P1.22 THE INFLUENCE OF LAKE MICHIGAN ON A WINTERTIME COLD FRONT

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1. INTRODUCTION AND BACKGROUND

Lake-effect snow is a unique weather phenomenon that often occurs to the east of the Great Lakes in the late fall and winter months. These snow events often produce heavy amounts of snow that can bring communities to a standstill. Many studies (e.g., Dockus 1985; Niziol 1987) have documented the processes that are involved in the formation of lake-effect snow. Generally, lake-effect snow develops when arctic air plunges over the relatively warm lake waters. The movement of the cold air creates vertical fluxes of heat and moisture from the lake surface to the lower part of the troposphere. Many times, the vertical fluxes can lead to convective clouds and develop into mesoscale lake-effect snow bands. This occurs due to the unstable thermal stratification, where warm, less dense air near the lake surface is overlain by colder, denser air above the lake surface. In addition to the snowfall from the small mesoscale lake-effect events, synoptic-scale storms traveling across the region can be enhanced, or modified by the collective effects of the lake surface. These effects can thereby contribute to the higher precipitation rates downwind of the lakes.

Previous studies have focused on traditional lake-effect processes including numerical simulations of lake-effect snow (e.g., Hjelmfelt 1983, 1990, 1992), observational studies (e.g., Kristovich and Steve 1995, Kristovich and Laird 1998), and operational forecasting parameters for lake-effect activity (e.g., Niziol 1982, 1987). Sousounis and Fritsch (1994) and Gallus and Segal (1999) undertook less traditional studies. Sousounis and Fritsch (1994) looked at the aggregate effects of the entire Great Lakes on regional weather and climate. Basically, they found that the warmer Great Lakes alter large-scale synoptic patterns and modify downwind climates (Sousounis and Fritsch 1994).

The focus of Gallus and Segal's work was to model the aspects of the interface between a relatively cool water surface and a surface cold front. Their results indicate two competing mechanisms are responsible for the movement and intensity of a surface cold front. The first would be through a change in the frontal temperature gradient directly caused by changes in thermal fluxes between land and water. A second mechanism by which the lake could alter speed and intensity would be through changes in surface roughness between the lake and land. Their results suggested an acceleration or frontal bulge and strengthening of the frontal temperature gradient as it progressed across the cooler Lake Michigan surface (Gallus and Segal 1999).

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The main purpose of this study is to undertake Gallus and Segal's theories and analyze cold season interactions between synoptic-scale frontal boundaries with Lake Michigan. This research deals with a relatively warm, unfrozen lake surface compared to a cooler land surface. In this study, both an observational case study and numerical simulation using a mesoscale model are completed to investigate the impacts of the lake on these features. Another goal of the study is to investigate possible enhancement of associated frontal precipitation and frontal structure change as it progresses over the relatively warm lake. The case chosen for this study was observed during the Lake-ICE research project. An overview of Lake-ICE operations and goals are given in Kristovich et al. (2000). The case study chosen for the research is 0000 UTC 10 January 1998 to 0000 UTC 11 January 1998.

2. 10 JANUARY 1998 CASE DAY

The case of 10 January 1998 provides an example of a relatively shallow arctic front and associated frontal precipitation crossing the Great Lakes. The arctic front approached the Lake Michigan region early on the 10th of January. The front proceeded across the lake between 0300 UTC and 0600 UTC, bringing strong cold air advection at the surface. Fig. 1 shows approximate locations of the surface cold front as it progressed eastward during 10 January 1998. Associated with the surface front was a weak area of frontal precipitation.

At 0000 UTC 10 January 1998, (Fig. 1a) the arctic cold front was located just to the west of Lake Michigan. The boundary was depicted by the strong west-east temperature gradient, the notable pressure trough extending from the main surface low over southern Ontario, and the wind shift line of westerly winds over western Illinois and Wisconsin, and west-southwesterly winds ahead of the boundary (Fig. 1a). Associated with the surface front was a weak area of frontal precipitation located over eastern portions of Wisconsin (Fig. 1a).

By 0235 UTC (Fig. 1b), the front was apparently located over central portions of Lake Michigan. Notable at this time was the enhancement of the frontal precipitation along the eastern shores of Lake Michigan. Fig. 2 further depicts the enhancement over eastern Lake Michigan.

At 0535 UTC, (Fig. 1c) the artic boundary had crossed Lake Michigan into western Michigan. The enhancement of precipitation still was evident along the eastern shores of the lake.

Finally, by 1135 UTC, the frontal boundary had pushed into eastern Michigan, and the enhancement of frontal precipitation had weakened considerably. Actually, at this time pure lake-effect snow was occurring over western Michigan, as strong cold air advection occurs in the lowest layers of the atmosphere (Fig. 1d).

Radar observations (Fig. 2) suggest that as the frontal precipitation crossed Lake Michigan, an apparent enhancement occurred over the central and eastern portions of the lake. As the frontal system moved east away from the lake surface and cold air deepened, more classic wind parallel multiple bands developed. Lapse rates behind the frontal boundary became highly unstable with 850 hPa temperatures colder than -20°C. Wind direction did not change too strongly with the passage of the arctic boundary. Before the boundary the surface winds were generally out of the west-southwest, but as the front crossed the region winds veered to the west. This wind direction allowed for adequate fetch of any mesoscale effects across the Lake Michigan surface.

At the upper levels of the atmosphere, especially at 500hPa, there was a strong east-west oriented long-wave trough at 0000 UTC, which developed into a closed low over southern Ontario by 1200 UTC, and remained closed at 0000 UTC 11 January. A short-wave trough axis extended from northern Minnesota to northern Illinois throughout the period. This allowed the Lake Michigan region to be under the influence of general cyclonic vorticity advection. This could aid in any lake-effect activity by increasing the height of any subsidence inversion present.

