THE ROLE OF LAKE ENHANCEMENT IN THE EVOLUTION OF
THE 2011 CHICAGO-AREA GROUNDHOG’S DAY BLIZZARD

BY

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THESIS

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ABSTRACT

On 1-2 Feb, 2011, a mid-latitude cyclone moved through the US Midwest, covering much of the region in deep snow or sleet. This study analyzes the role that the Great Lakes played in modifying this cyclone. Two different Weather Research and Forecasting (WRF) simulations were conducted, one featuring the lakes and the other with the lakes removed. Prior to the arrival of the comma head, reverse lake effect precipitation was noted only in the with-lakes run, indicating that the lakes were effectively removed from the model. During cyclone passage, downwind modification of stability and thermal structure was noteworthy in the with-lakes run, but not in the no-lakes run. After the arrival of the comma head, small differences in the pressure field led to striated patterns in the overall liquid equivalent accumulation difference field, but these were minimal. The biggest liquid equivalent precipitation accumulation increase in the with-lakes simulation compared to the no-lakes simulation was seen in the Chicago area, downwind of Lake Michigan’s long axis, but even this was barely over half a centimeter. The frontal inversion limited atmospheric moisture uptake. Large differences, however, were noted in downwind temperature and dewpoint fields, and wind fields over the lakes. Noteworthy changes were also observed in ground-level to 850 hPa lapse rates and surface layer instability.
ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

The Laurentian Great Lakes often serve as a trigger for intense lake effect precipitation. The reasons for this precipitation and its impact on downwind shores are well documented [e.g. Wiggin (1950), Peace and Sykes (1966), Hjelmfelt and Braham, Jr. (1983), Norton and Bolsenga (1993), Barthold and Kristovich (2011)]. As cold air flows over warm water, the air is warmed and moistened, destabilizing the air. When the air reaches the leeside shoreline, the air’s buoyancy, combined with shoreline convergence owing to increased friction, result in rising air, inducing often intense precipitation. In cases where synoptic conditions are already causing precipitation but the lakes supplement the total precipitation, the term “lake enhancement” is often applied [Bard and Kristovich (2012)].

Therein lies an important question, however: What influence do the lakes have on a cyclone as it passes over them? What “enhancements” are occurring? Dewey (1979) proposed a lake effect forecast model for each of the Great Lakes, but was forced to omit “days which occurred concurrently with synoptic-scale precipitation events” from his analysis. Are we now able to determine the lakes’ contributions?

Recent studies have isolated the influence of the Great Lakes by analyzing ice cover effects. Vavrus et al. (2013) imposed 100% ice coverage on the Great Lakes (both individually and entirely) in multi-decadal regional climate model simulations, finding downwind snowfall reductions, particularly for Lakes Superior and Michigan, when ice is imposed. Precipitable water and low-level clouds also decreased, while downstream pressure increased upon freezing
the lakes. Slowed winds across the lakes also limited shoreline convergence, serving to further minimize downwind precipitation.

Gerbush et al. (2008) analyzed the energy fluxes above ice-covered lakes, measured during the Great Lakes Ice Cover-Atmospheric Flux (GLICAF) experiment. They found the temperature difference between the air and sea surface to have a greater impact on sensible heat flux than the impact of the wind speed, though both were important. Sensible and latent heat fluxes were found to vary nonlinearly and linearly, respectively, with pack ice concentration. From 70% to 100% coverage, they found a rapid decrease in sensible heat fluxes, whereas the change below 70% coverage was minimal. Cordeira and Laird (2008) used HYSPLIT back trajectories to analyze the influence of ice cover. They found a significant influence on energy fluxes related to the thickness of ice cover; when a lake was iced over, lake effect precipitation could still occur if the ice was not thick enough to substantially inhibit energy transfer. Wright et al. (2013) conducted four Weather Research and Forecasting (WRF) model runs of a lake-enhanced snow event, wherein the lakes modified the precipitation patterns of a passing cyclone. Besides their control case, they conducted model runs with all ice removed, increased lake surface temperature, and complete ice cover. They noted a sharp decrease in precipitation in their all-ice case. In general, they found ice coverage to have a greater influence on precipitation coverage than did lake surface temperature. Lake Ontario, in particular, experienced a 500% increase in downwind precipitation when all ice was removed. Over the lake itself, narrow updrafts were shown to develop, but precipitation increases were minimal.

