

A Case Study of Great Lakes Aggregate Effects on Lake-Effect Snow in Michigan

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ABSTRACT

The Penn State University/National Center for Atmospheric Research mesoscale numerical model is used to assess wintertime effects of the Great Lakes aggregate on lake-effect snowstorms (LESSs) during a selected cold air outbreak. A simulation including only Lake Michigan (ML) is performed and compared to previously performed simulations that included all of the lakes (WL) and none of the lakes (NL). While previous comparison of the WL and NL simulations identified a large lake aggregate scale disturbance that developed in response to forcing from all of the lakes over a 1-2 day period and that affected weather on the synoptic-scale, it did not assess in detail the specific impacts on accompanying, small-scale LESSs.

Lake aggregate impacts on LESSs near Lake Michigan are assessed more quantitatively by comparison of the WL and ML simulations. This comparison suggests that, for the event examined, the lake aggregate enhances lake-effect snow in the northwestern part of the lower peninsula of Michigan but diminishes lake-effect snow in the southwestern part. The effects are likely the result of changes in fetch, boundary layer wind, temperature, and moisture characteristics.

Current LES forecasting techniques do not account for lake aggregate circulations. Thus, the locations where heavy snowbands develop may change and cause unexpected hazards.

Key Words: lake-effect, snow, aggregate, Great Lakes.

INTRODUCTION

The sensitivity of lake-effect snowstorms (LESSs) to environmental conditions has long been known. Mitchell (1921) noted early that wind direction determines the fetch and thus to a significant degree the modification of polar or arctic air by underlying warm lakes. Long fetches usually result in heavy snowfalls. Short fetches also may produce significant snowfalls if the pre-lake-modified air is relatively unstable, if the lake-shore geometry enhances radial convergence, or if the nearby orography enhances lifting (Lavoie 1972).

Numerous studies since Mitchell (1921) have focused on other aspects of LES wind sensitivity. Rothrock (1969) examined storms in the vicinity of Lake Superior and found empirically that a geostrophic wind speed exceeding 5 ms^{-1} was required for significant LESSs (e.g., $> 5 \text{ cm}$ snow on the south shore within 24 hours) to develop. Kelly (1986) determined that, when the wind direction across Lake Michigan is between WSW and NNW, multiple bands develop 2-20 km apart and align themselves parallel to the wind. These results were confirmed theoretically by Hsu (1987), who used a linear analytic model and a nonlinear numerical model to study the effects of uniform wind direction on LESSs near Lake Michigan. His results indicated that three convergence centers develop near the eastern shore when a westerly wind prevails, two cells or snow bands develop when a northwesterly wind prevails, and one mid-lake band develops when a northerly wind prevails.

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Hjelmfelt (1990) verified numerically the observational results that Forbes and Merritt (1984) found regarding the impact of wind direction on storm morphology. Hjelmfelt (1990) also determined that as the wind over Lake Michigan becomes more northerly and less westerly, the regions of convergence shift away from the eastern shore and towards the center of the Lake. The results obtained very recently (e.g., Reinking, et al. 1993) during the Lake Ontario Winter Storms (LOWS) project indicate similar findings. For Lake Ontario, however, it is a westerly wind that yields a single mid-lake band, with northwesterly and southwesterly winds producing multiple bands.

The vertical structure of the environmental wind also affects LESs. Niziol (1987) found empirically, over many years of operational forecasting, that for a prevailing wind parallel to the long axis of Lake Erie, moderate directional shear (e.g., between 30° and 60°) from the surface to 700 mb causes multiple snow bands rather than a single snow band to occur. He also found that stronger shear (e.g., greater than 60°) over the Lake causes the breakdown of precipitating snowbands altogether. The stronger shear causes instead the development of a non precipitating stratocumulus deck.

Regarding the LES sensitivity to temperature and its vertical structure, Rothrock (1969) concluded empirically (based on thirty cases) that a minimum temperature difference of 13°C between the lake surface and the upstream airflow at 850 mb is required for LESs to develop, which means that the layer of air must be at least neutrally stable. He also concluded that any temperature inversions that may exist within the unmodified upwind air must be above one kilometer.