The 10 January cold front is a good case to investigate mesoscale effects on the frontal boundary because the lake surface temperatures were relatively warm for the time of year (4-6°C), large temperature gradients existed between the arctic air over the Midwest (-22°C) and warmer air over the eastern Great Lakes (+2°C), and the front crossed Lake Michigan oriented roughly from north to south, or parallel to the lake. The 10 January case also exhibits an unusual transformation from synoptic-scale to synoptic-mesoscale interactions and finally to purely mesoscale processes (lake enhancement of synoptic front to purely lake-effect snow).

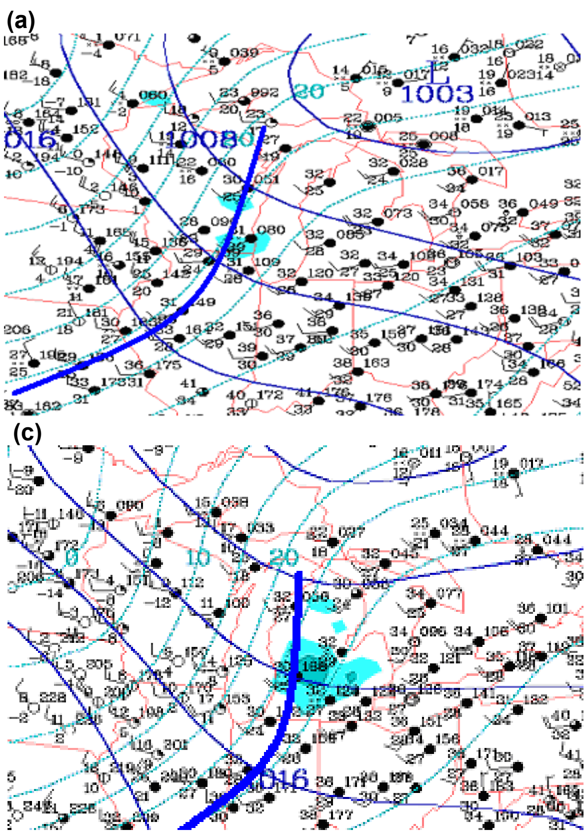

Figure 1. Joint Office of Scientific Support (JOSS) archived sea-level pressure composites (interval 2 hPa) and temperature (°F) indicate position of frontal boundary during the day of 10 January 1998. Dark blue line represents approximate location of arctic boundary. (a) 0000 UTC (b) 0235 UTC (c) 0535 UTC (d) 1135 UTC.

In this case it is reasonable to expect that the lake surface had a substantial impact on the frontal movement and precipitation associated with the arctic front. This study will use the observations of 10 January 1998, in a numerical weather model to quantify Lake Michigan's impact on the synoptic-scale frontal system. This will be accomplished by using the Mesoscale Model 5 (MM5) research model version 3. The MM5 is a nonhydrostatic model, utilizing many physics, cumulus, radiative and cloud schemes. Simulations were initialized at 0000 UTC 9 January 1998 and run to 0000 UTC 11 January 1998. Model simulations are compared to actual observations of the case to understand the impacts of the lake, on the synoptic situation. Methods include with-lake and without-lake simulations in which only Lake Michigan is removed, to understand the importance of the lake, in the simulation.

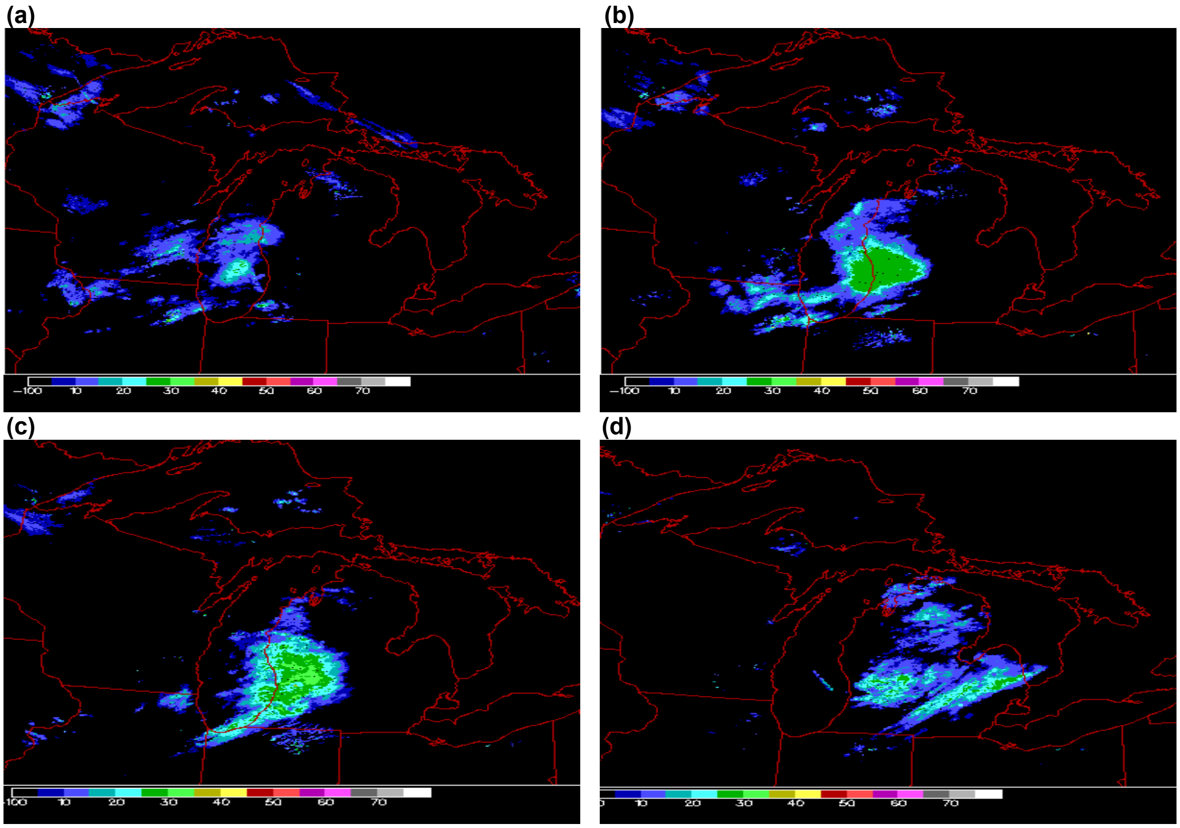

Figure 2. Joint Office of Scientific Support (JOSS) archived composite Great Lakes WSR-88D radar (a) 0000 UTC 10 January 1998 (b) 0235 UTC 10 January 1998 (c) 0535 UTC 10 January 1998 (d) 1135 UTC 10 January 1998.