The purpose of the present study is to analyze the overall influence of the presence of the lakes on a passing, exceptionally strong cyclone. Like Wright et al. (2013), the lake surfaces were altered in this study for a WRF model simulation, which was then compared to a control
simulation. Here, we replaced the lakes, whether they were open or ice-covered (or somewhere in-between), with the characteristics of the surrounding shorelines in an effort to simulate the complete absence of the lakes. Because Lake Erie was frozen over, the Groundhog’s Day Blizzard provides an opportunity to compare both open-water and ice-covered lakes to this third, no-lakes alternative.

The primary questions analyzed in this project can best be summed up as the following:
What influence did the presence of the lakes have on the cyclone as it traversed the Midwest? More specifically, how did the lakes affect the precipitation distribution? Was there more precipitation overall? Additionally, how were other parameters influenced by the lakes? What effect did the lakes have on low-layer stability, temperature, and dewpoint? How far downstream did these influences extend? Finally, just how much of the precipitation that fell in this event was caused by the lakes rather than by the extratropical cyclone circulation?
CHAPTER 2

METHODOLOGY

In order to answer these questions, the WRF model was set up using the National Centers for Environmental Prediction’s North American Model for initial and boundary conditions in order to conduct a case study of a cyclone passing over the Great Lakes. This model was then repeated with the lakes removed. The with-lakes (WL) and no-lakes (NL) simulations were then compared. Both the WL and the NL simulations utilized two domains (Fig. 1), with the outer domain having a grid spacing of 9 km, and the nested domain having a grid spacing of 3 km. The parameterizations shown in Table 1 were utilized for these simulations.

The goal was to remove the influence of the lakes as completely as possible. This allowed us to understand the influence of the lakes on the evolution of precipitation and other fields. In order to effectively remove the lakes for the NL run, an algorithm was developed to search for any grid cells that were defined as water within the Great Lakes region. The algorithm was designed to work with outputs from the WRF Preprocessing System (WPS), which takes archived model output and converts it into a file format suitable for WRF simulations. Latitude and longitude bounds (41.35° - 49.02° N, 76.05° - 92.30° W) were set around the Great Lakes, with separate bounds set for specific lakes or parts of lakes for certain parameters. Within these bounds, the algorithm searched through the region grid cell by grid cell and identified every grid cell with a land use index value set as water. This algorithm pinpointed all water bodies within the Great Lakes region, including smaller water bodies such as Lake St. Clair and Georgian Bay.

Once the lakes were identified, a number of parameters were changed to remove all lake influence. First, the binary masks that distinguish between water bodies and land were converted to land, as in the top two panels of Fig. 2 (which only shows one of the masks, since both look
nearly identical). Another mask deals specifically with lake ice. Lake Erie was entirely iced over, while much of Lake Huron was covered, as well. The other lakes had ice only on their peripheries. Since this ice would not have been present without the lakes, it was removed, as shown in the middle row of Fig. 2. Smaller ice patches remained on bodies of water outside of the latitude and longitude bounds specified by the algorithm.

Land use had a unique identifier for water bodies. The bottom row of Fig. 2 shows the results of changing water to other land uses for this parameter. This is the first of several fields to be discussed where lake removal required specific decisions in order to closely match on-shore values of the parameter in different parts of the Great Lakes region. Different boundaries had to be defined for Lake Ontario (which was switched from “water body” to “deciduous broadleaf forest”), Lake Superior (“mixed forest”), eastern and western Lake Erie (“deciduous broadleaf forest” and “dryland, cropland, and pasture,” respectively), and, for areas not otherwise specified, the northern and southern Great Lakes (“mixed forest” and “cropland/grassland mosaic,” respectively). As can be seen in the figure, these land use boundaries match the surrounding land uses to a close approximation, effectively removing the lakes’ presence.

