P2.2

Numerical Simulation of Impacts of the Great Lakes on Cold Frontal Passages

T.S. Axford[1,2], M.R. Hjelmfelt[*2], W.J. Capehart[2], and D.A.R. Kristovich[3]

[1]Meridian Environmental Technology, Grand Forks, ND
[2]South Dakota School of Mines and Technology, Rapid City, SD
[2]Illinois State Water Survey, INRS, University of Illinois, Champaign, IL

ABSTRACT

Each year numerous frontal systems pass through the Great Lakes region and interact with the large bodies of water. Much has been learned about the impacts of the Great Lakes on weather, but effects on synoptic-scale fronts are not well established. The purpose of this study is to determine the influence of relatively warm and cool lake surfaces on cold fronts.

This study examines the frontal passages of 21-22 January 2004 and 24-25 April 2002 over Lake Michigan. The 21-22 January 2004 period is an example of a cold frontal passage over relatively warm lake waters with associated pre-frontal precipitation and represents a typical lake-effected snow scenario. The 24-25 April 2002 period is an example of a cold frontal passage over a relatively cool lake and represents a typical spring convective precipitation event. Observational analysis reveals that the presence of Lake Michigan resulted in an apparent enhancement of the pre-frontal precipitation associated with the 21-22 January 2004 cold front and an apparent suppression of convective development associated with the 24-25 April 2002 cold front.

Numerical simulations with the Weather Research and Forecast – Advanced Research WRF (WRF-ARW) model are compared with observations of the two cases to understand the impacts of the lake surface on the frontal characteristics of each case. With-lake (WL) and no-lake (NL) simulations are performed to better understand the importance of the lake on the frontal boundary. Two model sensitivity tests are conducted for each case: one involving increasing the surface roughness lengths of the Great Lakes to values similar to the surrounding land surface to further understand the effects of surface roughness on the frontal boundary. The second test involves modifying the lake surface temperatures to match the temperatures of the surrounding land. This provides a better understanding of the impacts of lake-land temperature difference on a cold frontal passage.

Examination of observations and the differences between model simulations reveals that Lake Michigan had a substantial impact on the synoptic-scale fronts. The lake slowed the progress of the 21-22 January 2004 cold front, weakened the temperature gradient across the front, and enhanced the pre-frontal precipitation associated with the cold front. The effects of increased lake-land temperature difference and decreased surface roughness appeared to compete, with the lake-land temperature difference being the dominating factor in the slowing of the frontal boundary. Thus, it was concluded that a cold front progressing over a relatively warm lake surface will propagate slower than the same front progressing over land surfaces. Passage over the lake surface appeared to accelerate the 24-25 April 2002 cold front, develop a near-surface stable layer, and strengthen the temperature gradient across the frontal boundary. The effects of increased lake-land temperature difference and decreased surface roughness appeared to be working together in accelerating the frontal boundary. Therefore, it was concluded that a cold front progressing over a relatively cool lake surface will propagate more quickly than the same front progressing over land surfaces.

1. INTRODUCTION AND BACKGROUND

Each year numerous synoptic-scale frontal passages occur over the Great Lakes region, often bringing storms and precipitation with them. The Great Lakes can have dramatic effects on the overlying weather conditions. Water has a much higher specific heat capacity than land and therefore does not heat up or cool down nearly as fast as the land does. From early spring to late summer, warmer lake waters are usually relatively cooler than nearby land surfaces and overlying air. From early autumn to late winter, this reverses and cooler air is brought into the region above relatively warm lake waters. During late autumn and winter, when a considerable difference between water and air temperature is present, lake-effect snows can be produced.

Past studies, primarily focused on lake-effect snow storms, have led to an understanding of the processes involved. However, there have not been nearly as many studies conducted on frontal systems that interact with the lakes and condition the environment to produce lake-effect snow. This study seeks to investigate the effects of Lake Michigan on passing cold fronts.

The movement of surface cold fronts over warm lake surfaces can be compared to cold fronts progressing over urban heat islands. Loose and Bornstein (1977) examined the effect of the New York City urban heat island on a frontal passage based on analysis of data from an extensive mesoscale network. Results indicated that there was as much as a 50% reduction in the speed of the front during a non-heat island period. The reason for the slowing of the front was said to be due to surface friction from the increased roughness of the city compared to the surroundings. Results for a period with a pronounced urban heat island effect were similar, as there was as much as 50% reduction on the speed of

Corresponding author address: Dr. Mark R. Hjelmfelt, SDSM&T, 501 East Saint Joseph Street, Rapid City, SD 57701. E-mail: mark.hjelmfelt@sdsmt.edu.

the front, but only over the upwind half of the city. Over the downwind half of the city, the front accelerated by as much as 25% compared to the upwind portion. Based on these results, Loose and Bornstein concluded that the horizontal pressure gradient induced by the urban heat island played a vital role in the frontal acceleration over the downwind portion of the urban area.

A climatology of frontal passages over the Great Lakes for the winters of 1999/2000 through 2004/2005 was combined with a more detailed analysis of observed frontal movement and associated precipitation for the 1999/2000 and 2003/2004 seasons by Cousins (2006). Results revealed a total of 381 frontal passages over the six-year period with most (209) being cold fronts. Analysis of the 1999/2000 and 2003/2004 winters revealed that, on average, precipitation increased downwind of the lakes during frontal passages, except for stationary and secondary cold fronts. The statistical analysis provided evidence of significant slowing of cold fronts over warmer lakes as well as a statistically-significant decrease in frontal temperature gradient for cold fronts crossing a warmer lake (Cousins, 2006).

Dreher *et al*. (2004) performed numerical simulations of a wintertime cold front passing over the long axis of Lake Michigan. The 10 January 1998 case study involved a shallow arctic boundary with associated weak precipitation. Meteorological observations and data were taken from the Lake-Induced Convection Experiment (Lake-ICE; Kristovich *et al*., 2000) and implemented into the Fifth-Generation (PSU/NCAR) Non-hydrostatic Mesoscale Model Version 5 (MM5; Grell *et al*., 1994). Simulations were made with and without Lake Michigan, and a sensitivity test was conducted to examine the effects of surface roughness on the frontal passage over Lake Michigan. Dreher concluded that Lake Michigan had a substantial impact on the synoptic-scale front, most importantly by slowing the progression of the front relative to portions over land, modifying the local wind field, and enhancing frontal precipitation downwind of the lake. The no-lake simulation revealed no slowing of the arctic front compared to portions over land as well as no detectable enhancement of the precipitation associated with the frontal boundary (Dreher, 2004).

Gallus and Segal (1999) used a high-resolution numerical model to simulate a strong, relatively dry, late winter surface cold front passing over southern Lake Michigan on 9 March 1992 during the Storm-Scale Operational Research Meteorology Fronts Experiment Systems Test (STORM-FEST; Szoke *et al*., 1994). Because of the late winter timing of this case, the cold front was passing over a lake that was much cooler than the air over the surrounding land, which makes this a unique case study. Gallus and Segal (1999) described two primary processes by which a lake of sufficient size could modify the progression of a cold front. The first is through changes in frontal temperature gradients directly caused by changes in thermal fluxes compared to those over land (Garratt, 1986). The second process is alteration of the surface roughness and near-surface thermal stratifications that could modify the effects of friction on the front (Gallus and Segal, 1999). Their results indicated a pronounced acceleration and bulge in the front for portions over southern Lake Michigan. A couple of reasons for acceleration of the front over the lake were given. One was that the front passed at an oblique angle to the long axis of the lake rather than perpendicular to it, which meant a more northerly component of wind in the cold sector was working to strengthen the front. Another reason sug-gested was that the front encountered a reduction in friction when passing over the lake surface due to the reduced daytime buoyancy-generated turbulence within the boundary layer caused by the cooler lake surface

The main purpose of the present study is to analyze both cold and warm season interactions between synoptic-scale frontal boundaries and Lake Michigan. The analysis involves both observations and numerical simulations with and without Lake Michigan (WL = with Lake Michigan, NL = without Lake Michigan). The cool season case chosen for the study occurred from 1200 UTC 21 January 2004 to 1200 UTC 22 January 2004. This case involved relatively warm lake surface compared to the cold surrounding land, typical of a cold season lake-effect snow scenario. The warm season case chosen for the study occurred from 1200 UTC 24 April 2002 to 0600 UTC 25 April 2002. This case involved a relatively cool lake surface compared to warmer surrounding land and was chosen to represent a typical warm season convective scenario. Two sensitivity tests were also conducted for both cases. The first sensitivity test involved modification of the surface roughness over the lake so that it was representative of the roughness values of the surrounding land. The second test involved modification of the lake surface skin temperatures to roughly match the surrounding land temperatures.

2. CASE STUDIES

2.1 *Case #1: 21 January 2004 – 22 January 2004*

The case of 21-22 January 2004 is an example of a cold season frontal system with associated pre-frontal precipitation crossing relatively warm Great Lakes. At 2100 UTC on 21 January, a low pressure center that originated in northern Saskatchewan was centered north of Sault Ste. Marie, Michigan with a surface pressure of 986 hPa and the shallow, arctic air mass associated with the low was at the western shore of Lake Michigan. The cold front crossed the lake from approximately 2100 UTC 21 January to 0400 UTC 22 January, with pronounced cold air advection at the surface behind the front. The 0300 UTC observations indicated an approximate 8^{o}C per 110km potential temperature gradient across the front, thus the 21-22 January 2004 case fits the definition of a cold front by Sanders (1999) and Sanders (2005). Significant precipitation was located ahead of the cold front with a weaker band along the frontal boundary. As the front moved to the east-southeast diagonally across Lake Michigan, the precipitation at the front appeared to be enhanced, before subsequently weakening as the front moved away from the lake. After the passage of the cold front, the temperature contrasts between the warm lake and the arctic air above resulted in lake-effect snows along the eastern shore of Lake Michigan.

Figure 2.1 depicts the surface low pressure center and associated surface cold front that progressed southeastward across the Great Lakes during 21 and 22 January 2004. Frontal positions represented in this image were analyzed by the National Centers for Environmental Protection (NCEP) and are not necessarily advocated by this author. The contours of the surface pressure and potential temperature are 2 hPa and 2 K respectively.

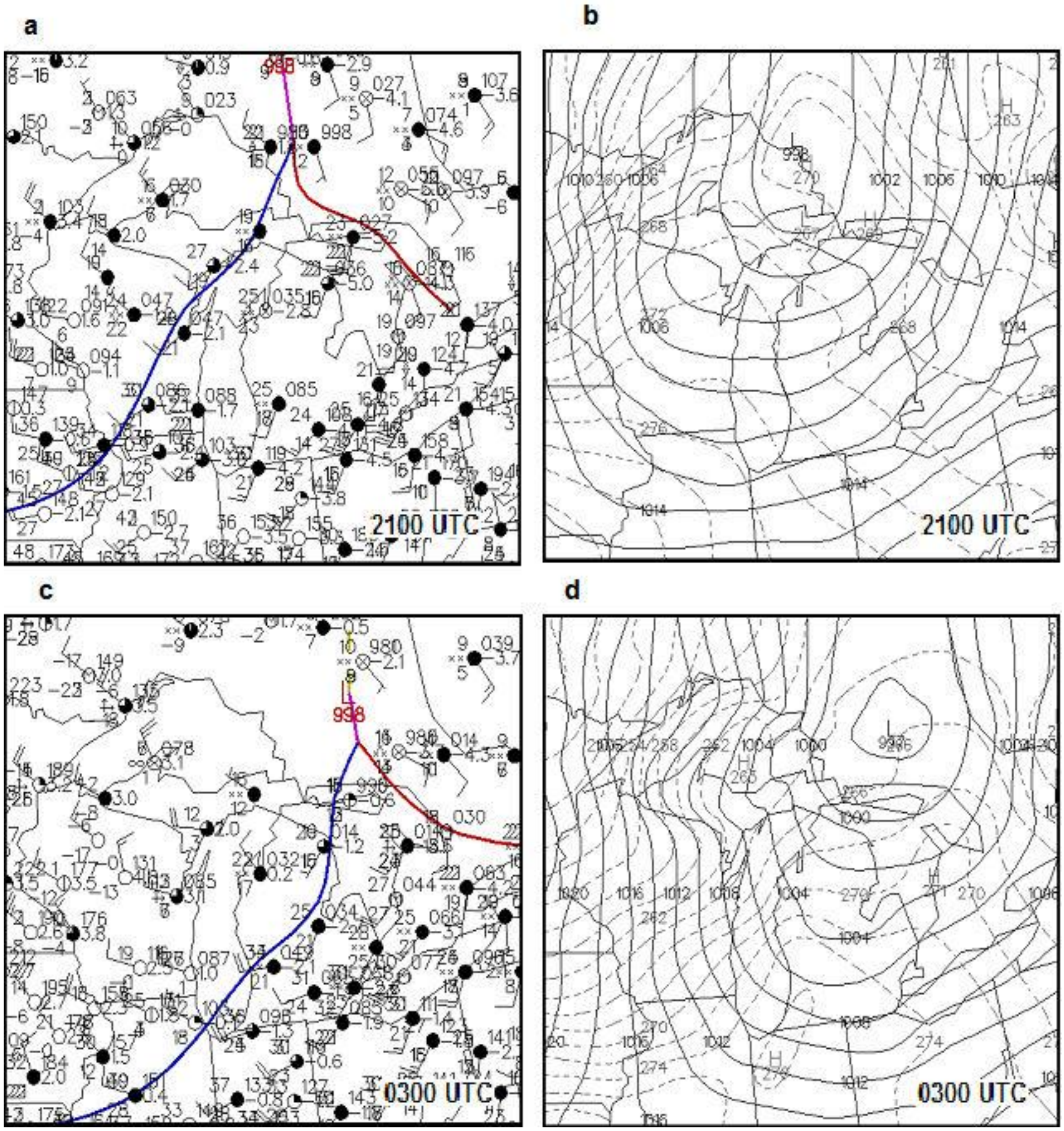

Figure 2.1 Surface station plots and approximate NCEP frontal locations with accompanying sea-level pressure (interval 2 hPa) and potential temperature (interval 2^{o}C [2 K]) charts. (a) and (b) 2100 UTC, (c) and (d) 0300 UTC 21-22 January 2004. From the Plymouth State College Weather Center archive. Red line indicates approximate location of the warm front. Blue line indicates the approximate location of the cold front.