3. MESOSCALE MODEL

3.1 Model Overview

The Penn State University (PSU)/National Center for Atmospheric Research (NCAR) mesoscale model, version 5 (MM5), was used in the study. The MM5 is a limited area, nonhydrostatic, terrain following sigma-coordinate model. The model is designed to predict and/or simulate mesoscale atmospheric phenomena. It has been developed as a community mesoscale model and is continuously being revamped and improved by users at universities and government. The model has undergone many changes since its release several years ago. These include: multiple nesting capability, nonhydrostatic dynamics, which allows the model to be applied at very high resolution scales, multi-tasking capability on shared and distributed memory machines, and four dimensional data assimilation capability (MM5 2003). The MM5 includes variable resolution of the terrain, landuse type; soil type, deep soil properties, vegetation fraction, and land-water mask datasets. Another important feature included is the ability to use the new high resolution 30-second terrain data (MM5 2003).

The model also allows for flexible and multiple nesting capability (MM5 2003). This means that the model is able to run from global or synoptic-scale down to cloud resolving scale, in one model run. The MM5 can be run in both 2-way and 1-way nesting modes (2-way: multiple nests and moving nests, 1-way: fine-mesh model driven by coarse model). The nest domain can also start and stop at anytime during the model run (MM5 2003).

3.2 Model Setup

A coarse grid domain was centered at 44ºN and 86ºW with 125 X 125 horizontal grid points with a 13.5 km grid spacing. A second domain was placed inside the coarse grid, centered over the region of interest. The middle domain consisted of 130 X 142 horizontal grid points and a horizontal grid spacing of 4.5 km. Finally, a third grid was set up to be able to analyze the small-scale features of the lake-effect snow. The inner domain allowed for high resolution by having 151 X 160 grid dimensions and 1.5 km grid spacing. This domain was centered over central Lake Michigan and along the eastern shores of the lake, where the most apparent enhancement took place (Fig. 3).

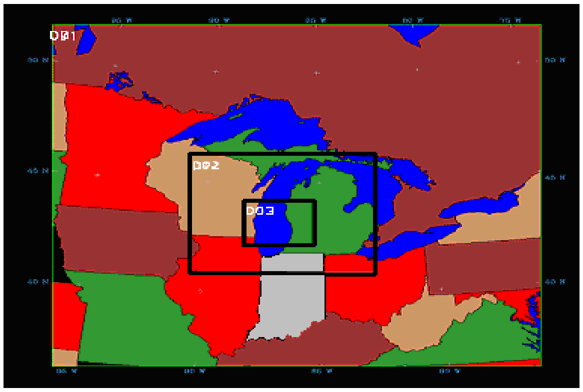

Figure 3. MM5 domain selections for the with-lake and without-lake model simulations. The outer box (D01) represents the outer coarse grid centered over the Great Lakes (13.5 km grid spacing). The second box (D02) represents the middle domain, which is centered over Lake Michigan (4.5km grid spacing). The inner box (D03) represents the high resolution inner domain, and is centered over central Lake Michigan (1.5km grid spacing).

Lambert Conformal map projection was used considering the region of interest. Model nesting was also used in order to obtain high resolution over the lake and aid in computational efforts. Landuse and terrain data for the model were obtained from the United States Geological Survey (USGS). For the outer two domains, 2-minute global and terrain landuse data were used and for the high resolution inner domain the new 30 second global terrain and landuse data were used in the model. Coupled with the landuse data the NOAH Land Surface Model (NOAH LSM) was also used in the model. The land surface model is able to predict soil moisture, temperature in four layers (10, 30, 60, and 90cm thick), canopy moisture and snow depth. When used with the Eta planetary boundary layer scheme, it seems to accurately depict the interactions between the land surface and the boundary layer fairly well (Chen and Dudia 2001).

The model used 64 vertical levels. Approximately 35 levels were chosen in the lowest 250 hPa to fully resolve the interaction between the synoptic-scale front and the lake, and also, to resolve the strong low-level inversion associated with arctic air and to prevent the development of spurious gravity waves (Persson and Warner 1991). The model top was also set at 100 hPa.

The course domain was initialized using Eta AWIPS data from 0000 UTC 09 January 1998. These first guess fields were obtained for the mandatory pressure levels from the NCAR data archives. The first guess fields were then read into the model, and interpolated to the proper sigma levels that are useful for implementing the model run. In addition to the Eta AWIPS data, detailed actual vertical sounding and surface station data were obtained from NCAR data archives to provide boundary conditions for the outer domain. The sounding and surface data were used to further nudge the model towards a more accurate initialization. The boundary condition data were also applied at 3-h intervals during the entire run, as it enables the model to make corrections, as it progresses. The inner domains were initialized at 1200 UTC 09 January 1998 (middle domain) and 1800 UTC 9 January 1998, to study region and time of interest.

Lake-surface temperatures were obtained from a real time data archive at NOAA Great Lakes Environmental Research Laboratory (GLERL). Lake surface temperatures were assumed to be constant throughout the entire model run, as steady lake temperatures are a reasonable assumption for a 48-h period. A second model run was also completed, in which the water surface of Lake Michigan was completely removed to investigate the impacts of the lake surface, on the synoptic-scale conditions. All MM5 parameters were unchanged except for the altering of land surface files in the LSM. The resulting water surface was replaced with a random selection of land surface points, of the surrounding land and vegetation types.

Several model runs were conducted in order to determine which physics and surface schemes best represented actual observations. Boundary conditions and domain nesting methods were also tested during the several model runs. Table 1 depicts the physics and surface schemes used, as well as various model specifications.