Skin temperature, shown in the top two panels of Fig. 3, clearly showed the presence of non-ice covered portions of the Great Lakes, standing in stark contrast to the colder land surface. The frozen-over portions, on the other hand, closely matched the nearby shores. Removing the lakes involved changing the skin temperature for all of the Great Lakes. This included the frozen-over portions, although the changes were of a far greater magnitude in the areas that were not frozen over. In general, lake removal led to colder surfaces, as the lakes were warmer than the shores. In addition to skin temperature, soil temperature (the middle two panels of Fig. 3) needed to be introduced into the region because soil was now present where previously there had
only been a flag to indicate a lack of soil. In addition to the general soil temperature field, soil temperatures needed to be set at specific depths (0 – 10 cm, 10 – 40 cm, 40 – 100 cm, and 100 – 200 cm). These, too, were given the values of the nearby shores. The topmost of these layers is shown in the bottom two panels of Fig. 3.

Soil moisture data, recorded at the same depths, needed to be introduced in the region occupied by the lakes, too. The changes to the topmost layer of soil moisture are depicted in the top two panels of Fig. 4. Since snow cover was present in the region, snow was also added to the lakes in order to maintain consistency with the surrounding areas. Snow depth (the middle two panels of Fig. 4) and snow albedo (the bottom two panels of Fig. 4) both required specific values for different parts of the Great Lakes region. The large differences between snow depth on the northern shore of Lake Superior and on its southern shore required an intermediate value to be chosen. Soil category (top two panels, Fig. 5) was the next parameter changed, again receiving the values of the adjacent shorelines.

All of the replacements discussed thus far have been for parameters stored as two dimensional arrays, with a single value for each parameter at each grid point. The model initialization files include three-dimensional fields, as well, where the parameters at each grid point are multi-valued. Some 3D variables’ added dimension represents different times (e.g. twelve layers, one for each month). Some 3D fields’ added dimensions represent depth. Subgrid-scale coverage for some parameters (such as land use) are also stored in this manner.

3D soil categories (not shown) were split evenly among the four major soil types near the Great Lakes, meaning that each redefined grid cell was assigned 25% coverage for each of these soil types. Soil moisture and soil temperature (not shown) had to be specified at different depths. They were given nearby shoreline values. Monthly surface albedo (middle row of Fig. 5) and
green fraction (bottom row of Fig. 5), the sub-grid proportion of each cell that is covered in foliage for each month, were given shoreline values appropriate for the time of year.

At each grid point, land use fraction values between zero and one were stored as a 3D parameter, representing the percentage of that grid cell that was covered by each of the model’s land use types. For instance, the grid cells for the Great Lakes had values of one in the water body layer and values of zero in all other layers. All of the lake grid cell values in the water layer were reset to zero, bringing it from 100% water coverage to 0%. The layers corresponding to prominent shoreline land uses were then assigned some fractional land usage for each of the former lake grid points.

The parameters discussed heretofore are the ones that were changed to remove the influence of the lakes, but they were not the only ones that clearly showed the lakes’ presence. Topography was not changed; though the lakes were removed, their surfaces were kept flat. Thus, parameters related to topography, such as various orographic asymmetry parameters, were left unchanged.

The characteristics of the atmosphere above the lakes were also left unedited in the initialization fields. The final stage in removing the lakes’ influence was done by allowing ample spin-up time (discussed in detail below) in order to advect all lake-influenced air masses out of the Great Lakes region and to allow wind and pressure fields to stabilize prior to the arrival of the cyclone. Were we to have changed parameters such as surface pressure, it may have changed the characteristics of the atmosphere in undesired ways, such as inducing unrealistic cross-shore pressure gradients.
CHAPTER 3

EVENT OVERVIEW

Between 1 Feb and 2 Feb 2011, a deep midlatitude cyclone tracked across much of the Midwestern United States, bringing heavy snow, sleet, and freezing rain to the Great Lakes region. This event is often colloquially referred to as the “Groundhog’s Day Blizzard.” According to the National Weather Service’s overview, Chicago’s O’Hare Airport received over twenty-one inches of snow from the event (Allsopp and Castro 2011), making it the third largest snowfall event on record in Chicago (NWS). Fig. 6 conveys the composite radar reflectivity at four different times (18 UTC 1 Feb and 00, 06, and 12 UTC 2 Feb) throughout the passage of the cyclone across the Great Lakes region (Iowa Environmental Mesonet). It is clear from these composites that the comma head of the cyclone featured intense precipitation throughout much of its life span and passage over the Great Lakes.