At 2100 UTC, the arctic cold front was located along the northwestern shores of Lake Michigan and stretched down through Wisconsin (Fig. 2.1a). A noticeable temperature gradient across the cold front is evident in the surface observations. Also detectable is a shift in the surface winds from light and southwesterly ahead of the front to more intense and northwesterly behind the front. The surface pressure and potential temperature reveal a trough of low pressure located through Wisconsin, with tightly-packed isentropes (e.g., Sanders, 1999) just behind the axis of the trough (Fig. 2.1b). As the front moved across the lake, the potential temperature gradient increased behind the surface pressure trough, indicating a strengthening of the cold front and stronger advection of cold air at the surface just behind the front.

Aloft, the low pressure at 850 hPa was centered over James Bay with a secondary low pressure centered over the northeastern shores of Lake Superior. Cold air advection was evident over Minnesota, Wisconsin, and Iowa, indicative of a strengthening cold front at that level. At 500-hPa, the low pressure center was located over western Ontario. Thus the low was vertically tilted from 850 hPa to 500 hPa. Positive vorticity advection, which is associated with rising air, occurred behind the location of the surface cold front. This is counter-intuitive as air behind cold fronts usually sinks. In this case we have competing influences of strong cold air advection from the surface to at least 850 hPa, and fairly weak positive vorticity advection through the 500-hPa level. Although partially offset by the rising motion associated with the positive vorticity advection, the sinking motion associated with cold air advection is the dominant influence.

At 0300 UTC, the frontal boundary had progressed east-southeastward and could now be found just over the southern portion of Lake Michigan, while the low pressure center progressed eastward and had started to occlude (Fig. 2.1c). A strong gradient in surface potential temperature could be seen behind the axis of the trough, depicting intense cold air advection over Lake Michigan (Fig. 2.1d). There appears to be a stronger gradient of isentropes over Lake Michigan than over Wisconsin adjacent to the lake, which could indicate the intensification and slowing of the front over the lake compared to over the land.

By 0600 UTC, the low pressure center had progressed northeastward as the system continued to occlude. By this time the cold front associated with the low stretched southwestward over Lake Huron. During this period, Lake Michigan's water temperatures ranged from 3-5^{o}C which resulted in most of the lake surface being ice-free. Significant ice coverage was only found over Green Bay and the western shores of Lake Michigan (Fig. 2.2).

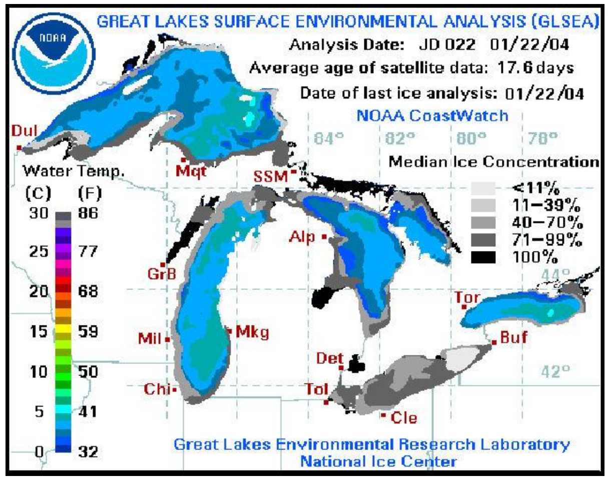

Figure 2.2 Gridded lake temperature and ice coverage for the Great Lakes. From the Great Lakes Environmental Research Laboratory.

2.2 *Case #2: 24 April 2002 – 25 April 2002*

The case of 24-25 April 2005 is an example of a warm season frontal system crossing relatively cold Great Lakes. At 1500 UTC 24 April, a surface low pressure center of 999 hPa that appeared to have originated over Montana was centered west of Thunder Bay, Ottawa. The cold front associated with the low reached the western shore of Lake Michigan at approximately 2200 UTC 24 April and crossed the lake, reaching the eastern shore at approximately 0100 UTC 25 April. The 0000 UTC observations indicated a potential temperature gradient across the front greater than 8^{o}C per 110km, so the 24-25 April 2002 fits Sanders' (1999) definition of a strong cold front. Convective precipitation was located along the cold front. As the cold front moved from west to east over the long axis of Lake Michigan, the precipitation associated with the frontal boundary appeared to weaken considerably over the lake while the convective precipitation associated with the frontal boundary over land to the south of Lake Michigan appeared to remain strong.

The locations of the surface low pressure center and the associated surface cold front that progressed eastward during 24 and 25 April 2002 are shown in Figure 2.3. Fronts represented in this figure are as placed by NCEP. The contours of the isobars and isentropes are 2 hPa and 2^{o}C (2 K) respectively.

At 2100 UTC, the surface low pressure center was located near the center of Ontario with the associated cold front stretching southward over Lake Superior and through Wisconsin and Illinois (Fig. 2.3a). A strong temperature gradient existed across the cold front with temperatures ahead of the front in the mid to upper 60s (^{o}F) and temperatures in the 40s (^{o}F) and 50s (^{o}F) behind the front. A wind shift is seen across the cold front as winds ahead of the front are approximately 10 to 15 knots from the south and 15 to 20 knots from the west-northwest behind the front (Fig. 2.3a). The surface pressure and potential temperature chart shows that a trough of low pressure was located through eastern Wisconsin, with packing of the isentropes behind the trough axis (Fig. 2.3b). The orientation of the isobars perpendicular to the isentropes indicate that cold air advection was occurring behind the front over much of Wisconsin.

At 0000 UTC 25 April, the surface low pressure center was still located over central Ontario approximately 150-200 km east of the 2100 UTC location (Fig. 2.3c). A secondary low pressure area had formed in the axis of the trough over the northern portion of Lake Michigan where the cold front had almost overtaken the warm front. The cold front had now progressed across much of Lake Michigan, with a noticeable bulge in the front that has made landfall on western Michigan. The isentropes, which were still tightly packed behind the location of the front, appear to confirm the bulge seen in the approximate frontal location (Fig. 2.3d). A slight curvature in the isentropes is seen over the area of western Michigan that coincides with the area of bulge in the front. If this is indeed the case, it may be caused by the front experiencing less resistance as it progressed over the cool, smooth surface of Lake Michigan.

At 0000 UTC 25 April, the low pressure center was located over north central Ontario at 850-hPa, with a trough of lower heights extending southward over eastern Illinois and Wisconsin (Fig. 2.3c). Cold air advection was occurring over portions of Minnesota, Wisconsin, and Iowa behind the cold front. At 500-hPa, the low pressure center was located over northwestern Ontario, which indicates vertical tilting of the low pressure center. A vorticity maximum was present within the 500-hPa trough, with strong positive vorticity advection over much of Wisconsin. This feature acted as upper air support for the rising air motions along and just behind the surface frontal boundary and convective development associated with the front.

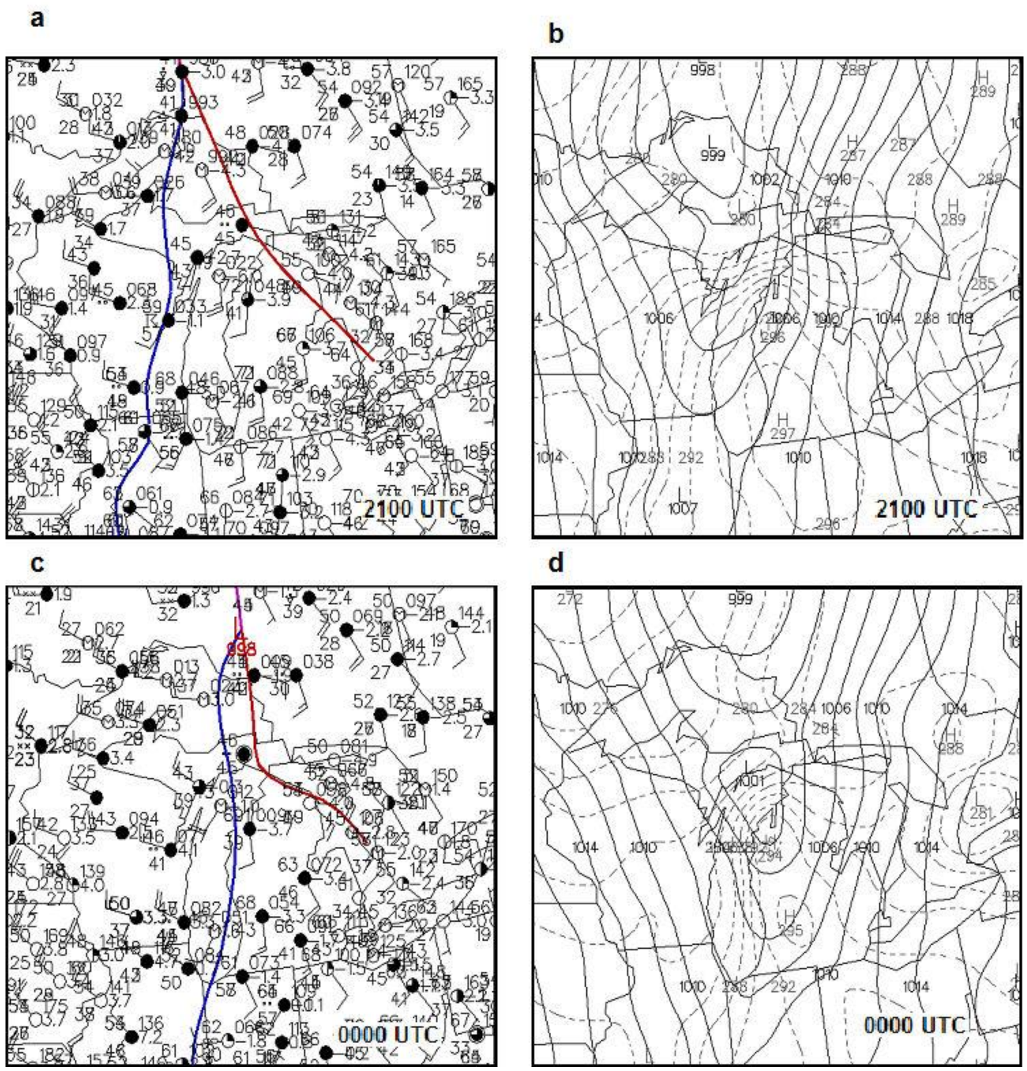

Figure 2.3 Surface station plots and approximate NCEP frontal locations with accompanying sea-level pressure (interval 2 hPa) and potential temperature (interval 2^{o}C [2 K]) charts. (a) and (b) 2100 UTC 24 April 2002, (c) and (d) 0000 UTC 25 April 2002. From the Plymouth State College Weather Center archive. Red line indicates approximate location of the warm front. Blue line indicates the approximate location of the cold front.

By 0300 UTC, the low pressure center was located just east of the location at 0000 UTC, with a secondary low pressure center located over northeast Michigan (not shown). The cold front had overtaken the warm front north of the secondary pressure center and became occluded. The cold front extended southward through central Michigan and Indiana, well east of the lake.

During this period, Lake Michigan's surface water temperatures averaged 3-4°C which resulted in the lake surface being completely ice free (Fig. 2.4). Small areas of warm water are visible along the shores of Lake Michigan with an approximate maximum water temperature of 8°C just offshore of Chicago, Illinois and Green Bay, Wisconsin.

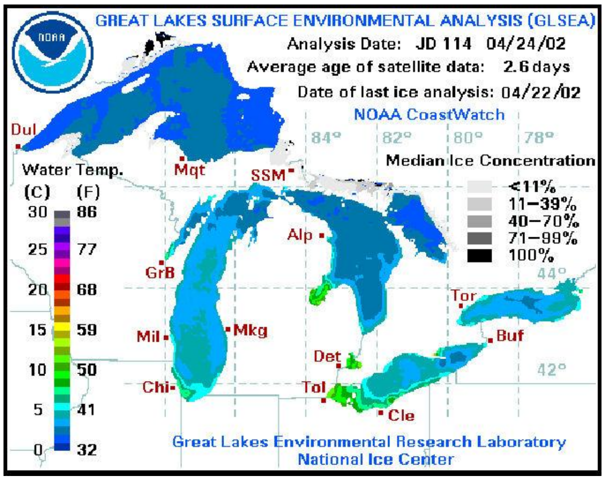

Figure 2.4 Gridded lake temperature and ice coverage for the Great Lakes. From the Great Lakes Environmental Research Laboratory.