Table 1. MM5 parameters and schemes used in with-lake and without-lake simulations.

Physics Option	Domains Applied	Scheme Used
Cumulus parameterization	Outer	Grell Convective (Grell et al. 1994)
Cumulus parameterization	Middle and inner	Explicit Convection
Shallow convection	Outer	Shallow convection option used
Planetary boundary layer	All domains	Eta-Mellor-Yamada used in conjunction with NOAH LSM (Janic 1990)
Explicit moisture scheme	All domains	Reisner mixed-phase microphysics (Reisner et al. 1998)
Radiation scheme	All domains	Rapid radiative transfer model (Mlawer et al. 1997)
Soil temperature model	All domains	NOAH LSM (Chen and Dudia 2001)

4. WITH-LAKE VS. WITHOUT-LAKE NUMERICAL SIMULATIONS

In the following section, the focus is on MM5 simulations of the front moving across the Lake Michigan vicinity. Without-lake simulations were accomplished by removing only the Lake Michigan surface. Both with-lake and without-lake simulations are included to demonstrate how the lake modifies the frontal boundary and accompanied arctic air. Shown in Fig. 4 are results from the outer domain (13.5km grid spacing). These show overlays of sea-level pressure, temperature, and surface wind speed and direction.

At 0000 UTC 10 January 1998 (24-h after simulation began), for both simulations the cold front was located just to the west of the lake over eastern Wisconsin (Fig. 4a,b). However, looking at the without-lake simulation (Fig. 4b), the removal of Lake Michigan has altered the strength and position of the main surface low over southern Ontario. The removal of the heat and moisture flux had allowed the main surface low to migrate eastward, away from the lakes. It is evident in the with-lake simulation (Fig. 4a), that the Great Lakes as an entity, create a thermal induced trough, and tends to modify the existing synoptic-scale low pressure system as discussed by Sousounis and Fritsch (1994). Because, lake surface temperatures were around 4-6°C, the modification of the air that moves across Lake Michigan is apparent in the thermal fields for the with-lake simulations, noted by the thermal ridge over the eastern portions of the lake and western Michigan (Fig. 4a).

By 0800 UTC, the cold front had progressed to the eastern portions of Lake Michigan for the with-lake simulation (Fig. 4c); however, for the without-lake simulation the cold front appears to have progressed into central Michigan (Fig. 4d). The associated temperature gradient also appears to be stronger for the without-lake simulation. Arctic air for the with-lake simulation wraps around the southern portion of the lake forming a bulge in the actual arctic boundary (Fig. 4c), while over the lake the cold air was retarded from the added heat flux from the warmer surface. The changes in frontal movement were apparently facilitated by large temperature gradients between the lake surface and colder arctic air.

Also, apparent by 0800 UTC, between the two simulations are the slight differences in the sea-level pressure troughs associated with the frontal boundary. The with-lake simulation (Fig. 4c) had a gradual pressure trough extending from the surface low over Lake Huron southward to central Indiana. While for the without-lake simulation (Fig. 4d), the pressure trough was slightly more defined from the low over southern Ontario southward to eastern Indiana (the approximate location of the arctic boundary is noted by the dark blue line in Fig. 4). The frontal temperature gradient also appears to be more defined in the without-lake simulation, as the modifying effect had not occurred.

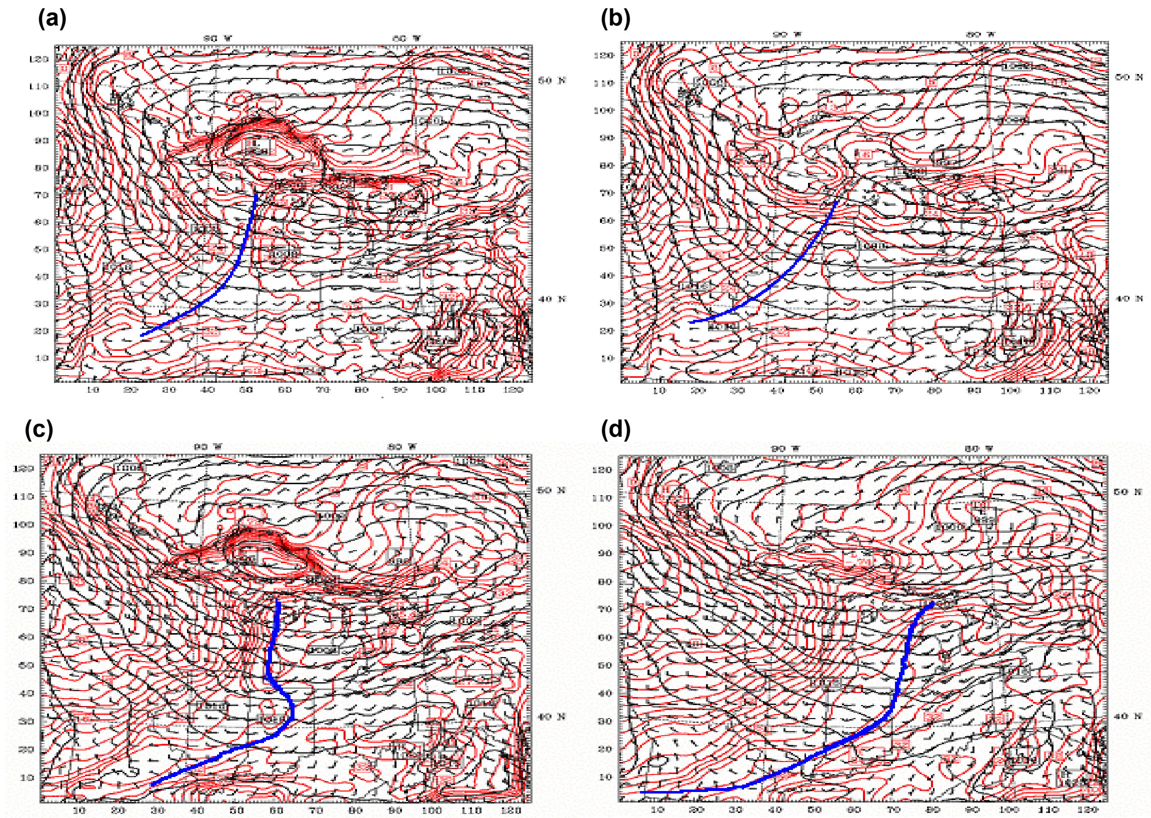

Figure 4. MM5 Outer domain (13.5 km) simulations of sea-level pressure (interval of 2 hPa), 1000 hPa temperature (interval of 2°F), and 1000 hPa winds (interval of 5 knots), during the day of 10 January 1998. Dark blue line represents approximate location of arctic boundary. (a) With-lake simulation at 0000 UTC, (b) Without-lake simulation at 0000 UTC, (c) With-lake simulation at 0800 UTC, (d) Without-lake simulation at 0800 UTC.