Niziol (1987) noted empirically that the height and the strength of the (capping) inversion are significant limiting factors to cloud depth and therefore to precipitation. He also noted that the most convectively active LESs have inversion heights exceeding three kilometers and that sometimes the capping inversion is entirely absent. During such cases, thunder and lightning typically accompany copious (e.g., exceeding 10 cm hr⁻¹) snowfall rates. Hjelmfelt (1990) also examined numerically the effects of stability on LESs and confirmed earlier hypotheses about the limiting capabilities of low-level inversions.

While a long list of studies has documented the sensitivity of LESs to large-scale environmental conditions, few studies have focused on the causes for changes in these environmental conditions. A

major cause of changes may be the Lake aggregate (defined as the five major Great Lakes) itself.

Lake-aggregate effects have been defined recently by Sousounis and Fritsch (1994) as meso- α scale changes in any atmospheric field such as pressure, temperature, or wind that are the result of heating and moistening by the Great Lakes. It is likely that the lake aggregate may affect LESs for a variety of reasons; not only because it may alter prevailing wind speed, direction, and vertical structure, but also because it may alter boundary layer stability, inversion height and strength. The aggregate effect when fully developed may pose unexpected hazards because current forecasting techniques (e.g., Niziol 1987, Burrows 1991) do not incorporate it.

The purpose of this study is to address more explicitly some of the lake aggregate impacts on LESs in Michigan, so that ultimately they may be incorporated into LES forecasting strategies. The study is organized as follows: (1) An overview is given of the synoptic-scale aspects of the cold air outbreak that was examined by Sousounis and Fritsch (1994), (2) A comparison of WL and ML simulations is performed to demonstrate that winds across the Lake Michigan shore regions were influenced from the combined heating effect of the lake aggregate rather than from just Lake Michigan alone, (3) An explanation of how the lake aggregate affects LESs is provided, and (4) A summary and conclusions are presented.

OVERVIEW OF SYNOPTIC SCALE EVENTS DURING 00Z 13-15 NOVEMBER 1982

The case examined by Sousounis and Fritsch (1994) spanned 48 hours beginning 0000 UTC 13 November 1982 and included a 12 h *cold air outbreak* period during which time cold air became established over the Lakes region, and a subsequent 36 h *recovery* period during which time relatively cold air remained over the Lakes region. The case is described more thoroughly by Sousounis and Shirer (1992). The reasons for selecting it included: (1) exceptionally cold air for mid-November; (2) slow air-mass progression (allowing for an extended period of air-lake interaction); and (3) lack of upper-level support during surface development of a mesoscale low over the Great Lakes.

Extreme cold (e.g., -27°C at nearby Canadian stations) at the start of the period coupled with relatively warm lake surfaces (e.g., 5-6°C for Lake Superior and 9-10°C for Lake Erie) created lake-air temperature differences exceeding 30°C. As a

result, combined sensible and latent heat fluxes from the lake surfaces within the northwest flow behind the exiting synoptic-scale low were very strong ($> 1000 \text{ W m}^{-2}$). A high pressure system maintained cold air over the Great Lakes region for more than 48 h as it slowly shifted eastward. Surface pressures over the western portion of the Lakes region remained relatively low and the flow continued to be cyclonic even though an upper level ridge and relatively cold air were building into the region. A noticeable lag existed in the eastward advance of the surface isotherms (not shown) over the Lakes region compared to areas farther south and east.

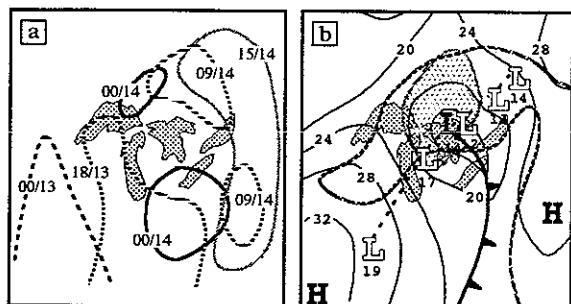


Figure 1. Evolution of synoptic-scale events. (a) Positions of 1028 mb isobar for UTC times shown (hour/day). (b) Positions and intensities of synoptic-scale low every six hours from 1200 UTC 14 - 1800 UTC 15 Nov 82. Isobars (thin curves), positions of high and low centers (bold), and region of active precipitation (shaded) are valid for 0000 UTC 15 Nov 82. Heavy curve shows area with measurable precipitation during the 30 hour period.