3. NUMERICAL SIMULATIONS OF CASE STUDIES

The Weather Research and Forecasting–Advanced Research WRF (WRF-ARW) Version 2.2 non-hydrostatic mesoscale model (Skamarock *et al*., 2005) was utilized to simulate the two cases. Simulations of the cool season case were initialized at 1200 UTC 21 January 2004 and run to 1200 UTC 22 January 2004. Simulations of the warm season case were initialized at 1200 UTC 24 April 2002 and run to 0600 UTC 25 April 2002. Results from the model simulations were compared to the observations to verify model performance and to understand the impacts of the lake. Comparison of simulations with all of the Great Lakes present (WL) and simulations with Lake Michigan removed (NL), provided a better understanding of the effects of the lake surface. Two model sensitivity studies were also conducted. The first involved changing the surface roughness over the lake surface to match those of the surrounding land (RO), and the second modified the lake surface skin temperatures to match the land temperatures around the lake (TC). The results are compared to the WL simulations to gain a better understanding of the effects of surface roughness and lake-land temperature difference on the cold fronts.

3.1 *Mesoscale Model*

The WRF-ARW has been developed as a community model that may be used operationally, for research purposes, or as a teaching tool. WRF-ARW utilizes terrain-following hydrostatic-pressure vertical coordinates on a staggered Arakawa C-grid, and has the capability to be applied at very high resolution on shared and distributed memory machines. The model physics include parameterizations of microphysics, cumulus parameterizations, and optional schemes for surface, boundary layer and atmospheric radiation physics.

The model domains used in this study are shown in Fig. 3.1. A coarse grid domain (D01) was centered at 42° 50' N and 86° 50' W, with 160 x 110 horizontal grid points with 18 km grid spacing. A second domain (D02) was placed inside the coarse grid and centered over Lake Michigan. This middle domain consisted of 241 x 220 horizontal grid points with 6 km grid spacing. A third domain (D03) was centered over the central portion of Lake Michigan to cover the lake and surrounding land regions, containing 184 x 316 horizontal grid points with 2 km grid spacing. Timesteps of the coarse (D01), middle (D02), and high-resolution (D03) domains were 30, 10, and 3.33 seconds, respectively. The model employed a Lambert Conformal Conic map projection.

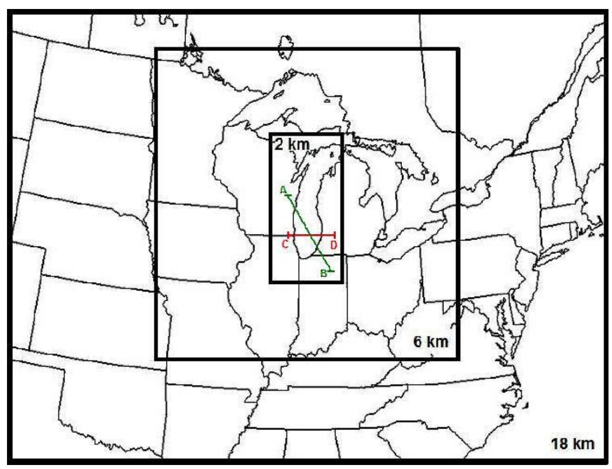

Figure 3.1 WRF domain selections for all model simulations. Cross-sections used for model output are shown. (A,B) used for 21-22 January 2004 case, (C,D) used for 24-25 April 2002 case.

The modeling system utilized global terrain and landuse data obtained from the United States Geological Survey (USGS). The coarse outer domain used the 5-min. (9.2 km) global terrain and landuse data, while the two inner domains used the 30-sec. (927.6 m) data. The model employed the NOAH Land Surface Model (NOAH LSM) which predicts soil moisture, temperature at four depths (10, 30, 60, and 90 cm deep), canopy moisture, and snow depth (Chen and Dudhia, 2001a,b). The NOAH LSM also provides latent and sensible heat fluxes to the boundary layer scheme that couples the surface to the atmosphere (Skamarock *et al*., 2005).

The model was initialized with North American Regional Reanalysis (NARR), which contains 32 km grid spaced analysis fields in each of the two cases. The WRF Pre-Processing System (WPS) ingested the NARR fields from 1200 UTC 21 January 2004 through 1200 UTC 22 January 2004 for the cool season case and 1200 UTC 24 April 2002 through 0600 UTC 25 April 2002 for the warm season case. After pre-processing, the data was interpolated from the 29 NARR pressure levels to 40 vertical levels. Approximately 18-20 of the vertical levels in the model were placed in the lowest 200 hPa to more fully resolve the interaction between the front and lake. The upper boundary for the simulations was chosen to be 100 hPa.

Lake surface temperatures were obtained from the NOAA Great Lakes Environmental Research Laboratory (GLERL) data archive with raster spacing of 3.6 km. The lake surface temperatures were assumed to be constant throughout the 18-24 hr simulation period. For each of the case studies, a second model simulation (NL) was completed in which the water surface of Lake Michigan was completely removed to serve as a comparison to the simulations with the lake present. The lake surface was replaced by land using the nearest non-lake grid soil temperatures and moisture, with the land cover and texture representing a blend of the nearby land classes. The terrain height remained at the original lake surface level to avoid introducing orographic effects.

Supplementary model simulations of each case were conducted in which the lake surface roughness and lake surface skin temperatures were modified. The aerodynamic surface roughness lengths of the lake surface were replaced by an average value of roughness length of the land surrounding Lake Michigan. Much of the land area surrounding Lake Michigan was represented by a cropland/woodland land use category with an associated roughness length of 0.2 m. The roughness length of the water area was then modified from a very small value (order 0.01m), dependent on wind speed, to a constant value of 0.2 m. Results of these simulations were compared with the WL simulation and provided insight into the effects of roughness on the speed and structure of the passing cold fronts. The second test involved modifying lake surface skin temperatures to replicate the average land temperatures observed around Lake Michigan. Since the cold season case involved a lake warmer than the surrounding land temperatures, the lake temperatures were changed by subtracting 15^{o}C from the lake temperature values. The warm season case involved a lake cooler than the surrounding land temperatures; for this case the lake temperatures were modified by adding 15^{o}C. Results of these simulations were compared to the WL simulation and gave evidence of the effects of lake-land temperature differences on the speed and structure of the passing cold fronts.

Inputs were fed into the modeling framework so that the higher resolution fields were laid on top of fields with less resolution. The order in which the fields were laid into the modeling domains were 2D and 3D NARR meteorology fields first, followed by NARR surface fields, and finally the high resolution GLERL sea surface temperatures and sea ice data. The NL simulations used NARR surface fields and GLERL fields with Lake Michigan masked out.

Several preliminary simulations were conducted to determine which surface and physics options, as well as vertical resolution, should be implemented to best represent the actual observations. The Thompson *et al*. (2004) microphysics option was employed for all domains. The Kain-Fritsch mass flux cumulus parameterization (Kain and Fritsch, 1993) was used for the outer (D01) and middle domains (D02) with no cumulus parameterization needed for the innermost domain (D03). The atmospheric boundary layer was treated using the Yonsei University PBL option, explained in Hong *et al*. (2006). Atmospheric radiation was parameterized using the Rapid Radiative Transfer Model (RRTM; Mlawer *et al*., 1997) for longwave radiation and the Dudhia (1989) scheme for shortwave radiation, which are standard schemes taken from the MM5 model (Skamarock *et al*., 2005).

3.2 *Model Verification*

3.2.1 Case #1: 21 January 2004 – 22 January 2004

Model results for the WL run of the 21-22 January 2004 case compare very well with the observations. Figure 3.2 displays the observed surface analysis along with the simulated surface analysis for 0000 UTC 22 January 2004, 12 hours after the initialization of the model, while the cold front is located over Lake Michigan. The model simulates the wind field very well compared to observations; there is strong northwesterly flow behind the cold front in the cold sector in both the simulation and observations. The model also resolves the moderate southwesterly flow in the warm sector ahead of the cold front with accuracy.

Although the model accurately depicts the location of the low pressure center, the overall intensity of the low in the simulation is stronger than observed. The simulated low pressure center is around 991 hPa while the observed pressure is actually around 999 hPa. Even with the discrepancy of intensity, the location of the front does not appear to be affected drastically. The approximate location of both the simulated and observed cold fronts in Fig. 3.2 was drawn with the aid of the surface potential temperature fields shown in Fig. 3.3.

The simulated and observed potential temperature plots (Fig. 3.3) also compare favorably. The model is able to accurately simulate the cold air outbreak over Minnesota and Wisconsin while also depicting the warmer potential temperatures in the warm sector over portions of Michigan, Indiana, and Ohio. The accuracy of the potential temperature simulation verifies the capability of the model to simulate the system.

3.2.2 Case #2: 24 April 2002 – 25 April 2002

Model results for the WL run of the 24-25 April 2002 case also compare well with the observed analysis. Figure 3.4 displays the observed surface analysis along with the simulated surface analysis for 0300 UTC 25 April 2002, 15 hours after the initialization of the model and after the front fully progressed past the lake. 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 also simulates the pressure field quite accurately, as indicated by the agreement in the location of the low pressure center and pressure trough, even though the depth of the simulated pressure trough is slightly greater than observed. The accuracy of the sea-level pressure and surface wind fields allows us to verify the approximate location of the simulated cold front. The approximate location of both the simulated and observed cold fronts in Fig. 3.4 was drawn with the aid of the surface potential temperature plots in Fig. 3.5.

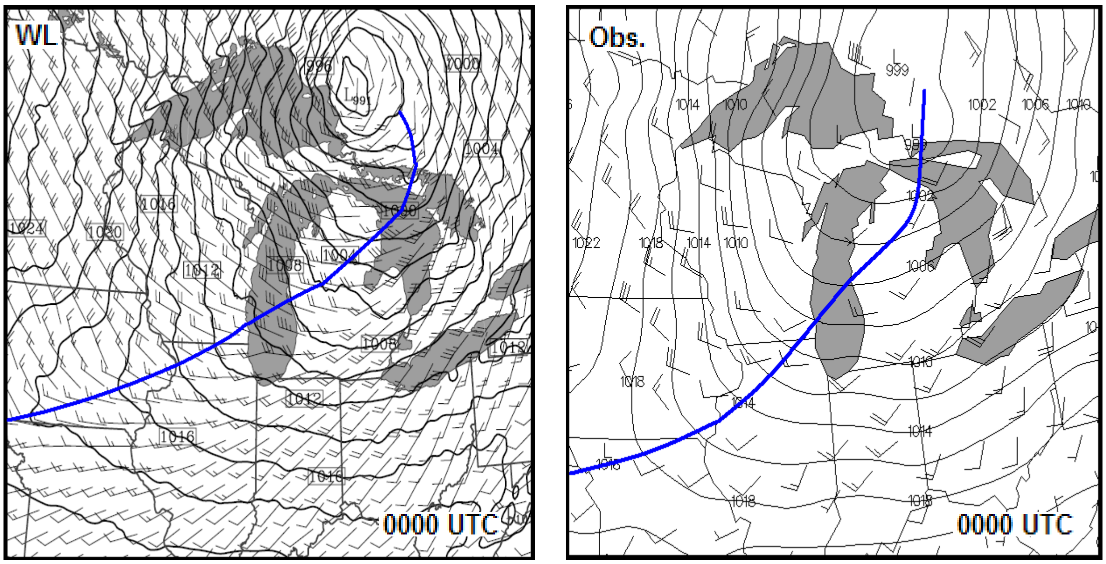

Figure 3.2 Surface analysis of sea-level pressure (interval 2 hPa), surface winds, and approximate frontal location at 0000 UTC 21 January 2004. (Left) Simulated results, (Right) Plymouth State College Weather Center archived data with NCEP analyzed frontal location. Thick blue line indicates approximate frontal location.

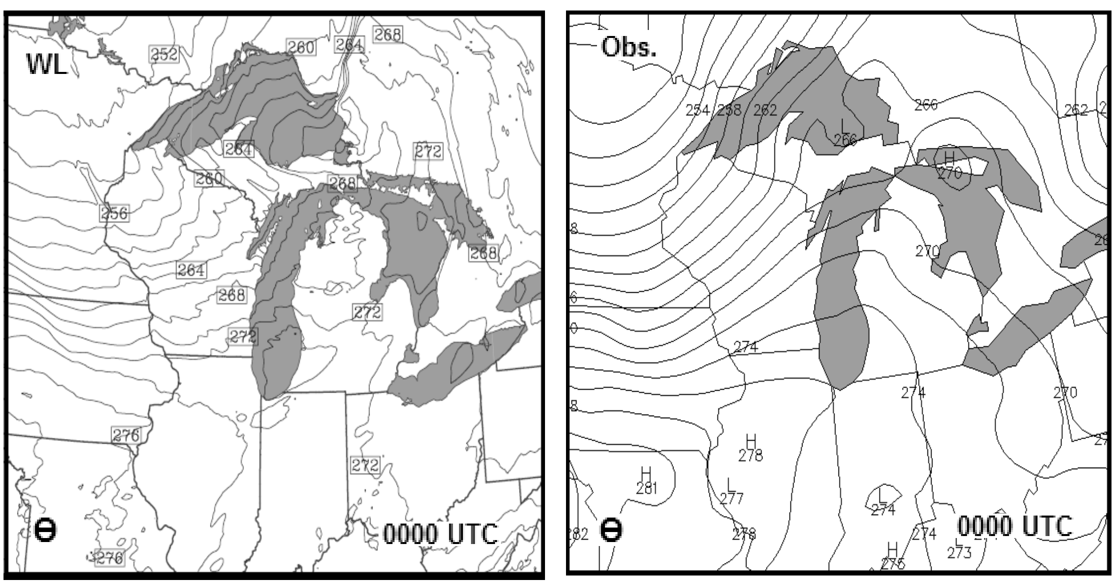

Figure 3.3 Surface analysis of potential temperature (interval 2°C [2 K]) at 0000 UTC 21 January 2004. (Left) Simulated results, (Right) Plymouth State College Weather Center archived data.