Accumulated liquid-equivalent precipitation data, as measured by Fischer-Porter rain gauges throughout the region, were obtained from the National Centers for Environmental Information (NCEI). Point shapefiles were created in ESRI ArcMap based on the latitude and longitude information from these data, while polygon shapefiles were collected from the United States Geological Survey (The National Map). A geostatistical interpolation method called an ordinary kriging was then used to produce a precipitation accumulation map from the point dataset (the top map in Fig. 7). Local maxima are observed in northern and northeastern Illinois, including the Chicago area and along the western Lake Michigan shore. The most noteworthy maximum, however, is a large swath of high precipitation values extending from the western shores of Lake Erie toward the southwest.
The lapse rates in the middle troposphere present during the more intense part of the passage of this cyclone were steep enough to create elevated convective available potential energy (CAPE) sufficient for thundersnow in the comma head region [Rauber et al. (2014)]. The bottom map in Fig. 7 shows lightning reports, color-coded by time, that were gathered from the National Lightning Detection Network (NLDN). Because the NLDN is geared more toward detecting cloud-to-ground lightning [Steiger et al. (2009)], this map represents a conservative estimate of lightning prevalence in this storm. The spatial breadth of these reports suggests that the conditions necessary for elevated convection were present throughout the western portion of the Great Lakes during much of the cyclone’s passage.

A synoptic overview from four different levels thirty hours into the WL run (06 UTC on 2 Feb) is presented in Fig. 8, showing the structure of the cyclone responsible for the Groundhog’s Day Blizzard. A jet streak (Fig. 8, top left) was present at the 300 hPa level, with its left-exit region roughly coincident with the cyclone’s low pressure center as it traversed northeastward. This, along with the differential positive vorticity advection (DPVA) present at 500 hPa (Fig. 8, top right) and its placement east of the trough, suggests that the atmosphere was primed for ascent in the vicinity of the low pressure center. At 850 hPa (Fig. 8, bottom left) and at the surface (Fig. 8, bottom right), temperature gradients consistent with the fronts within the cyclone are seen. They also show the freezing line’s placement at these two levels – while Chicago received heavy snow, other stations within the Great Lakes region received sleet or freezing rain.

Figs. 9 – 12 show the time evolution of 300 hPa winds, 500 hPa absolute vorticity, and 850 and 925 hPa temperatures, respectively, throughout the passage of the cyclone over the Great Lakes. In Fig. 9, we see that the 300 hPa jet streak associated with the cyclone grew in
breadth and intensity with time, tracking northeastward. Its left exit region remained to the south of the western Great Lakes, eventually passing over Lakes Erie and Ontario. DPVA, shown in Fig. 10 at the 500 hPa level, followed a similar path. The temperatures at 850 hPa (Fig. 11) and 925 hPa (Fig. 12) show the progression of the strong frontal temperature gradients. The strong geopotential height gradient on these same figures, with an interval of 40 geopotential meters, reflects the intensity of the cyclone as it passed through the Great Lakes region.

The surface temperature and dewpoint (Figs. 13 and 14, respectively) show that conditions in the vicinity of the Great Lakes, north of the warm front, were cold and dry. Since the Great Lakes were already receiving precipitation from the comma head of the cyclone, the cold temperatures and winds created the possible conditions for the relatively warm lakes to induce lake-enhanced precipitation on the west and south sides of the lakes, where precipitation was already falling from the cyclone.
CHAPTER 4

SPIN-UP TIME ANALYSIS

It was necessary to give the WRF model a sufficient amount of time to advect out the influence of the lakes that had been inherent in the initial conditions; the lakes had been present up to the start of the WRF simulation, so their impact in the atmosphere was present at the time of initialization of the WRF model with the NAM fields. The comma head of the cyclone associated with the Groundhog’s Day Blizzard did not reach the southern tip of Lake Michigan until around 20 UTC on 1 Feb, but the simulation started at 00 UTC on the same day. Analysis comparing WL and NL fields suggests that this was an ample amount of time to remove residual lake influence.

This spin-up time showed evidence of successful removal of the lakes’ influence. The top two panels of Fig. 15 show the simulated reflectivity at 20 UTC on 1 Feb for both the WL and NL runs. In the WL run, there is clear lake-effect precipitation occurring downwind of Lake Superior across the upper peninsula of Michigan and southward into Wisconsin. In the NL run, on the other hand, the precipitation is absent.

