1. INTRODUCTION

Each year the Great Lakes region experiences numerous frontal systems that pass through and interact with the large bodies of water. Given the right conditions, a frontal passage through this region can often result in debilitating lake effect snows. Due to heat capacitance differences, the land surrounding the Great Lakes heats and cools much faster than the adjacent lake surface. These environmental conditions create heat fluxes that are suggested to affect the structure of a passing front and can modify its overall progression through the region.

Past studies that focused observational analysis and numerical simulations of lake effect snow storms have led to a fair understanding of the processes involved. There have not been nearly as many studies conducted on the frontal systems that interact with the lakes and condition the environment to produce lake effect snow. Gallus and Segal (1999) found that a strong, dry cold front crossing a relatively cool Lake Michigan surface would accelerate compared to portions over the land to the south. Dreher (2004) reported the deceleration of an arctic boundary as it progressed over a relatively warm Lake Michigan surface. Possible mechanisms responsible for the alteration in frontal speed are suggested to be changes in frontal temperature gradients caused directly by the difference of thermal fluxes over water and land as well as through alteration of the surface roughness and near-surface thermal stratifications that could modify the effects of friction on the front (Garratt 1986, Gallus and Segal 1999).

The current study utilizes the WRF-ARWV2 (Weather Research and Forecasting – Advanced Research WRF Version 2) to conduct numerical simulations of two cold frontal passages over Lake Michigan: 21-22 January, 2004 was a cold frontal passage over relatively warm lake waters chosen to represent a typical lake effect snow-producing scenario; 24-25 April, 2002 was a cold frontal passage over relatively cool lake waters that was chosen to represent a typical spring convective event. Numerical simulations of the two case studies were conducted with Lake Michigan present and with Lake Michigan taken out.

The current study seeks to verify the simulation to the observational analysis as well as investigate the effects of Lake Michigan on the structure, progression, and precipitation associated with the cold fronts. Due to length constraints, only results of the 24-25 April, 2002 case will be discussed within this paper.

2. MODEL DESCRIPTION AND METHODS

Observational analysis involved examination of surface observations, upper air charts and soundings, and radar imagery. Numerical simulations were conducted using the WRF-ARWV2 non-hydrostatic mesoscale model. Three nested domains were centered over the lower portion of Lake Michigan with spatial resolutions of 18, 6, and 2 km. The model was initialized with North American Regional Reanalysis (NARR) data from the National Center for Environmental Protection (NCEP) archives as well as Great Lakes Surface Environmental Analysis (GLSEA) provided by the Great Lake Environmental Research Laboratory (GLERL).

The simulations made use of the NOAH Land Surface Model (NOAH-LSM) that contains four-layer soil moisture and temperature fields and provides sensible and latent heat fluxes to the boundary layer scheme (Skamarock et al. 2005). The boundary layer scheme chosen for the simulations was the Yonsei University boundary layer scheme explained in Hong et al. (2006). The Thompson et al. (2004) microphysics option was employed in all domains. The Kain-Fritsch (1993) mass flux cumulus parameterization was used for the outer (d01) and middle domains (d02) with no cumulus parameterization needed for the innermost domain (d03).

As a part of multiple simulations that were conducted for each of the two case studies, one simulation was made with Lake Michigan present and another with Lake Michigan taken out. The Lake Michigan surface was replaced with adjacent land use categories taking the place of the lake surface with no interpolation of topography. Taking
Lake Michigan out of the numerical simulation allowed us to quantify and better understand the direct effects of Lake Michigan on the passing cold front.

Problems within the modeling process arose when the NARR data was incorporated on the larger, outside domain. Inconsistencies between the NARR grib landmask and the land surface fields led to errors in the soil moisture values over Hudson Bay that would inhibit the completion of the simulation. Other problems arose while trying to fit landmasks and datasets of differing scales and spatial extents together within the modeling framework. The problem first appeared while implementing the GLERL data within the NARR data around the Great Lakes region. This issue was responsible for creating a faulty interpolation of skin temperatures over the Lake Michigan area when the land use was applied in that area. These problems were alleviated by modifying the missing value parameter and variable-specific land-sea mass parameters within the metgrid table.

3. RESULTS

3.1 Model Verification

Model results from the 24-25 April 2002 simulation involving the presence of Lake Michigan verify well with the observed analysis. Figure 1 displays the observed surface analysis along with the simulated surface analysis for 0300 UTC, 15 hours after the initiation of the model and after the front fully progressed past the lake surface. It is evident that the simulated wind field matches the available observations well, as there is moderately strong west and northwesterly flow in the post-frontal cold sector, as well as weaker southerly flow in the pre-frontal warm sector. The model has also simulated the pressure field with some accuracy, as the location of the low pressure center and pressure trough appears to be unchanged, while the depth of the simulated pressure trough appears slightly greater than that of the observed analysis. The accuracy of the sea-level pressure and surface wind fields allowed us to verify the approximate location of the simulated cold front to that analyzed from observations. The approximate locations of the cold front in Figure 1 were drawn with the aid of simulated and observed surface potential temperature plots which revealed a considerable gradient representative of the frontal location (not shown).