The simulated and observed potential temperature plots also agree with each other quite well, although there is an obvious discrepancy in the tightness of the gradient across the frontal boundary in Michigan and Indiana. The tight packing of the isentropes along the frontal boundary in the simulated results can be attributed to the 6 km resolution of the modeling domain while the observed isentropes are spaced much farther apart. The weak potential temperature gradient across the frontal boundary in the observations is due to the sparse observations within the region and resulting interpolations. The simulated results are able to resolve portions of the front just north of Lake Superior and in southern Indiana. The model also performs well in simulating the pre- and post-frontal isentropes, especially in locating areas of higher potential temperatures in south central Iowa and southeastern Ohio and Indiana (Fig. 3.5).

Overall, the model is able to accurately simulate the synoptic-scale system and the associated cold frontal progression across the Great Lakes region. In both cases, the wind fields are accurately simulated and the locations of the low pressure centers and pressure troughs agree well with observations. Discrepancies that are apparent in both cases are that the model tends to over-intensify the synoptic system and generates a

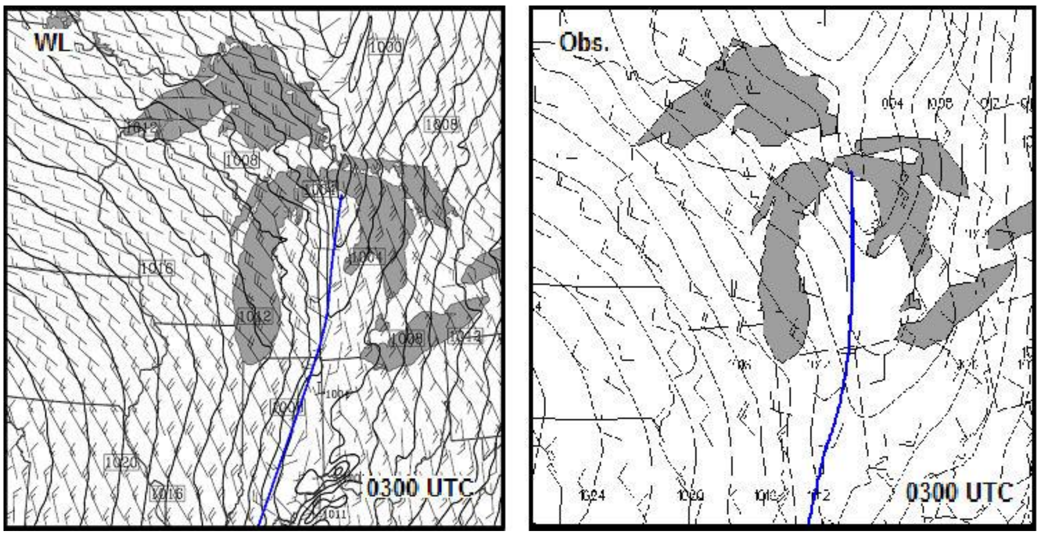

Figure 3.4 Surface analysis of sea-level pressure (interval 2 hPa), surface winds, and approximate frontal location at 0300 UTC 25 April 2002. (Left) Simulated results, (Right) Plymouth State College Weather Center archived data with NCEP analyzed frontal location. Thick blue line indicates approximate frontal location.

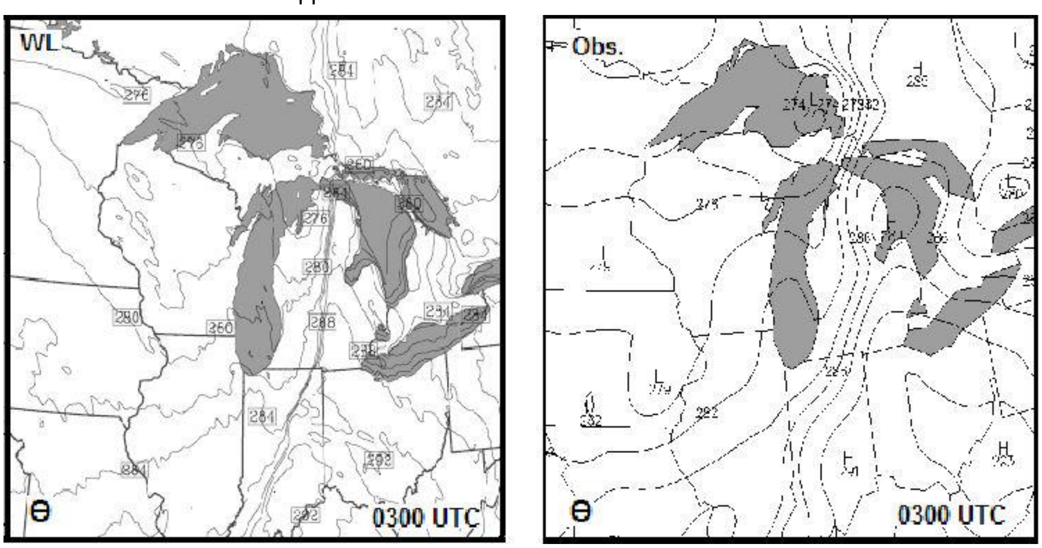

Figure 3.5 Surface analysis of potential temperature (interval 2^{o}C [2 K]) at 0300 UTC 25 April 2002. (Left) Simulated results, (Right) Plymouth State College Weather Center archived data.

stronger low pressure center than actually observed, but this issue does not significantly alter the frontal locations. The good agreement between observations and model results for the WL runs of both cases give credence to the comparisons between WL simulations and NL simulations.

3.3 *With Lake (WL) vs. No-Lake (NL) Simulations*

A comparison of WL and NL simulations is conducted in order to quantify the interactions between the frontal boundaries and the lake surface. NL simulations were accomplished by removing the Lake Michigan surface from the modeling domains by replacing the lake surface characteristics (temperature, moisture, roughness) with neighboring land surface values.

3.3.1 Case #1: 21 January 2004 – 22 January 2004

Figure 3.6 displays the sea-level pressure and wind fields for the WL and NL simulations from 2000 UTC 21 January 2004 to 0500 UTC 22 January 2004. One characteristic trait of this particular system is that at no time is a very strong pressure trough seen, or a dramatic wind shift, that usually defines the frontal location. Because of this, potential temperature (Fig. 3.7) discussed further below, was analyzed to better establish the location of the front, as advocated by Sanders (1999).

At 2000 UTC 21 April 2004 (8 hours after initialization of the model), the cold front is located over northwestern portions of Lake Michigan and stretches westward through Wisconsin for both WL and NL simulations (Fig. 3.6a,b). The relative intensities of the WL and NL pressure centers are almost exactly the same with no discernible difference in location of the low. It is evident from the figures that cold air is being advected strongly behind the front from the northwest. Also, warmer air is brought up ahead of the cold front in both simulations but with stronger low-level winds in the WL simulation, which can be attributed to lower surface roughness lengths associated with the lake surface.

At 0100 UTC, the frontal boundary has progressed over much of Lake Michigan in both simulations, but dramatic differences are evident (Fig. 3.6c,d). With the aid of the isentropic analysis (Fig. 3.7c) and cross sections of potential temperature (not shown), the WL front is located over the southern portion of Lake Michigan but has taken on a concave shape over the lake surface (Fig. 3.6c). The lake surface alters the progression of the WL front considerably. It can be seen that the NL front is able to pass over the modified Lake Michigan surface with relative ease, as the NL surface has the same characteristics as the adjacent land surface (Fig. 3.6d, Fig. 3.7d). It will be demonstrated later that the modification of the boundary-layer turbulent friction caused by increased surface fluxes of heat and moisture is the primary reason for the pronounced slowing of the frontal boundary over the lake.

At 0300 UTC, the WL and NL cold fronts have traversed the lake surface and are situated over the land just south and east of Lake Michigan (Fig. 3.6 e,f). The strength and intensity of the synoptic-scale system is very similar for the WL and NL simulations with only subtle differences seen between the two systems. The location of the front in the WL and NL simulations also shows good agreement except for the area around the southeast corner of Lake Michigan. The portion of the WL simulated front in northern Indiana and southwestern Michigan still exhibits a concave shape that extends back towards the lake surface (Fig. 3.6e). This feature can be easily seen in the potential temperature plot (Fig. 3.7e). The NL simulated front is, again, not affected by the lake surface and is able to progress easily over the lake at the same pace as over the adjacent land (Fig. 3.6f).

The frontal locations during the period can also be seen in vertical cross-sections of potential temperature across the lake surface (Fig. 3.8). The cross-sections were taken from point A to B in Fig. 3.1 for the inner domain simulations (D03, 2 km grid spacing). These cross-sections were chosen to be approximately perpendicular to the frontal boundary as it progressed across the lake. The lake surface is located from approximately grid point 25 to 130 in Fig. 3.8, with the arrows along the x-axis representing the analyzed location of the frontal boundary. The cross-sections of potential temperature were also utilized to supplement the surface potential temperatures (Fig. 3.7) used to analyze frontal location.

At 2300 UTC the WL and NL simulations have the cold front situated at approximately the same location (Fig. 3.8a,b). The leading edge of the cold fronts are at about grid point 37, or about 74 km into the cross-section. This shows that in the 11 hours simulated prior to the analysis of the cross-sections, there was virtually no difference in the speed of the front which will serve as a basis for comparison at later times.

By 0300 UTC, the cold front has progressed across the lake in both simulations and is making landfall over northern Indiana and western Michigan (Fig. 3.8c,d). The WL simulation reveals the front at approximately grid point 134 or about 268 km into the cross-section (Fig. 3.8c). Effects of the relatively warm lake surface can still be seen in the near surface isentropes, exhibiting a superadiabatic lapse rate, and in the greater depth of the near-neutral mixing layer. Increased turbulent mixing within the boundary layer has led to an overall decrease in the intensity across the leading edge of the cold front. The NL front is situated at approximately grid point 139 or about 278 km into the cross-section (Fig. 3.8d). The leading edge of the NL front shows very erect potential temperature isentropes gradually sloping back at about 600 m coinciding with an inversion that is lower than the WL inversion which is still at about 1200 m.

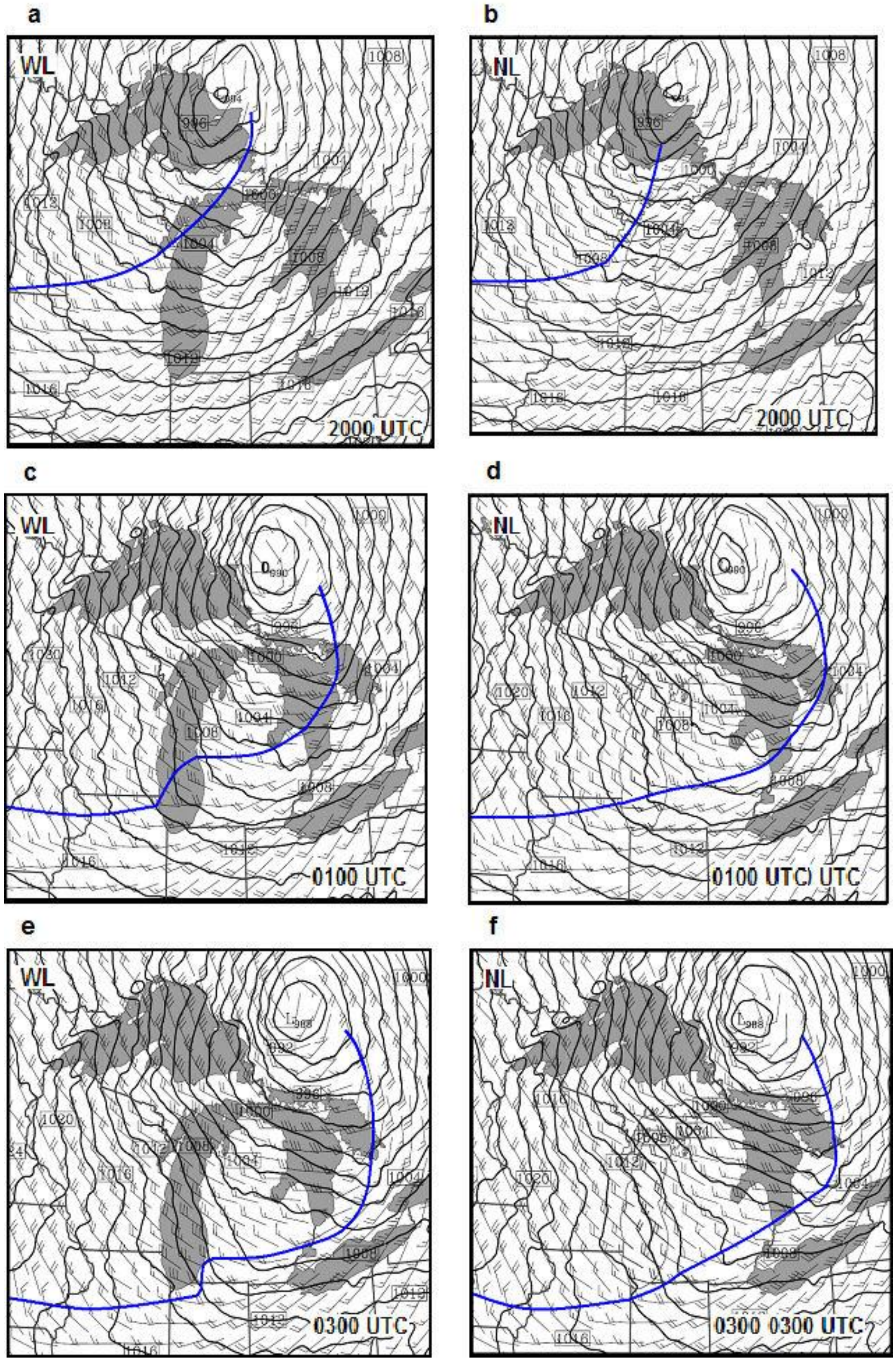

Figure 3.6 Simulated surface analysis of sea-level pressure (interval 2 hPa), surface winds, and approximate frontal location for the 21-22 January 2004 case. (a) 2000 UTC WL, (b) 2000 UTC NL, (c) 0100 UTC WL, (d) 0100 UTC NL, (e) 0300 UTC WL, (f) 0300 UTC NL.

