E-5 kgkg^{-1} in the innermost domain at 18Z (bottom) for 02 December 2003.

Shown in Figure 5 is a cross section of potential temperature and relative humidity along the L2L bands for the base run. In Figure 5, the potential temperature contours depict that the surface layer air over Lake Superior is superadiabatic with a well-mixed boundary layer that warms as the air traverses the lake eastward. Boundary layer height is approximately 1 km with evidence of slight boundary layer growth at the intersection of the Upper Peninsula. As air passes over the Upper Peninsula, mixing decreases as heating is cut off from the land. Lower relative humidity in the lower boundary layer is also evident over the Upper Peninsula, but does not extend high enough to impact the cloud layer (seen in gray). Above the boundary layer, evidence of gravity waves is seen in the potential temperature pattern. Boundary layer patterns similar to these were present through the majority of the event and began to decrease by nightfall.

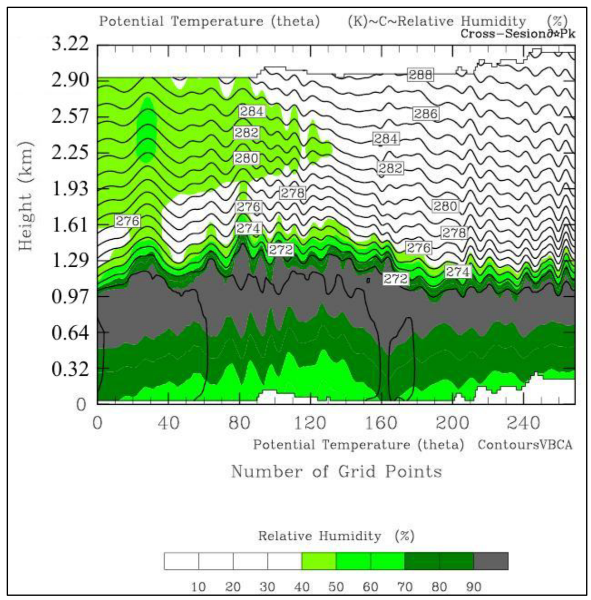

Figure 5: Cross section of potential temperature and relative humidity at 17Z from domain 3 output for the 02 December 2003 base run. The cross section shows a vertical slice from Lake Superior (starting at left) through the Upper Peninsula (from grid points 90 to 140) and northern Lake Michigan (from grid points 140 to 200) to northern Lower Michigan.

Several other fields, along with the above mentioned, were used in comparison of the base run with the sensitivity runs. For example, 2-m temperature differences between the base run and the plus 5 degrees lake temperature run reveal that an increase in lake surface temperatures causes warming of near-surface air temperatures (not shown). Similarly, the mixing ratios near the surface for the lake surface temperature increase run are larger than for the base run (not shown). As a result, L2L bands still exist in many of the same locations but cloud bands are located farther south down the shoreline of Lake Michigan on each side of the lake. However, these new bands are not connected to form L2L bands. Further results will be presented at the workshop.

6. SUMMARY

A lake-to-lake band case on 02 December 2003 was simulated using WRF to determine the important properties of the boundary layer that lead to L2L band formation and to record boundary layer and L2L band changes as sensitivity tests are conducted upon the base case. Despite complications with landmasks when incorporating lake data into the model, simulations were completed for a base run, a run adding 5 degrees to the base lake temperatures, a run subtracting 5 degrees from the base lake temperatures, and a run replacing the snow-dependent roughness length with background roughness length.

The model adequately reproduced the L2L bands. By plotting cross sections of potential temperature, relative humidity, etc., the evolution of the convective processes related to the L2L bands and the survival of these boundary layer perturbations across land was shown. Further research includes simulations of a cold air outbreak case similar to this L2L case, however with no L2L bands produced. This will serve as further comparison to determine the conditions that allow for bands to survive the passage over intervening land.

7. ACKNOWLEDGEMENTS

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