Two synoptic-scale effects were observed. Figure 1a presents the temporal evolution of the 1028 mb isobar during the 48 h period of interest. The analysis suggests that the Lakes split a high pressure ridge into two distinct circulation centers as it crossed the region. Upon passing to the east of the Lakes, the two centers merged back into a single system. The lake aggregate also affected a weak extratropical cyclone that passed through the region just after the split high pressure system merged and moved eastward. Figure 1b shows the observed path and central pressure of the cyclone, which advanced quickly into the center of the Lakes region and then lingered. The central pressure fell steadily as the system approached the region and began to rise only after the storm exited the region.

The consequences of lake-aggregate effects on the speed and path of these systems were substantial as was verified by Sousounis and Fritsch (1994) in

their numerical simulations with all the lakes (WL) and without any of the lakes (NL). The simulations were performed using the Penn State University/National Center for Atmospheric Research (PSU/NCAR) mesoscale model. Their results showed that the synoptic-scale effects were manifested by the development of a large meso- α scale circulation centered over the Great Lakes with a horizontal extent of nearly 1000 kilometers. This developing circulation, which was cyclonic at the surface and anticyclonic at 700 mb, impacted the paths and intensities of a synoptic-scale high and low (cf. Fig. 2) and influenced local, regional, and distant precipitation distributions. Regional WL-NL precipitation differences were significant throughout the 48 h period; not only because the Lakes acted as an additional moisture source, but also because the Lakes altered synoptic scale and mesoscale temperature and wind fields (cf. Fig. 3) from 1000-700 mb across the region. The observed 24 hour precipitation totals for the period 6Z 13-16 November 1982 are shown in Fig. 4. Because the lake aggregate altered the paths of two traveling systems during this period, the locations and intensities of LESs near the downwind lake shores during this period were also likely affected.

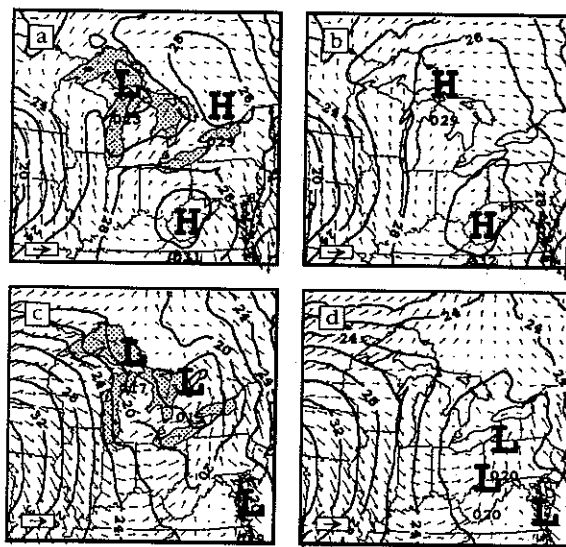


Figure 2. Fine grid mesh domain sea-level pressure and surface wind fields for the WL (shaded Lakes) and NL (unshaded Lakes) simulations at 27 h (a and b) and at 48 h (c and d). Vectors of length equal to the grid separation distance indicate 10 m s^{-1} winds.

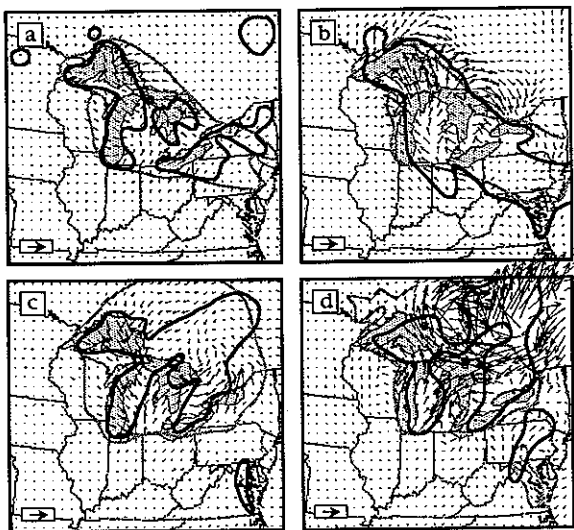


Figure 3. Fine grid mesh WL-NL differences at 24 h (a and b) and at 48 h (c and d). Sea-level pressure (gray curve is -1 mb), 12 hourly precipitation (black curve is 0.025 cm), and surface wind (key barb is 10 ms^{-1}), differences shown in a and c. Humidity (black curve is 10% isohume) temperature (gray curve is $2 \text{ }^\circ\text{C}$), and 700 mb wind (key barb is 2 ms^{-1}) differences shown in b and d.