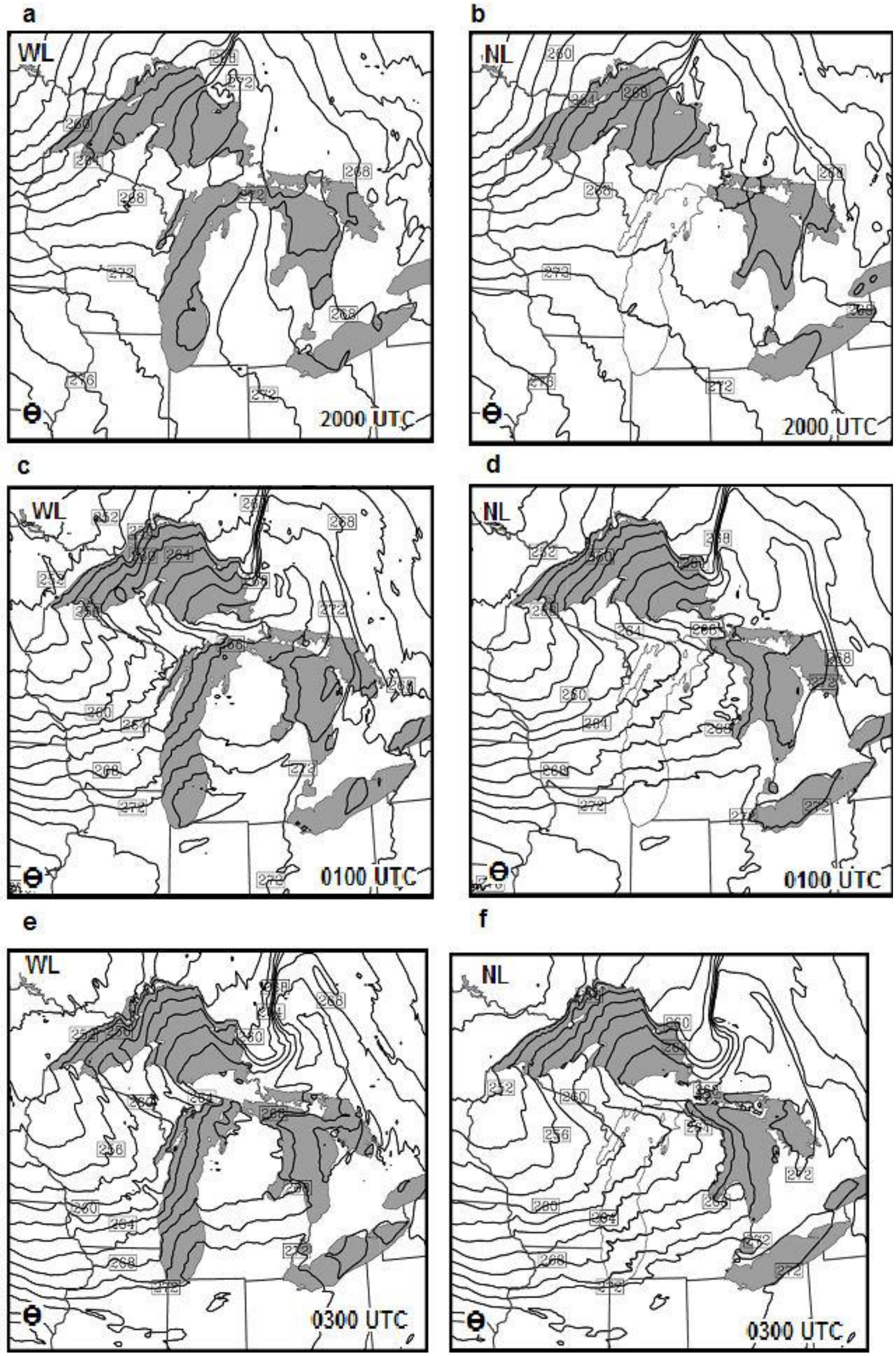

Figure 3.7 Surface analysis of potential temperature (interval 2^{o}C [2 K]) at (a) 2000 UTC WL, (b) 2000 UTC NL, (c) 0100 UTC WL, (d) 0100 UTC NL for the 21-22 January 2004 case, (e) 0300 UTC WL.

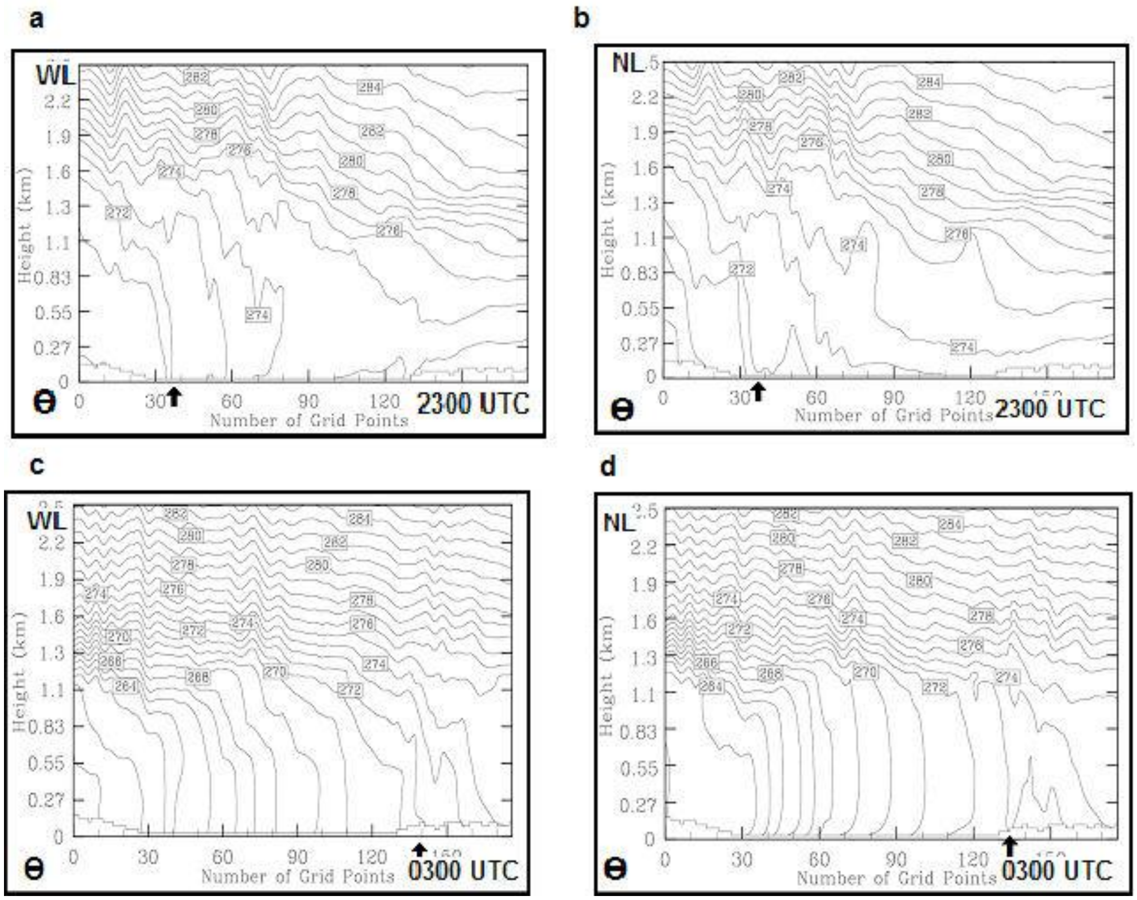

Figure 3.8 WRF inner domain (2 km) vertical cross-sections of potential temperature (interval $2^{o}C$ [2 K]) for 21-22 January 2004. Lake surface from approximately grid point 28 to 130. Black arrow denotes analyzed frontal location. (a) 2300 UTC WL, (b) 2300 UTC NL, (c) 0300 UTC WL, (d) 0300 UTC NL.

3.3.2 Case #2: 24 April 2002 – 25 April 2002

Figure 3.9 displays the sea-level pressure and wind fields for the WL and NL simulations from 2300 UTC 24 April 2002 to 0200 UTC 25 April 2002. Approximate cold frontal locations have been drawn with the aid of surface potential temperature contours (Fig. 3.10). At 2300 UTC 24 April 2002 (11 hours after simulation began), the cold front is located just over the western portion of Lake Michigan and stretches approximately through Chicago and Illinois for both the WL and NL simulations (Fig. 3.9a,b). However, the removal of Lake Michigan has slightly modified the intensity of the low pressure center for the NL simulation (Fig. 3.9b). The removal of the relatively cool lake allows the main surface low pressure system to strengthen slightly over northern portions of Lake Michigan, due to the warmer air temperatures over the region.

The surface potential temperature fields reveal a tight gradient stretching southwestward from the western shore of Lake Michigan at the border of Wisconsin and Illinois for both WL and NL simulations (Fig. 3.10a,b). The tight potential temperature gradient associated with the cold front becomes obscure over Lake Michigan in the WL simulation as the relatively cool lake surface creates an area of cool potential temperature. The pre-frontal southerly flow over the lake surface has advected relatively cool lake air over the Upper Peninsula of Michigan which has also caused the front to be hidden in that region (Fig. 3.10a). This effect is not evident in the NL simulation as the lake surface temperatures are relatively consistent with those over the adjacent land surface and thus allow the potential temperature gradient across the front to remain visible throughout the domain (Fig. 3.10b).

At 0000 UTC, the frontal boundary has moved over the central and eastern portions of Lake Michigan for both simulations (Fig. 3.9c,d). Only subtle differences are seen in the pressure troughs between the WL and the NL simulation. A slight bulge has developed in the cold front over the lake in the WL simulation. For the NL simulation, the frontal boundary appears to remain linear as it stretches along the long axis of the lake surface. The surface potential temperature analysis reveals a noticeable bulge in the WL frontal boundary over southern Lake Michigan related to the warm lake surface temperatures (Fig. 3.10c,d).

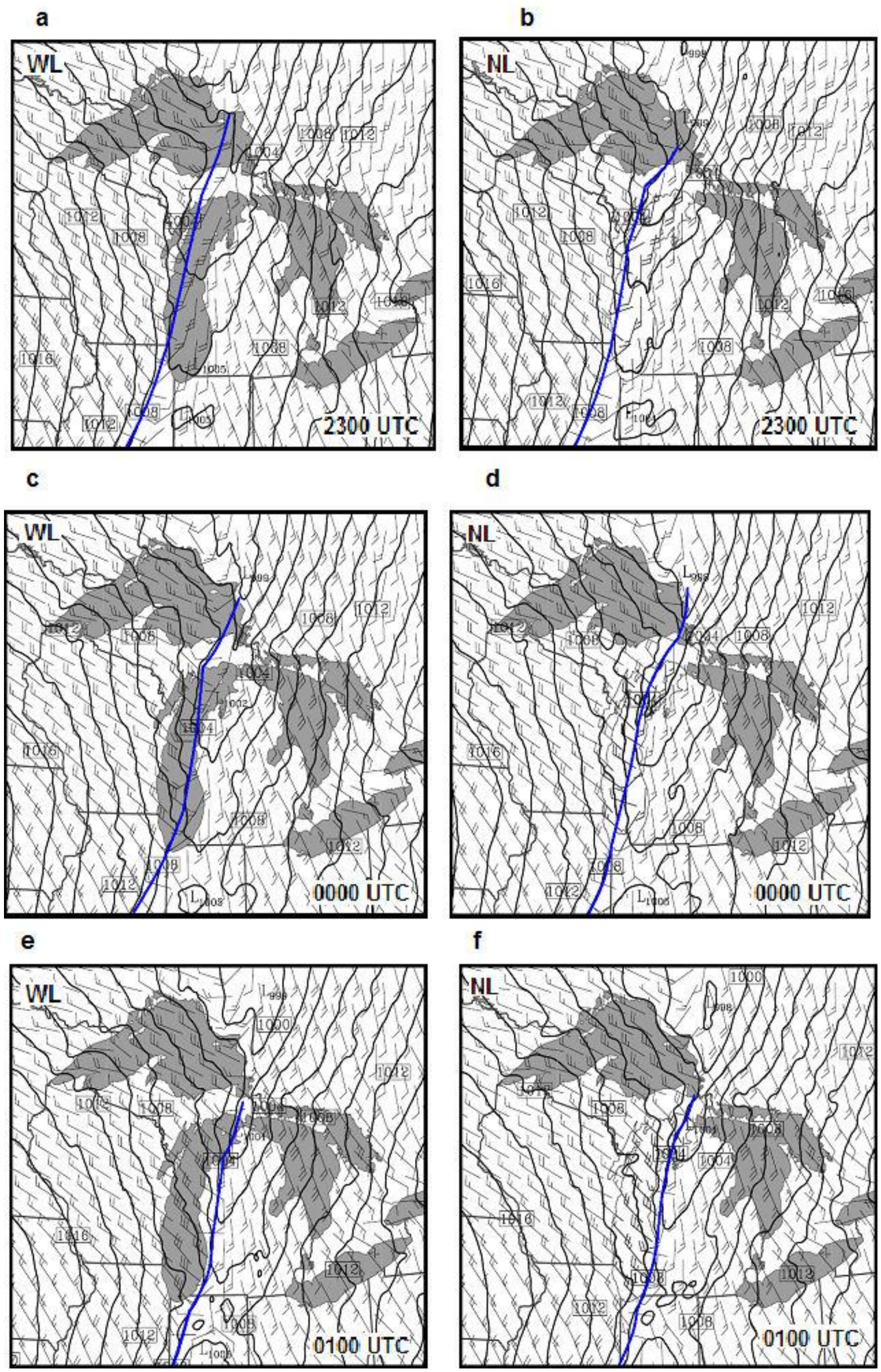

Figure 3.9 Simulated surface analysis of sea-level pressure (interval 2 hPa), surface winds, and approximate frontal location for the 24-25 April 2002 case. (a) 2300 UTC WL, (b) 2300 UTC NL, (c) 0000 UTC WL, (d) 0000 UTC NL, (e) 0100 UTC WL, (f) 0100 UTC NL.