A higher resolution domain further depicts the modification of the frontal boundary, as it migrates across the lake surface. Shown in Fig. 5 are 1000 hPa potential temperature and surface wind speeds and direction. Again, at 0000 UTC, the frontal boundary lies to the west of Lake Michigan over central Illinois and Wisconsin (Fig. 5a,b). The boundary is depicted by the tighter gradient in potential temperature and by the wind shift line. Ahead of the boundary the surface winds are west-southwesterly, while behind the front the winds are more westerly.

By 0400 UTC, the frontal boundary had progressed to central Lake Michigan for the without-lake simulation (Fig. 5d), while for the with-lake simulation the boundary is further west over the western shores of the lake (Fig. 5c). Also noted in the with-lake simulation is the thermal ridge over the eastern portions of the lake. This shows up as a weak thermal low in the inner domain (1.5km grid spacing) for the with-lake simulation (not shown here). The presence of the thermal ridge acts as a barrier for the movement of the arctic boundary. While, in the without-lake simulation (Fig. 5d) the cold air moves unimpeded across the surface. A pronounced slowing of the frontal boundary occurred by 0800 UTC (Fig. 4e), as the thermal ridge is maintained over Lake Michigan and the front had slowly moved east-southeastward. However, for the without-lake simulation, at 0800 UTC (Fig. 5f), the front had progressed into central Michigan and the arctic air mass (noted by strong gradients over Wisconsin and Illinois) continues to move eastward.

Some enhancement of low-level convergence can be seen at 0400 UTC and 0800 UTC (Fig. 4c,e), in southwestern Michigan as the low-level cold air wraps around the southern tip of Lake Michigan. This is most pronounced by the southwesterly winds that develop along the southern shore of the lake. These southwesterly winds converge with the faster (decrease in surface roughness) westerly winds advecting across the central portions of the lake. For the without-lake simulation (Fig. 5d,f) the migrating effects are negated and the winds are generally westerly. The with-lake simulation developed a convergence maximum by 0200 UTC, over southern Michigan, while the without-lake simulation has no such maximum. Thus it appears the lake had an impact on low-level winds and associated convergence along the frontal boundary.