A COMPARISON OF WL AND ML SIMULATIONS OVER MICHIGAN

The two simulations (WL and NL) by Sousounis and Fritsch (1994) identified regional scale impacts of the lake aggregate and suggested significant local scale impacts. A third simulation (ML) that included only Lake Michigan was performed in the present study using the same numerical model as did Sousounis and Fritsch (1994) to identify more closely the impact of the lake aggregate circulation on LESs along the western shores of lower Michigan. Figure 5 shows selected WL and ML results for surface wind, surface temperature, and precipitation fields at 12, 24, 36, and 48 hours over Lake Michigan and the lower peninsula of Michigan. Although some of the largest differences between the two simulations were over Lakes Superior and Huron, these are not shown fully in Fig. 5 because a lake aggregate-Lake Michigan comparison is not meaningful in these regions.

In Fig. 5, surface wind and temperature differences between the WL and ML simulations are already evident (cf. Figs. 5a, b) at 12 h. The differences are most prominent over the northern part of Lake Michigan, and along the western shore of the lower peninsula of Michigan. In these areas,

the WL surface winds are northwesterly and exhibit weak cyclonic curvature. The ML surface winds are more northerly, and exhibit weak anticyclonic curvature. The enhanced westerly component of the surface winds in the WL simulation is likely the response to a broad plume of relatively warm surface air that has developed from strong surface sensible and latent heat fluxes from the Lakes. Precipitation differences are negligible at this time.

By 24 h the WL surface winds are almost westerly across Lake Michigan. The winds turn cyclonically and become southwesterly (cf. Fig. 5c) over Michigan. The WL winds are likely the continued response to the seemingly stationary broad plume of relatively warm air ($> -4 \text{ }^\circ\text{C}$) that extends eastward across much of Michigan. The ML surface winds are northwesterly over much of Lake Michigan, and southerly over much of lower Michigan, exhibiting almost a closed cyclonic circulation on the scale of the lake (cf. Fig. 5d). Regions of precipitation differences are evident. Two regions where WL precipitation exceeds ML precipitation exist over north central lower Michigan and over Lake Huron. The enhancement over Lake Huron is anticipated because the ML simulation does not include Lake Huron. Comparing Figs. 5c and d, it is evident that by 24 h, the surface wind, temperature, and precipitation patterns along the eastern Lake Michigan shoreline are not just the result of modified synoptic-scale flow across Lake Michigan.

At 36 h, the synoptic-scale flow has shifted from northwesterly to southwesterly, ahead of an approaching upper-level trough. Because Michigan is now essentially upwind from the other Great Lakes, the WL and ML simulations are more similar (cf. Figs. 5e, f) with respect to surface winds. Precipitation differences, however, have continued to grow over the previous 12 h. Maximum WL precipitation amounts are located just onshore along the northwestern coast of lower Michigan, while maximum ML precipitation amounts are located just offshore.

At 48 h, a surface cyclone with minimum sea level pressure of 1015 mb (cf. Fig. 2) was centered over northeastern Lake Huron. Once again, northwesterly flow developed behind the low across all of Michigan. Once again, the WL flow is more westerly than the ML flow (cf. Fig. 5g, h). The 48 h WL and ML precipitation amounts along the northwestern coast show maxima onshore and offshore respectively. Farther to the south, slightly more precipitation has accumulated just onshore in the ML simulation than in the WL simulation.