Accumulated liquid equivalent precipitation (the bottom two panels of Fig. 15) again at 20 UTC on 1 Feb, also shows clear evidence of lake effect. The precipitation accumulation on the eastern Wisconsin shoreline is substantially higher in the WL run than in the NL run. Similarly, precipitation on the southern shore of Lake Superior disappears when the lakes are removed. The orientation of the precipitation plume stretching from Wisconsin through Iowa in the WL run suggests a short fetch across Lake Michigan, lending evidence to the claim that this was, in fact, a case of lake-enhanced precipitation. This precipitation came from a system that
was present in the Great Lakes region during the spin up time, so it needed to be accounted for in later analyses.

Clear differences are seen in the downwind surface dewpoint temperature between the two runs at hour 20 in the top row of Fig. 16. This is particularly true for Lake Michigan, which has a plume of moist air extending downwind all the way to northeast Missouri in the WL run that is gone in the NL run. The surface temperature (not shown) also shows strong signs of downwind modification, with plumes of warmer air extending from the lakes in the WL run but not in the NL run. Both of these are consistent with what would be expected from lake removal; without the warm, moist lake surface, air parcels remain cold and dry, similar to the upwind characteristics from both runs. The extent to which the downwind plumes of modified air stretch in both the temperature and dewpoint temperature WL runs shows that the modification of the lakes is not something that need only be analyzed close to shore – rather, the lakes have a strong influence on the temperature and dewpoint for large swaths of land downwind.

Removal of the lakes increased the overall surface friction, a fact that is borne out by changes for both the wind speed and direction between the WL and NL runs (not shown). Because the cross-shore surface friction gradient was removed when the lakes were taken out, downwind shoreline convergence (the bottom row of Fig. 16) nearly disappeared for all five Great Lakes.

The direction of the winds would be expected to be closer to perpendicular relative to the isobars when more friction is added by removing the lakes. This, too, is seen in these spin up time analyses (not shown). For Lake Michigan, this had the effect of increasing the fetch across the lake (albeit without water underneath, somewhat defeating the purpose of measuring fetch).
Pressure differences appeared early on in the model runs. Fig. 17 shows the fine-scale pressure differences (NL subtracted from WL) that were present at 0015 UTC on 1 Feb (fifteen minutes into the simulation) and at 0100 UTC. In both panels from Fig. 17, it is readily apparent that the lakes are the cause of these pressure differences. The presence of the relatively warm water served to lower the surface pressure over the lakes. Lake Erie and the ice-covered parts of the other lakes, on the other hand, showed very little change.

All of these WL/NL comparisons have shown distinct differences between the two simulations that are consistent with what would be expected from removing the lakes. Also worth noting, very few differences are seen outside of the lake bounds and the difference plumes extending from them. Upwind and far-away differences are minimal, suggesting that it was, in fact, the lake removal that was the cause of these modeled differences.
CHAPTER 5

WL/NL SIMULATION COMPARISONS

Fig. 18 shows the surface temperature change that resulted when the NL run was subtracted from the WL run. When the relatively warm waters were in place instead of the land, plumes of warmer air were transported downwind throughout the WL simulation. By thirty-six hours into the simulation (three hours before the end), the difference plume is seen extending several hundred kilometers downwind. Lake Superior’s and Lake Michigan’s plumes merged into one large plume, extending as far south as far northwestern Mississippi. The orientation of the plumes’ axes shifted from southwestward toward the south over time, following the wind flow around the moving low pressure center. Lake Erie showed no plume. Since Lake Erie was frozen over throughout this period, the lake removal process for this lake switched it from ice to land, rather than from water to land. This led to minimal changes in the surface temperature downwind of Lake Erie. The periphery of Lake Huron also lacked a difference plume, as this area was also frozen over. Lake Superior, by far, created the greatest downwind temperature changes.