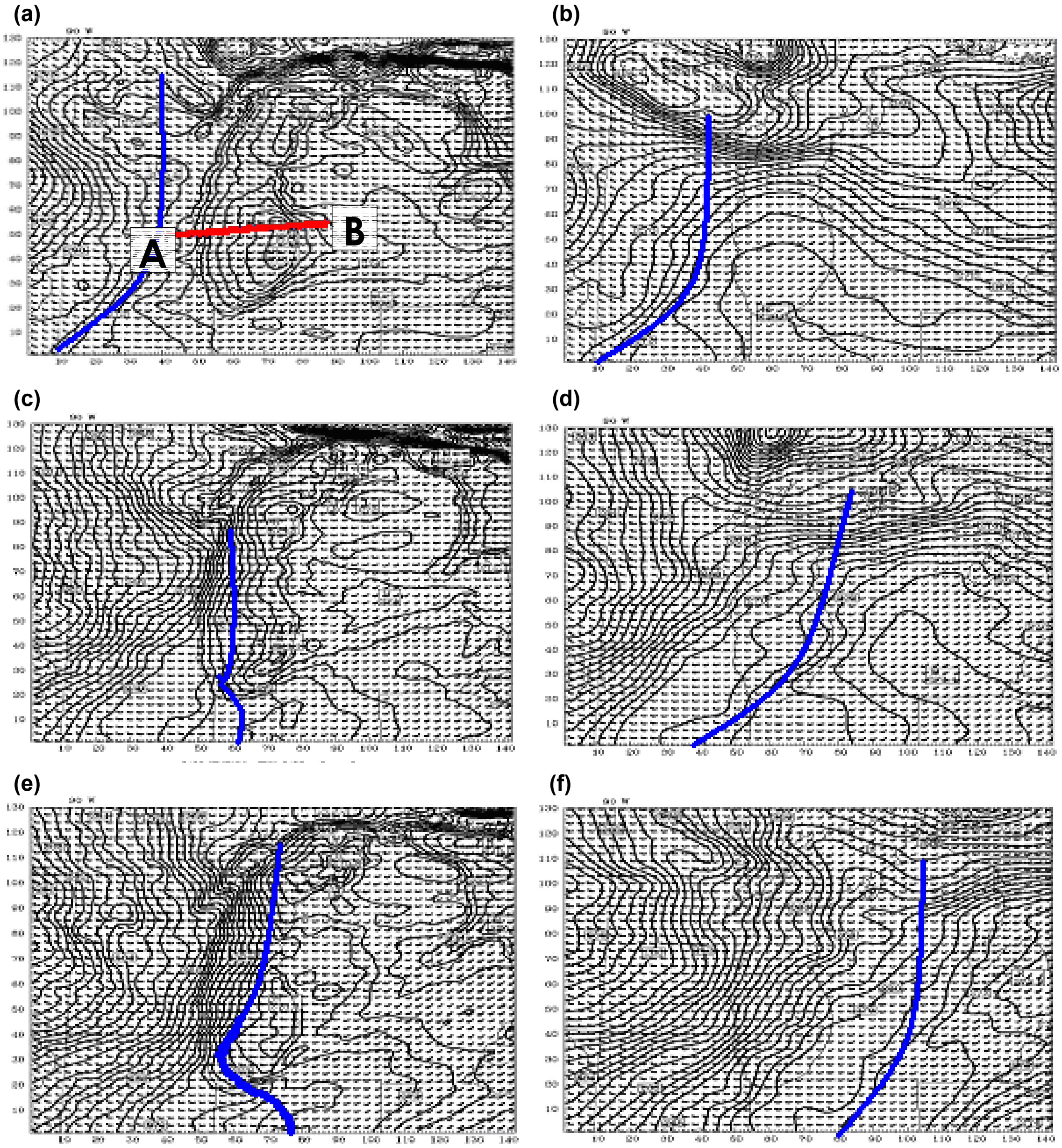

Figure 5. MM5 middle domain (4.5 km) simulations of 1000 hPa potential temperature (interval of 0.5 K), and 1000 hPa winds (interval of 3 knots), during the day of 10 January 1998. Dark blue line represents approximate location of arctic boundary. (a) With-lake simulation at 0000 UTC, (b) Without-lake simulation at 0000 UTC, (c) With-lake simulation at 0400 UTC, (d) Without-lake simulation at 0400 UTC, (e) With-lake simulation at 0800 UTC, (f) Without-lake simulation at 0800 UTC.

The frontal locations during the period can also be seen in vertical sections of potential temperature and vertical velocities across the lake surface (Fig. 6). The cross section was taken from point A to B in Fig. 5a, or roughly from KMKX to KGRR. The cross section was also chosen to be roughly perpendicular to the frontal boundary, as it would depict movement of the boundary across the lake. These cross sections are taken from the inner domain (1.5 km grid spacing).

At 0130 UTC, (Fig. 6a), the shallow arctic air is evident below 900 hPa, roughly where the height of the inversion base is located, west of 130 km (Fig. 6a). It already appears that the lake surface, approximately 30-180 km along the x-axis, had an effect of lifting the capping inversion, and mixing away the lowest levels of the cold air, as seen by potential temperature lines increasing with height in the lowest layers (Fig. 6a). At

0130 UTC, for the without-lake simulation (Fig. 6b), the arctic boundary is located over the western shores of the lake, depicted by gradual sloping of potential temperature lines from east to west.

By 0300 UTC, the arctic boundary had made it to approximately (110 km along the x-axis) the middle of the lake, for the with-lake simulation (Fig. 6c). Through heat fluxes, the lake has apparently weakened the actual arctic boundary over the lake. This is clearly evident in the vertical velocity fields over the central portions of the lake. It appears as though the mesoscale influences of the lake are dominating the synoptic-scale conditions. For the without-lake simulation (Fig. 6d), the boundary appears to be slightly east of the center of the lake (approximately 120-130 km along the x-axis). No such vertical velocities are evident, as was the case with the with-lake simulation.

By 0530 UTC, for the with-lake simulation, the arctic boundary had moved eastward slightly (~120 km along the x-axis) as the cold air had deepened and progressed eastward from the upper Midwest. Also, at 0530 UTC, still evident are turbulent fluxes depicted in the vertical velocity fields (Fig. 6e) over the lake, near the beginning of the arctic boundary. Also, evident is the lowering inversion upwind of the lake associated with the shallow arctic air mass and the increasing inversion height over the lake itself, due to turbulent mixing. The without-lake simulation (Fig. 6f) clearly shows the progression of the arctic boundary across the eastern shores of the lake and no slowing of the frontal boundary (~160 km along the x-axis). The boundary layer appears to be unchanged across the cross section, as no turbulent mixing had occurred. Throughout the period there also seems to be a maximum in vertical velocities for the with-lake simulation, from approximately 120 to 200 km. This appears to be related to the low-level convergence maximum found in the low-level wind fields, as the cold air wrapped around the southern edge of Lake Michigan (Fig. 6e). There could also be frictional convergence effects of the wind as it cross the shoreline, as well. No such vertical velocities are noted in the without-lake simulation (Fig. 6f).

By 0800 UTC, the arctic boundary was effectively pushing the modified air eastward very slowly (not shown here), and had brought an end to upward vertical motion over most of the lake. Lower Inversion heights are evident in the weakening of precipitation fields on radar observations from approximately 0600-1100 UTC. By 1100 UTC, the cold air further deepened, the 850 hPa trough crossed the region, the inversion rose, and pure lake-effect snow bands developed. It appeared as though there was a combination of weak frontal forcing and the heat and moisture fluxes from the lake that resulted in the enhancement along the eastern shores of the lake.