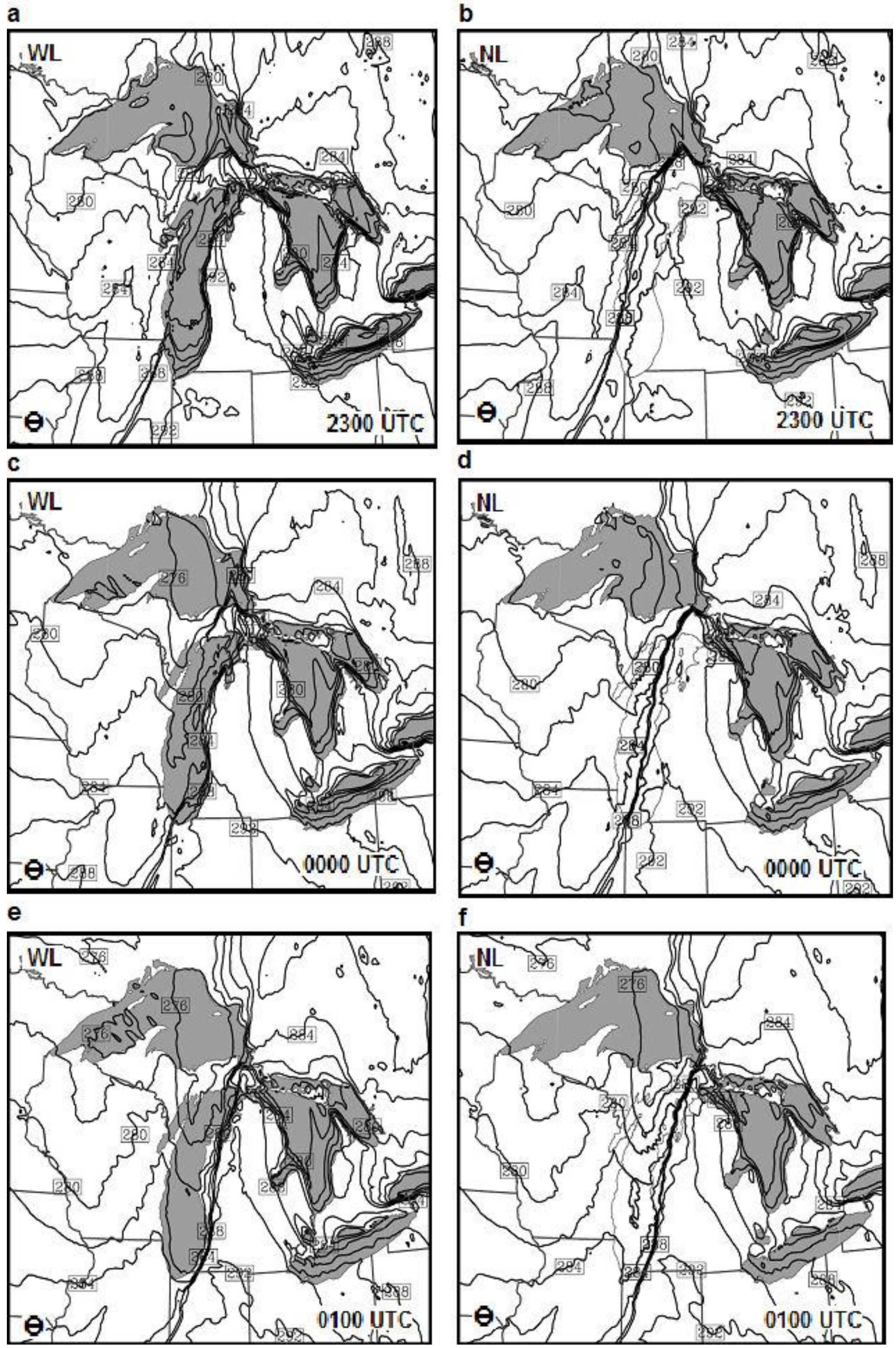

Figure 3.10 Surface analysis of potential temperature (interval $2^{o}C$ [2 K]) at (a) 2300 UTC WL, (b) 2300 UTC NL, (c) 0000 UTC WL, (d) 0000 UTC NL for the 24-25 April 2002 case, (e) 0100 UTC WL, (f) 0100 UTC NL.

The modification of the frontal boundary is more visible by 0100 UTC (Fig. 3.9e,f). While only subtle differences are evident in the pressure troughs between the WL and NL simulation, there are more pronounced variations in the frontal location. Both simulations indicate the frontal boundary is located over the eastern shores of Lake Michigan. The WL simulation reveals a noticeable acceleration of the portion of the front that has crossed the lake surface, while the NL simulated front remains fairly linear. This is best seen in the surface potential temperature analysis (Fig. 3.10e,f). A tighter potential temperature gradient exists over the southeastern shores of Lake Michigan in the WL simulation (approximately 0.53^{o}C per km) than in the NL simulation (approximately 0.30^{o}C per km). The tighter potential temperature gradient may be attributed to increased cold air advection in the air situated over the cold lake surface. By 0200 UTC, the cold front has moved entirely off of Lake Michigan and in both the WL and NL simulations it is located over central Michigan.

The frontal locations during the period can also be seen in vertical cross sections of potential temperature across the lake surface (Fig. 3.11). The cross sections were taken from point C to D in Fig. 3.1, and were chosen to be perpendicular to the frontal boundary in order to best depict the movement of the boundary across the lake. These cross-sections were taken from the inner domain simulations (2 km grid spacing). The lake surface is located from approximately grid point 5 to 68 in Fig. 3.11, with the arrows along the x-axis

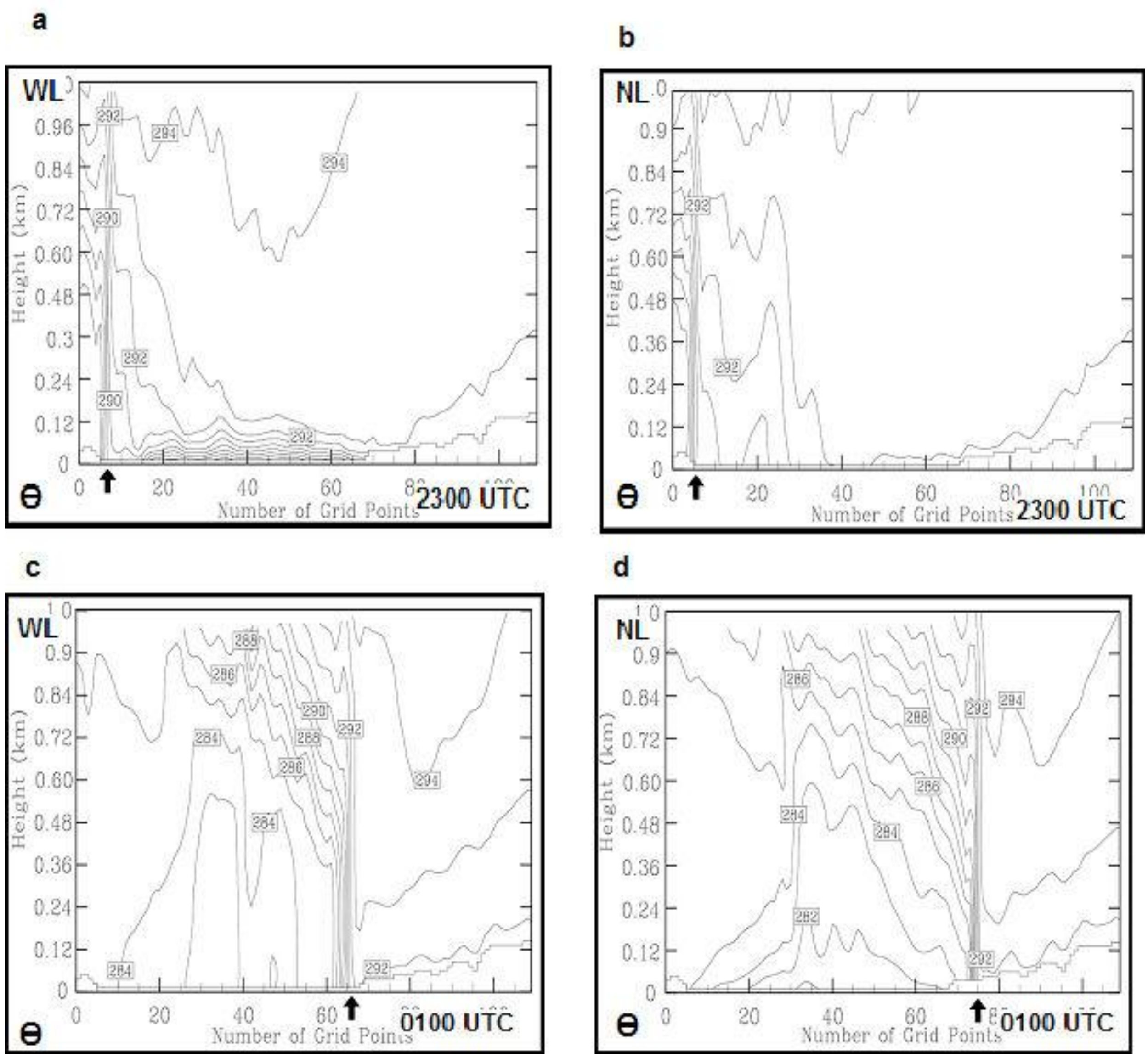

Figure 3.11 WRF inner domain (2 km) vertical cross-sections of potential temperature (interval 2^{o}C [2 K]) for the 24-25 April 2002 case. Lake surface from approximately grid point 5 to 68. Black arrow denotes analyzed frontal location. (a) 2300 UTC WL, (b) 2300 UTC NL, (c) 0100 UTC WL, (d) 0100 UTC NL.

noting the analyzed location of the frontal boundary. Additional cross-sections of potential temperature (not shown) were also utilized to supplement the surface potential temperatures (Fig. 3.10) used to analyze frontal locations.

At 2300 UTC, the WL simulation reveals a thermally-stratified layer extending to approximately 120 m above the surface (Fig. 3.11a,b). This is evidence of the lake surface temperatures remaining much cooler than the adjacent land around the lake, and is not seen in the NL simulation. In both simulations the front appears to arrive at the western shores of Lake Michigan at the same time. This shows that in the 11 hours simulated 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 later times.

At 0000 UTC (not shown), both simulations appear to have the fronts over the central portions of Lake Michigan, but there are considerable differences between the WL and NL runs. The WL simulation has moved the frontal boundary to approximately gridpoint 43, located about 86 km into the cross-section, while the NL simulation puts the frontal boundary at approximately grid point 35 or about 70 km into the cross-section. The WL simulation appears to be heavily influenced by the stable layer that exists directly over the lake surface, which allows the front to become at least partially decoupled from the surface. It appears that because the WL front largely passes over the top of the near-surface stable layer, the winds behind and ahead of the frontal interface are increased. Increasing the winds means increasing cold air advection behind and warm air advection ahead of the front. The increased cold and warm air advection results in a larger temperature gradient across the front which ultimately leads to a faster progression of the front across the lake.

At 0100 UTC, dramatic differences between the WL and NL simulations are evident (Fig. 3.11c,d). The WL simulation locates the front approximately at grid point 75, about 150km into the cross-section and over portions of western Michigan (Fig. 3.11c). The NL simulation places the front approximately at grid point 66 or about 122 km into the cross-section and still over the eastern portion of the lake surface (Fig. 3.11d). The relative intensities of both fronts appear to be dramatically altered as well, as the WL simulation's temperature gradient is approximately $1^{o}C\ km^{-1}$ and the NL simulation's temperature gradient approximately $0.7^{o}C\ km^{-1}$ across the frontal boundaries.

3.4 *Variation of Lake Surface Roughness*

Another model run, designated by RO, was conducted for each of the two cases in which the surface characteristics of the Great Lakes water surface were changed to test the sensitivity of cold frontal movement to roughness. The purpose for altering this roughness value of the lake surfaces was to distinguish between the effects of lake-land temperature difference from those due to surface roughness as discussed by Gallus and Segal (1999). For the RO simulation, the time varying roughness lengths over the Great Lakes was modified to be similar to surrounding land points. This implies that as the respective frontal boundaries move across the region, there should be no significant differences in surface roughness between water and land, which points to the lake-land temperature (and moisture) difference as the only factor influencing the front. The modified roughness lengths over water, as chosen for this sensitivity test, were 0.2 m which is representative of the roughness lengths of woodland/ cropland land use categories that are prevalent around Lake Michigan. Typical values for water roughness length vary between 0.001-0.01 m, and are dependent on wind speed and stability within the boundary layer.