Dewpoint temperature differences, shown in Fig. 19 for the same four times, similarly show plumes stretching far downwind of all of the Great Lakes except for ice-covered Lake Erie when the NL values are subtracted from the WL values. Like with temperature, Lake Superior shows the greatest moisture plume, while Lake Erie shows effectively no response. The fact that both temperature and dewpoint temperature differences extend several hundred kilometers downwind shows the importance of the lakes in modifying conditions downwind. Factors such as ice cover on the Great Lakes can affect conditions in states like Iowa, Missouri, and Kentucky.
850 hPa temperature differences (Fig. 20) actually displayed an early decrease downstream of Lakes Superior and Michigan when the warm lakes were present. Analysis of model soundings over Chicago (not shown) showed that the 850 hPa level was in the frontal inversion at these times. The NL simulation had a steeper inversion, so the temperatures were warmer at this level in this simulation. Later on, the 850 mb level was beneath the surface inversion, so this level was warmed by the lakes.

Fig. 21 shows that the Great Lakes were responsible for lowering the mean sea level pressure (MSLP) above them and downstream. This is related to their influence on temperature. Lake Superior shows the greatest response – its warmth helped to lower surface pressure downstream – while Lake Erie, being frozen over and therefore similar in temperature to the shorelines, showed practically zero surface pressure change, regardless of whether or not the lakes were present.

The downwind pressure differences shown in Fig. 21 are at their most intense at 12 UTC on 2 Feb over Indiana, Illinois, and Missouri. Model soundings from near Sainte Genevieve, MO, at 6 UTC on 2 Feb for both the WL and NL runs (Fig. 22) indicate the downwind, low-level cooling that occurred when the lakes were removed. The conditions were essentially unchanged above the frontal inversion. This lends confidence to the diagnosis that the cause of the MSLP differences was the lake surface temperature differences – when the lakes were present, this site, fairly far downstream, was warmed by a few degrees C in the boundary layer. Above about 840 hPa, the soundings are effectively identical.

The total precipitation differences (Fig. 23) developed a striated pattern with precipitation couplets that suggest a slight phase shift in the speed of the system throughout the course of the two runs. Fig. 24, which shows striations in the vertical motion at 850 hPa, was
likely also affected by these minor phase differences. Filtering out these small effects, a clearer result begins to emerge. Fig. 25 shows the same precipitation accumulation data with differing gaps around zero and with the precipitation prior to the arrival of the comma head at 20 UTC on 1 Feb subtracted out so that only the passage of the cyclone is included in the precipitation totals. When every change within five millimeters of zero was filtered out, the only areas that showed any precipitation changes were located immediately adjacent to the lakes’ shorelines, most notably downwind of Lake Michigan. Continuing to widen the white gap around zero (not shown), all differences get filtered out between ten and eleven millimeters, suggesting that this was the precipitation amount induced by the lakes.

When the lakes were replaced with land, they were replaced with a surface that induced greater friction. This is conveyed in Fig. 26, which shows an increase in wind speed over the Great Lakes (including Lake Erie) when the lakes were present. The presence of lakes increased shoreline convergence, explaining the patterns seen in Fig. 16.
CHAPTER 6
CROSS SECTIONS

In order to obtain a clearer picture of the lakes influence, a cross section across Lakes Superior and Michigan (Fig. 27) was taken. Looking from the west-northwest in Fig. 28, Lake Superior on the left side of each panel and Lake Michigan in the center of each panel both showed a clear influence on potential temperature and boundary layer depth. Fig. 29 shows the same for equivalent potential temperature. The warm lakes increased the near-surface potential temperature by several Kelvins. Differences above the frontal inversion were minimal. The time evolution of the potential temperature differences in Fig. 30 conveys clear downwind propagation of warmer air toward the south (the right side of each image). By the final panel, differences in excess of 3 K extended beyond the southern end of the cross section. This is consistent with our earlier hypothesis that downwind warming was a primary cause of the downwind MSLP decrease.

Equivalent potential temperature differences (Fig. 31) show patterns similar to the potential temperature differences in Fig. 30. The magnitude of the change, however, is greater. This is clear evidence that the presence of the lakes influenced both sensible and latent heat exchanges. By hour 36 (12 UTC 2 Feb), Lake Superior had caused a warming in excess of 13 K just to the north of its downwind shoreline.