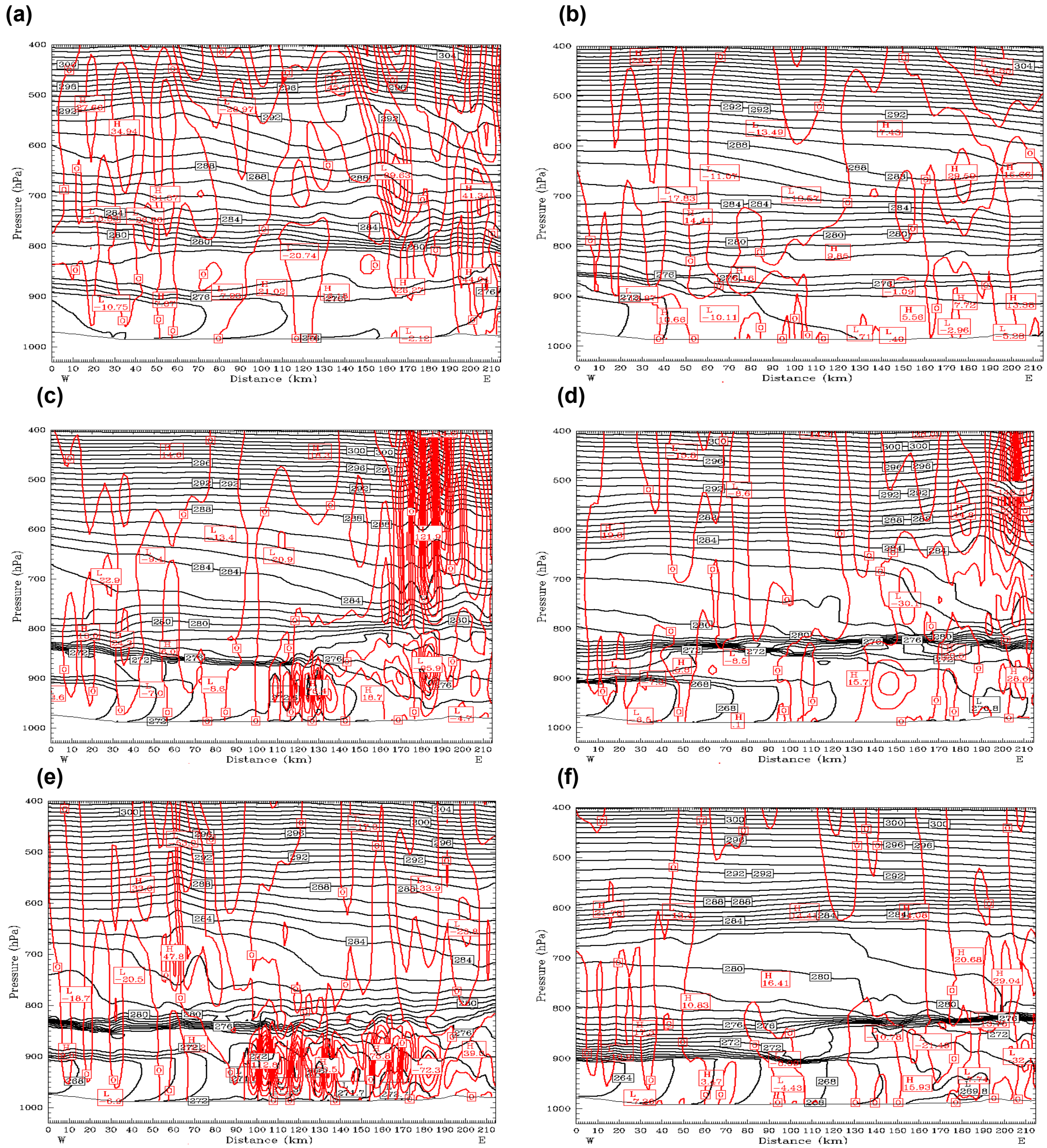

Figure 6. MM5 inner domain (1.5 km) vertical cross sections of potential temperature (K) (black lines) and vertical velocities (cm/s) (red lines), during the day of 10 January 1998. (a) With-lake simulation at 0000 UTC, (b) Without-lake simulation at 0000 UTC, (c) With-lake simulation at 0300 UTC, (d) Without-lake simulation at 0300 UTC, (e) With-lake simulation at 0530 UTC, (f) Without-lake simulation at 0530 UTC.

Finally, as seen in radar observations (Fig. 2), apparent enhancement of the frontal precipitation occurred as it crossed Lake Michigan. This enhancement can be seen in vertical cross sections of snow and total cloud mixing ratios across the lake (Fig. 7). The cross section is again taken from points A to B (Fig. 5a), or from KMKX across the lake to KGRR. Cloud mixing ratio and snow mixing ratio, approximate where the actual clouds and apparent precipitation are located.

At 0000 UTC, for both simulations (Fig. 7a,b) there was a weak area of precipitation associated with the frontal boundary, over the entire lake. However, for the with-lake simulation (Fig. 7a) there appears to be embedded areas of higher precipitation, especially across the eastern portions of Lake Michigan. As the precipitation moved across the lake (0000-0600 UTC) the clouds and snow intensified and grew in vertical depth (Fig. 7a,c). For the without-lake simulation the precipitation remains relatively weak or weakens as it progresses in time (Fig. 7f). Also, noted in the cross sections are the differences in effective boundary layer heights, between the two simulations. The with-lake simulation, due to turbulent flux of heat and moisture, had a greater effective boundary layer depth than the boundary layer of the without-lake simulation.

By 0600 UTC, for the with-lake simulation, (Fig, 7e) it appeared that there was a transition from lake and frontal precipitation to pure lake-effect precipitation of widespread nature. However, as the inversion comes down and the boundary finally crosses the lake, the precipitation weakens, which matches well with potential temperature cross sections (Fig. 6). Pure lake-effect eventually developed by 1100 UTC, as the cold air deepened. For the without-lake simulation (Fig. 7f), there appears only to be weak areas of precipitation after the frontal boundary moves eastward, and the inversion base lowers. The only evidence of increased precipitation are located around KGRR, due to gradual upslope of the mean flow (Fig. 7f).