3.4.1 Case #1: 21 January 2004 – 22 January 2004

Comparison of results from the RO sensitivity test with the original WL simulation show considerable agreement. The WL and RO simulations exhibited small differences in the sea-level pressure and surface wind fields. The location of the low pressure center in the RO simulation is slightly northward of its location in the WL simulation, as well as deepened by about 2 hPa. Also, the surface winds over Lake Michigan are less intense than those in the WL simulation. There are also several modifications to the front as it progresses across Lake Michigan. Figure 3.12 shows vertical cross-sections for the WL and RO simulations from 2300 UTC 21 January 2004 to 0300 UTC 22 January 2004. The cross-sections were taken from point A to B in Figure 3.1.

At 2300 UTC the WL simulation has the frontal boundary at approximately grid point 37 or about 74 km into the cross-section (Fig. 3.12a). The RO simulated cold front 600 m above the surface is located at approximately grid point 45 or about 90 km into the cross-section (Fig. 3.12b). The RO cold front does, however, stretch backwards near the surface to approximately the same location as the WL cold front. Thus the surface fronts are located in about the same place.

As the fronts progress over the lake, the RO simulated front progresses slower than the WL front owing to the fact that increased surface roughness generates increased heat and moisture fluxes that act to weaken and retard the progression of the cold front. Effects of the enhanced mixing within the boundary layer are also evident in the boundary layer depth. The WL simulated boundary layer depth is about 1300 m, while the RO simulated boundary layer depth has deepened to about 1700 m as a direct result of increased turbulent mixing.

By 0300 UTC, differences between the WL and RO fronts have become exacerbated as the WL front has made landfall and the RO front is still progressing slowly over the lake surface (Fig. 3.12c,d). WL simulation has the front at approximately grid point 134 or about 268 km into the cross-section (Fig. 3.12c). The WL front is able to progress about 58 km in one hour while the RO front only progresses about 32 km to approximately grid point 96 (Fig. 3.12d). Another interesting characteristic evident in the RO front is that the surface front trails the front aloft (600 m above surface) by about 38 km and the difference continues to grow due to the enhanced surface roughness.

Overall, this sensitivity study implies that the 21-22 January 2004 cold front is affected by an increase in surface roughness and a subsequent alteration of the near-surface turbulent friction. The RO front progresses considerably slower across the lake than the WL front. This suggests that a cold front progressing over a relatively warm lake surface is modified at least in part by the decreased surface roughness.

3.4.2 Case #2: 24 April 2002 – 25 April 2002

Comparison of the RO results with the WL simulation show agreement. Analysis of Sea-level pressure and surface winds indicate no discernible difference between the WL and RO simulated pressure fields, and only slight differences in the surface wind fields (not shown). Subtle differences are seen in the intensity of the surface winds between WL and RO simulations, which makes sense as air flow is inhibited by the increased roughness. There are also several modifications to the front as it crosses Lake Michigan. Figure 3.13 shows vertical cross-sections for the WL and RO simulations from 2300 UTC 24 April 2002 to 0200 UTC 25 April 2002. The cross sections were taken from point C to D in Fig. 3.1.

At 2300 UTC the WL simulation has the frontal boundary at approximately 7 grid points or 14 km into the cross-section with a thermally-stratified stable layer over the lake about 120 m deep (Fig. 3.13a). However, altering the surface roughness length over Lake Michigan has modified the depth of the stable layer, to approximately double that of the WL simulation (Fig. 3.13b). This can be attributed to the enhanced near-surface mixing of the cool air over the surface of the lake. The RO simulation also places the frontal boundary at approximately 7 grid points or 14 km into the cross-section, which verifies well with the WL simulation.

At 0100 UTC, both simulations have the frontal boundaries in approximately the same location, over western Michigan and off of the Lake Michigan surface (Fig. 3.13c,d). The WL simulated front is found at

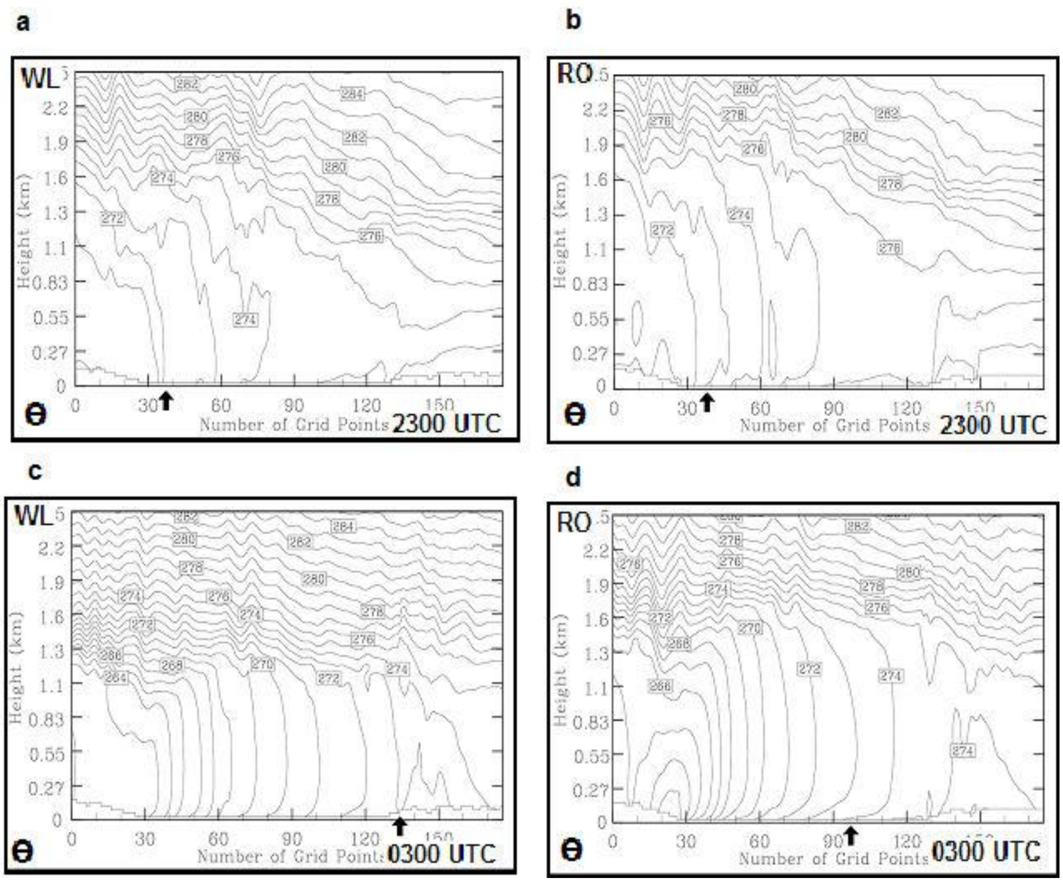

Figure 3.12 WRF inner domain (2 km) vertical cross-sections of potential temperature (interval 2^{o}C [2 K]) for the 21-22 January 2004 case. Lake surface from approximately grid point 28 to 130. Black arrow denotes analyzed frontal location. (a) 2300 UTC WL, (b) 2300 UTC RO, (c) 0300 UTC WL, (d) 0300 UTC RO.

approximately grid point 75, or about 150 km into the cross-section (Fig. 3.13c). The RO simulation locates the front at approximately grid point 74 or about 148 km into the cross-section (Fig. 3.13d). The relative intensities of the WL and RO simulated cold fronts are comparable with both being approximately $1^{o}C\ km^{-1}$ across the front.

Overall, this sensitivity study implies that the 24-25 April 2002 cold front is only slightly affected by an increase in surface roughness. The WL front accelerates slightly ahead of the RO front, but not as much as in the comparison between the WL and NL simulations.

3.5 *Variation of Lake Surface Temperatures*

To complement the RO simulations, another test, designated by TC, was conducted in which the surface skin temperatures of Lake Michigan were modified. The purpose for altering the temperature of the lake surface was to distinguish between the effects of surface roughness lengths described above to those induced by lake-land temperature differences. For the TC experiment, the sea-surface temperatures over Lake Michigan were modified from the GLERL data to be similar to the surrounding land points. This implies that as the respective frontal boundaries move across the region, there should be no differences in surface skin temperature between water and land. The lake surface skin temperatures for this test were reduced by $15^{o}C$ for the 21-22 January 2004 case and increased by $15^{o}C$ for the 24-25 April 2002 case. These temperature modifications were chosen by finding the approximate average lake-land temperature difference an hour before the frontal boundaries came into contact with Lake Michigan.

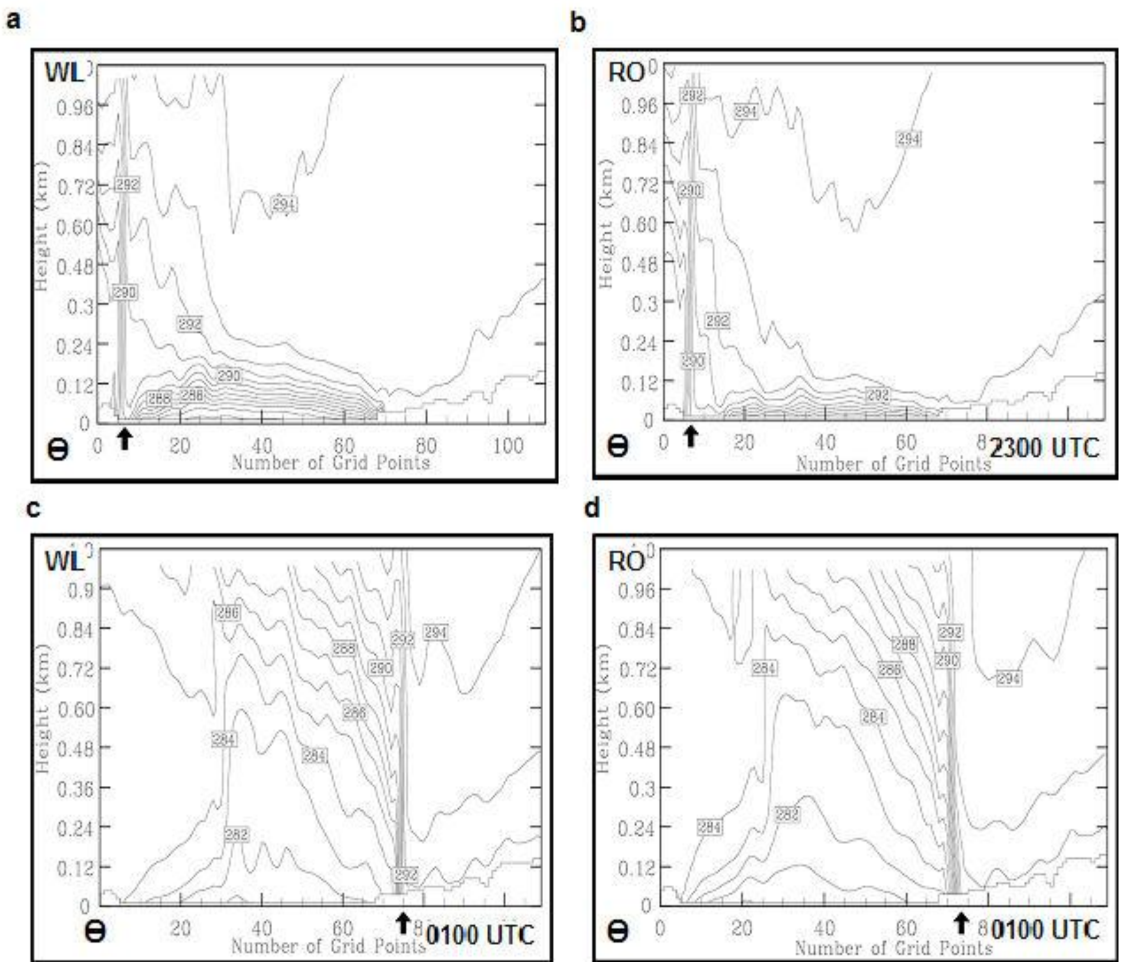

Figure 3.13 WRF inner domain (2 km) vertical cross-sections of potential temperature (interval $2^{o}C$ [2 K]) for the 24-25 April 2002 case. Lake surface from approximately grid point 5 to 68. Black arrow denotes analyzed frontal location. (a) 2300 UTC WL, (b) 2300 UTC RO, (c) 0100 UTC WL, (d) 0100 UTC RO.

3.5.1 Case #1: 21 January 2004 – 22 January 2004

F0r the 21-22 January 2004 case, the 15°C decrease in lake surface temperature over the Great Lakes results in surface temperatures of Lake Michigan falling below the freezing point for water. In this case, the ice-free portions of the Lake Michigan surface remain ice-free while cooler than the actual freezing point. This is physically unrealistic, but it provides a means of reducing the heat and moisture fluxes from the lake surface and permits examination of their impact on frontal properties. The goal was to ensure that the lake temperatures do not differ dramatically from those over the adjacent land. Comparison of results from the sensitivity test to the original WL simulation show considerable agreement. Sea-level pressure fields are consistent between the two simulations, but the TC surface winds are much weaker over the lake than the WL surface winds (not shown). There are also several differences in the frontal boundary as it progresses across Lake Michigan. Figure 3.14 is a comparison of vertical cross-sections for the WL and TC simulations from 2300 UTC 21 January 2004 to 0300 UTC 22 January 2004. The cross-sections were taken from point A to B in Fig. 3.1.