The instability caused by the warming and moistening of the low level air by the lakes, along with the shoreline convergence forced by the presence of the lakes, caused increased vertical motion on the downwind shore when the lakes were present (Fig. 32). This rising, moist air explains the increased precipitation extending from the downwind shore in Fig. 25, although it was hindered by the frontal inversion. Waves propagated through the troposphere near the
downwind shoreline and above the frontal inversion differently between the two simulations (not shown). These waves, which may have been a response to convection in the boundary layer, led to a striated vertical motion difference field through much of the troposphere near the lake shore.
CHAPTER 7

CONCLUSIONS

This study compared the results of two different WRF simulations of the same cyclone; one simulation was a control run, whereas the other had the Great Lakes and other nearby water bodies removed. This was done in order to determine the influence of the Great Lakes on passing wintertime cyclones. The lakes were removed from the model by replacing their grid cells’ values with nearby shoreline values. Many different parameters were edited because they were clearly influenced by the lakes’ presence. Twenty hours of spin-up time were allowed to advect out any residual lake influence that could not be removed directly via the algorithm.

Once the lakes were removed and the no-lakes simulation was conducted, the resulting model output was compared to the control run. In addition to regular plan-view and cross section plots for each run, difference plots were created to make clear the differences between the two simulations.

Prior to the arrival of the comma head over the Great Lakes, evidence was seen that the lakes were effectively removed. At the end of the spin-up time, simulated reflectivity values seen in the with-lakes run on the southern shore of Lake Superior were not seen in the no-lakes run. More precipitation accumulation on the Wisconsin coast, increased dewpoint temperature, and increased shoreline convergence served to further suggest successful lake removal.

Throughout the model simulations, a difference plume developed, extending from Lakes Superior, Michigan, Huron, and Ontario in the temperature and dewpoint fields. The lakes induced warmer and moister conditions downwind, with both temperature and dewpoint increasing by at least 2°C as far south as northwestern Mississippi within thirty-six hours of the start of the simulation. The plumes downwind of Lakes Superior and Michigan, which merged
into a single plume, were particularly pronounced, likely due primarily to Lake Superior’s greater warmth and the longer fetch across Lake Michigan. Lake Erie, which was frozen over, did not show any significant downstream influence in these fields, suggesting that ice cover is akin to complete lake removal for temperature and dewpoint downwind. Cross-sectional analysis of potential temperature suggested that these temperature differences were limited to the levels beneath the passing cyclone’s frontal inversion. Above the inversion, the only potential temperature changes seemed to be small, wave-induced changes.

The downstream temperature changes induced minor pressure deviations that served to shift the cyclone slightly. This shift is the likely cause of a striated pattern in the liquid equivalent precipitation accumulation differences at the end of the run. These precipitation accumulation difference striations were almost all of a magnitude less than three millimeters. Areas that saw greater than half a centimeter of liquid equivalent precipitation differences were limited to areas very near the lakes. The addition of precipitation from the lakes was likely inhibited by the frontal inversion, which limited the depth to which lake-induced convection could develop. Near-shore precipitation was likely aided by the shoreline convergence caused by the friction difference between the lake surfaces and their downwind shores. The maximum precipitation increase, which occurred over Chicago, was between ten and eleven millimeters. Assuming a ten-to-one ratio comparing snow depth to liquid equivalent, the lakes added slightly more than 10 cm (3.94 in), or about 19% of the 21+ inches recorded.

This study has shown that the lakes have a significant influence on temperature, moisture, and pressure fields far downstream. However, precipitation accumulation differences are minimal outside of the immediate downwind shoreline area, extending only a short distance inland. Ice cover diminishes these influences, making conditions downstream not dissimilar
from that which would develop if the lakes did not exist at all. Forecasters, even those several hundred kilometers downstream, would be advised, therefore, to take ice cover on the Great Lakes into account when their forecast area is in line to receive winds from the Great Lakes region.
CHAPTER 8
FIGURES AND TABLES

Figure 1 9 km outer domain and 3 km inner domain for the WRF simulation
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<td>15 UTC 2 Feb 2011</td>
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Table 1 Model Parameterizations
Figure 2 Land mask, lake ice, and land use before (left column, top to bottom) and after (right column, top to bottom) running the lake removal algorithm
Figure 3 Skin temperature, soil temperature and 0 - 10 cm soil temperature before (left column, top to bottom) and after (right column, top to bottom) running the lake removal algorithm.
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REFERENCES


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