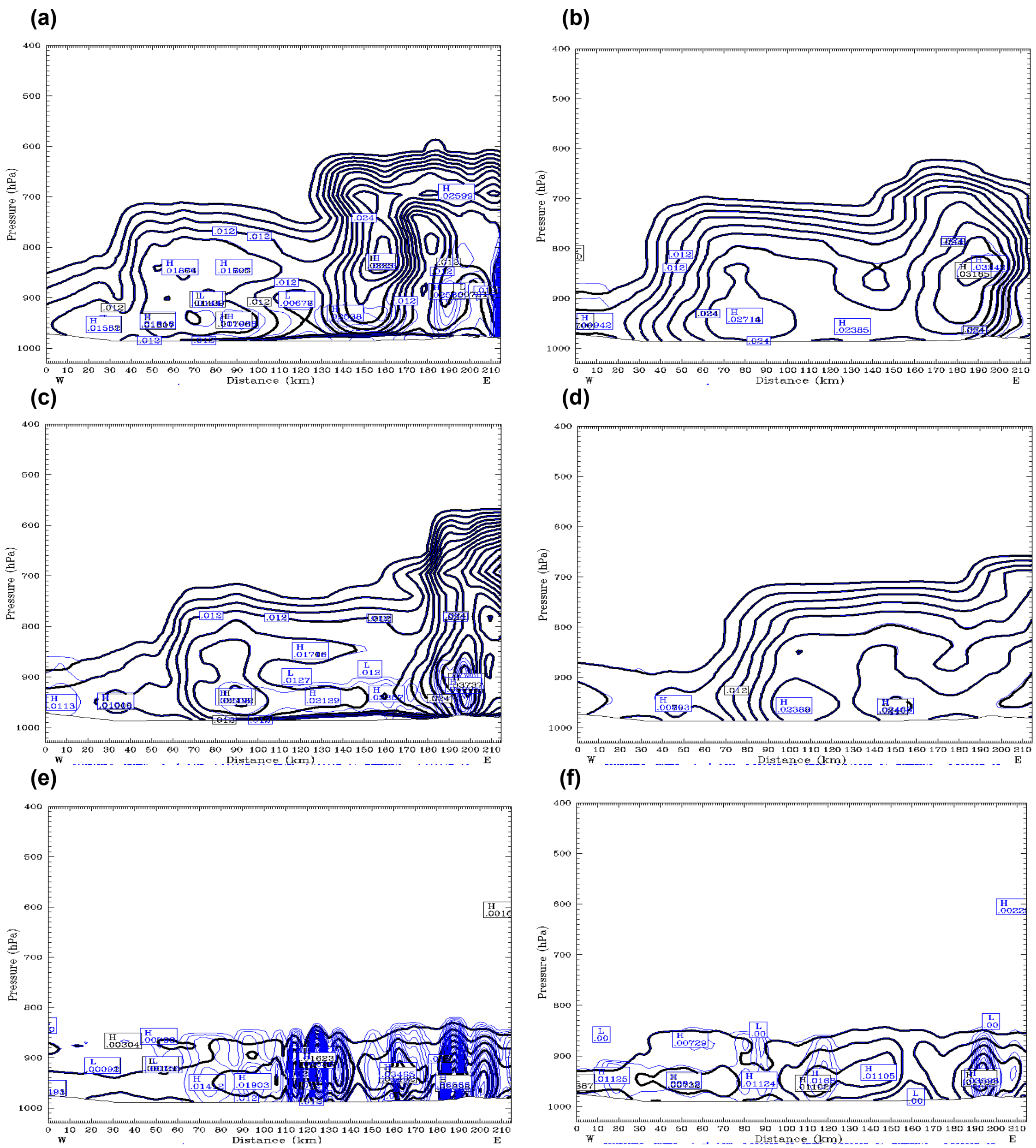

Figure 7. MM5 inner domain (1.5 km) vertical cross sections of snow mixing ratios (g/kg) (blue lines) and cloud mixing ratios (g/kg) (solid black lines), during the day of 10 January 1998. (a) With-lake simulation at 0100 UTC, (b) Without-lake simulation at 0100 UTC, (c) With-lake simulation at 0200 UTC, (d) Without-lake simulation at 0200 UTC, (e) With-lake simulation at 0600 UTC, (f) Without-lake simulation at 0600 UTC.

5. CONCLUSIONS

MM5 simulations of a shallow arctic cold front that occurred on 10 January 1998, during the Lake-ICE experiment, depict a gradual slowing, or retarding, of the frontal boundary, and a pronounced modification of the associated arctic air, as it crossed Lake Michigan. The case of 10 January 1998 represented a unique situation in which the synoptic-scale system transitioned, from purely synoptic-scale to mesoscale, in the end. Numerical simulations of with-lake and without-lake depicted that the increased heating in the lower boundary layer induced from the lake surface to be responsible for the slowing and weakening of the frontal boundary. Lake Michigan was also found to influence the regional wind pattern of the mean flow causing the cold air to effectively wrap around the southern portions of the lake.

As noted in Gallus and Segal (1998) there are two primary mechanisms impacting the speed and intensity of the frontal boundary as it progresses over the lake surface. The first dealt with the change in low-level temperature gradient induced by the lake itself. While, the second was the change in surface roughness between the lake and the land. They found that for cooler lake surfaces the reduction in turbulence (smooth flow) actually accelerates the frontal zone, which is attributed to reduced buoyancy-generated turbulence over the cool lake (Gallus and Segal 1999). This effect would be most pronounced in the late winter months and the springtime as the lake is generally cooler during these months. However, the 10 January 1998 case occurs during a time when lake temperatures were generally warmer than the surrounding land, and much warmer than the overlying air, such that a significant amount of buoyancy-generated turbulence occurred. Therefore, it is reasonable to expect a deceleration in the frontal boundary as it progresses across the lake surface, and this is noted in the simulations.

Both observational and modeling evidence show an apparent enhancement to the frontal precipitation as it moves across Lake Michigan. The enhancement was most likely due to the increased heat and moisture flux associated with the warmer lake surface. Another mesoscale feature evident from the study is the low-level convergence along the eastern portions of the lake, as the lake modified the local wind regime and effectively caused air to migrate around the heat source.

Ongoing research seeks to analyze WSR-88D radar images from both upwind and downwind sites to quantify both the horizontal and vertical structure of the precipitation as it crossed Lake Michigan. Of interest currently are local scale banding features embedded in the precipitation field near KGRR. This suggests the occurrence of horizontal roll convection embedded within the synoptic-scale precipitation. Numerical simulations are also planned, in the near future, to determine the impact of surface roughness on the simulations. Surface roughness of the lake surface will be varied to determine the dominate factors in frontal speed and intensity. These results will be compared to the current results.

The results from the research can be valuable to forecasters located in the Great Lakes regions, as forecasting of these events can be difficult due to their mesoscale nature. Further study is needed to investigate more factors; such as differing frontal types, changes in frontal speed (i.e. faster moving boundaries), further impacts of lake surface temperatures and roughness. Another aspect of this case is the fact that the frontal boundary had a gradual gradient between the arctic air over the Midwest to the warmer air over the Great Lakes (i.e. the front was driven primarily by the push of the arctic air). Further study needs to be done dealing with more classic frontal zones, in which the frontal zones have tighter gradients, and coincide with upper-level support.

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