3.2 With-lake vs. No-lake Simulations

Results of the 24-25 April 2002 simulations indicate the cold front progressed over the Lake Michigan surface much more quickly when the lake is present than when the lake is taken out. Figure 2 displays vertical cross-sections of potential temperature across the frontal gradient with and without the presence of Lake Michigan. Figures 2a and 2b are taken at 2300 UTC just before the front comes into contact with the lake surface, while Figures 2c and 2d are just after the cold front makes landfall on the eastern shores of Lake Michigan (0100 UTC). It is evident that the frontal location at 2300 UTC is relatively unchanged between the with-lake and no-lake simulations. This shows that before the front comes into contact with the lake surface there is virtually no difference in the speed of the front and will serve as a basis for comparison at a later timestep.

Figure 1. Surface analysis of sea-level pressure (interval 2 hPa), surface winds, and approximate frontal location at 0300 UTC. (Left) Simulated results, (Right) Plymouth State College Weather Center archived data. Thick blue line indicates approximate frontal location.
At 0100 UTC the front that passes over the lake progressed about 130km to the east and was located at approximately 150km into the cross-section (Figure 2c). During that same time period the cold front in the no-lake simulation only progressed about 110km to the east and can be seen at approximately 130km into the cross-section (Figure 2d). The acceleration of the front in the with-lake case can be attributed to a decrease in turbulent mixing in the lowest 120 meters as well as a marked increase in frontal temperature gradient across the front due to increased thermal advection on either side of the boundary. Figure 2a shows the impact of cooler air temperatures in creating a very stable environment in the lowest 120 meters that will act to retard the vertical motions and ultimately reduce vertical mixing and turbulent friction at the frontal boundary. As the cold front progressed over the lake surface, a large portion of it began to ride over the stable layer. This ultimately reduced the friction on the frontal boundary above a few hundred meters as it becomes partially decoupled from the surface layer.

The with-lake simulations reveal stronger low-level winds in both the cold and warm sectors during the period when the front traversed the lake than in the no-lake simulations. Increased westerly and northwesterly flow behind the front advected cold air behind the front more rapidly, while the increased southerly flow ahead of the front increased warm air advection. The increase in both the pre- and post-frontal winds in the with-lake simulations were due to the decreased surface friction and near-surface thermal stratification generated by the relatively cool lake surface and may only affect the lowest few hundred meters of the cold front. These results are in line with the results of Gallus and Segal (1999) where a frontal bulge was seen over the Lake Michigan surface.

The thermal stabilization of the near-surface atmosphere over the lake surface resulted in decreased vertical motion in the lowest few hundred meters across the frontal boundary as it crossed Lake Michigan. The vertical motion across the front above the lowest few hundred meters appear to be unaffected by the near-surface stabilization and are comparable to those in the no-lake simulation (not shown). The effect of increasing the thermal gradient across the frontal boundary appears to outweigh the effects of the near-surface thermal stratification inhibiting low-level vertical motions.

Because the vertical motions remain relatively consistent across the frontal boundary in the with-lake simulation, the front was able to remain convective in nature. After the with-lake simulated cold front crosses Lake Michigan, thermal stabilization prohibits further vertical motions,
leading to an overall decrease in post-frontal precipitation. Post-frontal precipitation was much more prevalent in the no-lake simulation due to destabilization of the near-surface atmosphere, creating vertical fluxes of heat and moisture. This results in more precipitation falling over the Lake Michigan surface in the no-lake simulations than in the with-lake simulations (Figure 3).

4. SUMMARY AND CONCLUSIONS

The 24-25 April, 2002 case is representative of a typical spring convective cold front progressing over a relatively cool lake. The WRF-ARWV2 model was utilized to simulate and quantify the effects of the cool Lake Michigan surface on the strong frontal boundary. The model seemed to have problems with integrating various scales of data and landmasks together, as well as properly filling the missing initialization data.

The model was able to accurately simulate the progression of the front as it traversed the Lake Michigan surface. Only subtle differences could be discerned between the simulations with Lake Michigan present and the observed analysis of what actually happened. When comparing the with-lake simulations to the no-lake simulations, the with-lake simulations revealed a marked acceleration of the frontal boundary over the lake. This acceleration could be attributed to an increase in the frontal temperature gradient. This was due to less surface friction and near-surface stabilization, generating increased wind speeds, which in turn were able to advect cool post-frontal air more rapidly than in the no-lake simulation. The no-lake simulation resulted in more precipitation over the lake surface than the with-lake simulation, due to suppressed fluxes of heat and moisture caused by post-frontal stabilization in the with-lake simulation. Numerical simulations of the 21-22 January, 2004 case with a relatively warm lake are also in progress.

5. ACKNOWLEDGEMENTS

This work was partially supported through NSF Grant ATM-0511967.

6. REFERENCES