At 2300 UTC the WL simulation again has the frontal boundary at approximately grid point 37 or about 74 km into the cross-section (Fig. 3.14a). The TC simulation (Fig. 3.14b) has the position of the front almost identical to the WL simulation. A very shallow stable layer is seen over the right side of the TC cross-section corresponding to a relatively cooler stretch of the lake surface. This will ultimately lead to modification of the boundary layer structure as well as the overall progression of the frontal boundary.

By 0300 UTC, both simulated frontal boundaries are situated over land, having completed their progression across the lake (Fig. 3.14c,d). The WL front is located at approximately grid point 134, or about 268 km into the cross-section. The TC front has progressed farther, to approximately grid point 143, or about 286 km into the cross-section. This difference verifies the effects of the lake-land temperature differences on the passage of a cold season cold front. The boundary layer over the lake in the WL case is deeper and strongly unstable, while in the TC simulation it is weakly stable.

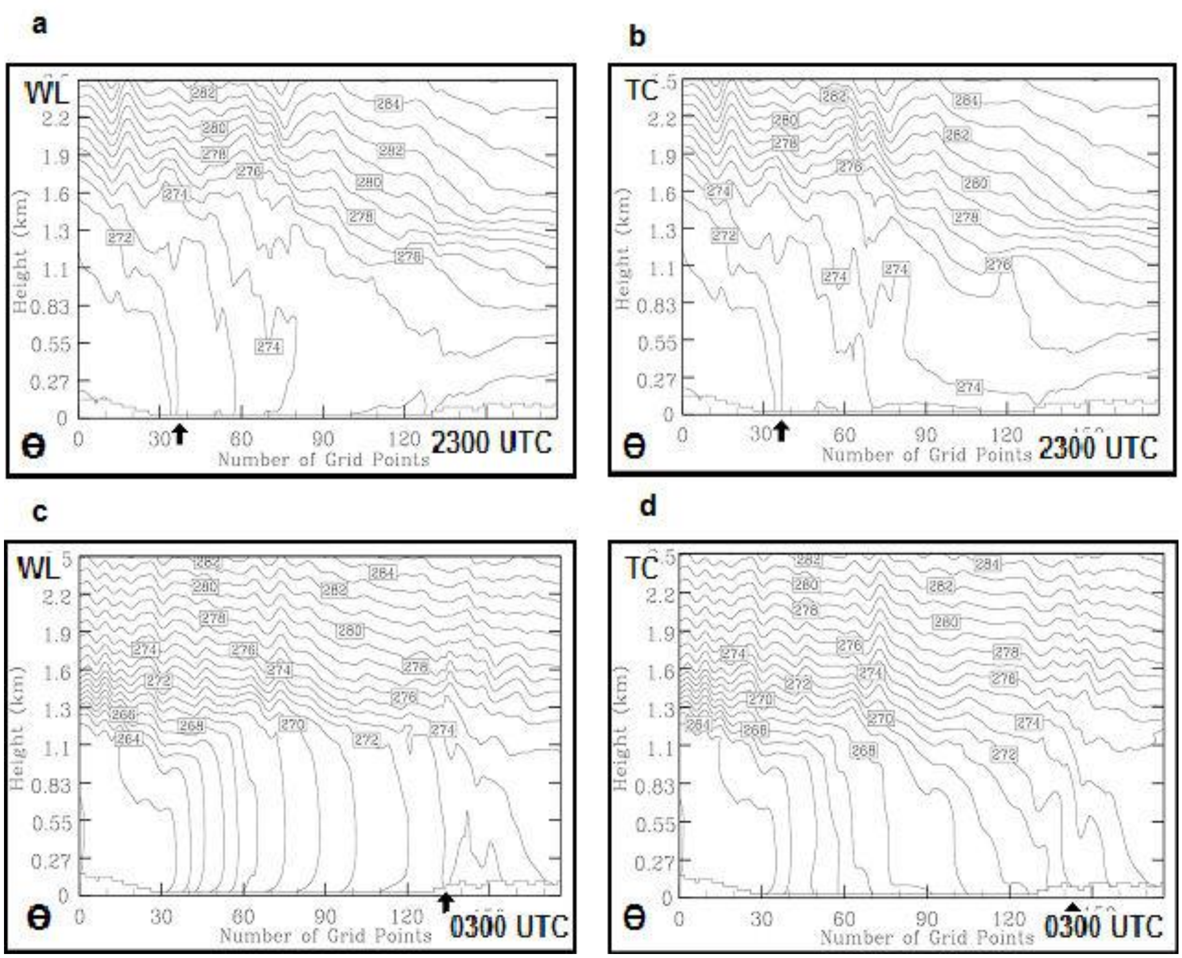

Figure 3.14 WRF inner domain (2 km) vertical cross-sections of potential temperature (interval 2°C [2 K]) for the 21-22 January 2004 case. Lake surface from approximately grid point 28 to 130. Black arrow denotes analyzed frontal location. (a) 2300 UTC WL, (b) 2300 UTC TC, (c) 0300 UTC WL, (d) 0300 UTC TC.

Overall, this sensitivity study implies that the 21-22 January 2004 cold frontal passage is affected by the temperature difference between the relatively warm lake and colder adjacent land surface.

3.5.2 Case #2: 24 April 2002 – 25 April 2002

Comparison of results from the TC test with the WL simulation show considerable agreement. Sea-level pressure and surface wind fields indicate some differences evident between the two simulations. The TC simulation produces a slightly deeper trough over the Lake Michigan surface than the WL simulation. This is caused by the elevated surface skin temperatures allowing the trough of low pressure to extend over the lake surface. The wind field is also slightly modified over the lake surface as the winds are 1 1/2 times more intense in the TC simulation than in the WL simulation. This can be attributed to the intensification of the low pressure center and the associated pressure trough. The TC simulation develops a secondary low pressure center over Michigan after the cold frontal passage.

Other modifications to the structure and speed of the front can be seen as the front progresses across Lake Michigan. Figure 3.15a,b is a comparison of vertical cross-sections for the WL and TC simulations from 2300 UTC 24 April 2002 to 0200 UTC 25 April 2002. The cross-sections are taken from point C to D shown in Fig. 3.1.

At 2300 UTC the WL simulation has the frontal boundary at approximately 7 grid points or 14 km into the cross-section, and a thermally-induced stable layer over the lake that is about 120 m deep (Fig. 3.15a). Altering the surface skin temperatures over the lake surface modifies the near-surface characteristics over the lake surface. The TC simulation positions the front in a similar location to the WL simulation, at about 7 grid points or 14 km into the cross-section, but has no stable layer near the surface (Fig. 3.15b). This is to be expected as the frontal boundary should experience similar lake surface skin temperatures to those seen over the surrounding land.

As the fronts progress across Lake Michigan they exhibit substantial differences. The frontal boundary in the WL simulation moves faster than in the TC simulation, and the TC front weakens significantly from when it started across the lake. This is due to the increased heating and moistening ahead of the front and the absence of a near-surface stable layer that allows the WL simulated front to ride up and over. Increased heat and moisture fluxes in the TC case generate more near-surface turbulent friction which both slows the progression of the front and weakens the front through reduced warm and cold air advection.

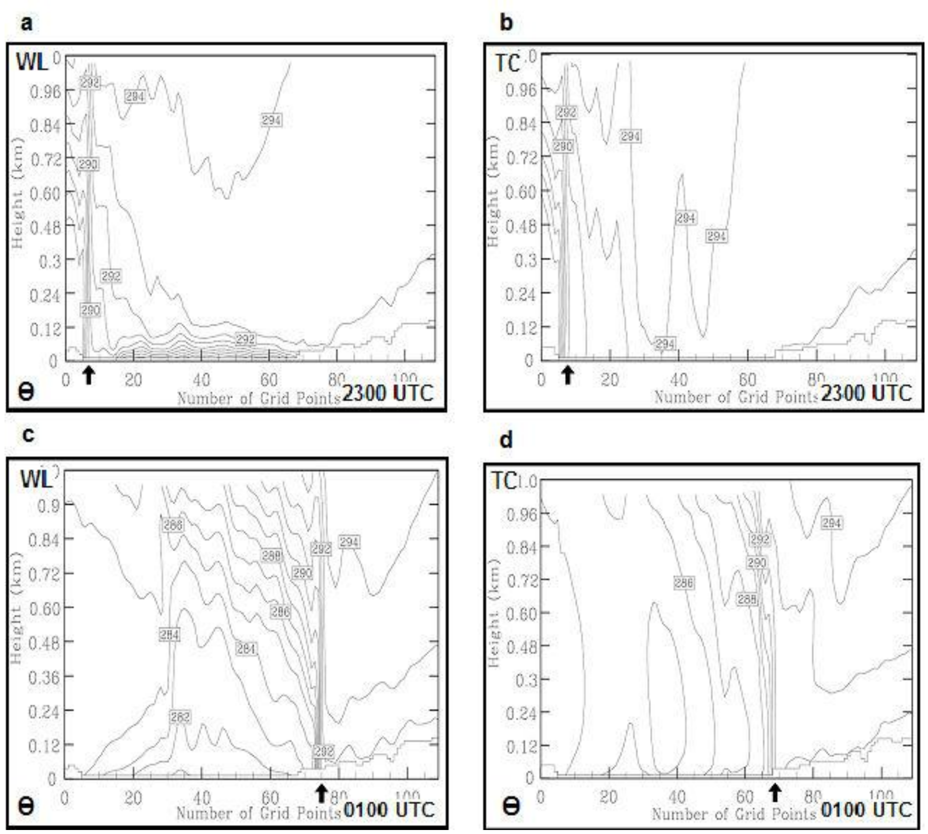

Figure 3.15 WRF inner domain (2 km) vertical cross-sections of potential temperature (interval 2^{o}C [2 K]) for the 24-25 April 2002 case. Lake surface from approximately grid point 5 to 68. Black arrow denotes analyzed frontal location. (a) 2300 UTC WL, (b) 2300 UTC TC, (c) 0100 UTC WL, (d) 0100 UTC TC.

At 0100 UTC, the WL and TC simulated fronts have progressed eastward at varying rates (Fig. 3.15c,d). The WL simulation again has the front at approximately grid point 75, or about 150 km into the cross-section and entirely over Michigan (Fig. 3.15c). The TC simulation places the front around the eastern coastline of Lake Michigan at approximately grid point 69 or about 138 km into the cross-section (Fig. 3.15d). Again, the relative intensities of the WL and TC fronts are significantly different. The WL front's temperature gradient is roughly $1^{o}C\ km^{-1}$ while the TC front's gradient has weakened to approximately $0.5^{o}C\ km^{-1}$.

4. DISCUSSION

The previous sections discussed observations and numerical simulations of the passage of two fronts across Lake Michigan. A cold season case was chosen from 21-22 January 2004 to represent a typical lake-effect snow producing cold frontal passage over a relatively warm lake surface. A warm season case was chosen from 24-25 April 2002 to represent a typical spring time convective precipitation event interacting with a relatively cool lake surface. Based on observations and numerical simulations, Lake Michigan had an impact on both cold fronts.

Comparison of the WL simulations and observations indicated the model was able to accurately simulate the progression of both fronts as they traversed over the Lake Michigan surface. Only subtle differences could be discerned between the simulations with Lake Michigan present and the observations.

A brief summary of each of the case study comparisons of frontal speed, structure and associated precipitation are provided in Tables 4.1 and 4.2. Numerical simulations of the 21-22 January 2004 cold season event with and without the presence of Lake Michigan revealed that the lake-enhanced heating of the boundary layer was responsible for slowing and weakening the cold front and ultimately led to increased precipitation downwind of the lake. Similar simulations of the 24-25 April 2002 warm season event showed that a lake-induced stable layer was responsible for modifying the near-surface roughness and ultimately increasing the speed and strength of the cold front with decreased post-frontal precipitation over the lake surface.

Model simulations identified the thermally-induced turbulence as the primary mechanism for the slowing and weakening of the 21-22 January 2004 cold front as it progressed over a relatively warm lake surface. This effect would be most pronounced in late autumn and winter when the lake remains much warmer than the surrounding land and primarily ice-free. As the winter season progresses and more ice coverage is seen, the effects of the lake surface would possibly be diminished and could present other alterations (surface roughness of ice). Simulations of the 24-25 April 2002 cold front passing over a relatively cool lake surface identified a reduction in buoyancy-generated turbulence and resulting reduction in near-surface friction as the primary mechanism for increasing the speed and intensity of the cold front. This effect would be most pronounced in late winter and springtime when the lake remains much cooler than the surrounding land, as long as the lake remains primarily ice free.

Table 4.1 Comparison of frontal speed, frontal structure, and associated precipitation for simulations of the 21-22 January 2004 case.

21-22 Jan. 2004	Frontal Speed	Frontal Structure	Associated Precipitation
WL vs NL	WL < NL	WL steeper than NL	WL > NL
WL vs RO	WL > RO	WL less steep and shallower than RO	negligible
WL vs TC	WL < TC	WL slightly deeper than TC	WL > TC

Table 4.2 Comparison of frontal speed, frontal structure, and associated precipitation for simulations of the 24-25 April 2002 case.

24-25 April 2002	Frontal Speed	Frontal Structure	Associated Precipitation
WL vs NL	WL > NL	WL more intense than NL	WL > NL at frontal boundary, NL > WL post-front
WL vs RO	WL > RO	RO has deeper near surface stable layer than WL	negligible
WL vs TC	WL > TC	WL more intense than TC	WL > TC at frontal boundary, TC > WL post-front

Results of this study point to several modifications on mesoscale features of larger scale systems caused by varying surface characteristics. This implies that cold fronts, as well as other synoptic-scale features, may be drastically altered by other regions with transitions in large scale surface characteristics.

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