Comparison of the WL and ML simulations suggests that significant contributions to the observed (or WL simulation) surface winds, temperature and precipitation totals over and in the

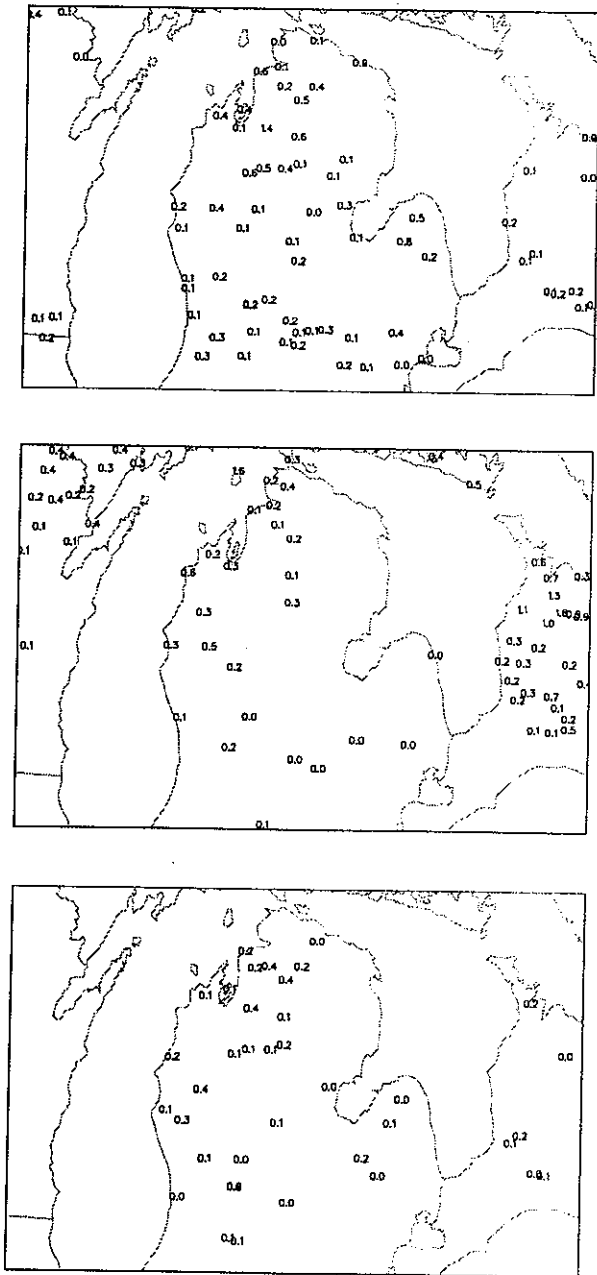


Figure 4. Daily precipitation totals (cm) over the Great Lakes Region for (a) 13, (b) 14, and (c) 15 November 1982.

vicinity of Lake Michigan are provided by Lakes other than Lake Michigan. These contributions are likely from Lakes Superior and Huron at least, which have apparently altered precipitation amounts along the northwestern and southwestern shores in a non uniform way.

Lake aggregate effects on local precipitation amounts are examined more closely in Fig. 6, which shows time-series of selected variables for northern and southern points in lower Michigan along the western shore. The time-series for the northern grid point indicates little or no change between the WL and ML simulations for the first six hours. Snowfall¹ is actually slightly more for the ML grid point in the second three hours, perhaps because the low level air is several degrees colder. During the next 18 hours however, the WL grid point experiences ~9 hours of significant snow, while the ML grid point experiences little or no additional snow. Surface winds during much of the first 24 h period are significantly different for the two points as well. The WL grid point surface winds remain northwesterly for the first 15 h, and then become light westerly by 24 h. The ML grid point winds veer continuously from northwesterly to northeasterly by 15 h and then to southeasterly by 24 h. The next 18 h (e.g. 24-42 h) shows little change between the two grid points. Recall that the reason for a weak lake-aggregate effect during this period is the result of the synoptic-scale flow shifting from northwesterly to southwesterly. During the last 6 h, the WL grid point accumulates once again more snow than the corresponding ML grid point.

In Figure 6c, the differences in the WL and ML time series for the southern grid point are more subtle than for the northern grid point. Indeed, except for the 3 hourly precipitation amounts, it is difficult to distinguish the WL and ML time series. As Figs. 5g and h suggested, the time-series precipitation totals show more clearly that more ML precipitation than WL precipitation occurs at the southern grid point during the 12-24 h period. The enhanced ML totals are likely the result of slight differences in wind speed and direction, and slightly greater lake-air temperature differences.

DISCUSSION

In general, it appears that Lakes Superior and Huron enhanced the westerly component of the flow across northern lower Michigan most significantly when the synoptic-scale flow was northwesterly.

¹ The PSU/NCAR model that was used does not distinguish between precipitation types reaching the ground. Type assessment is based on surface temperature.

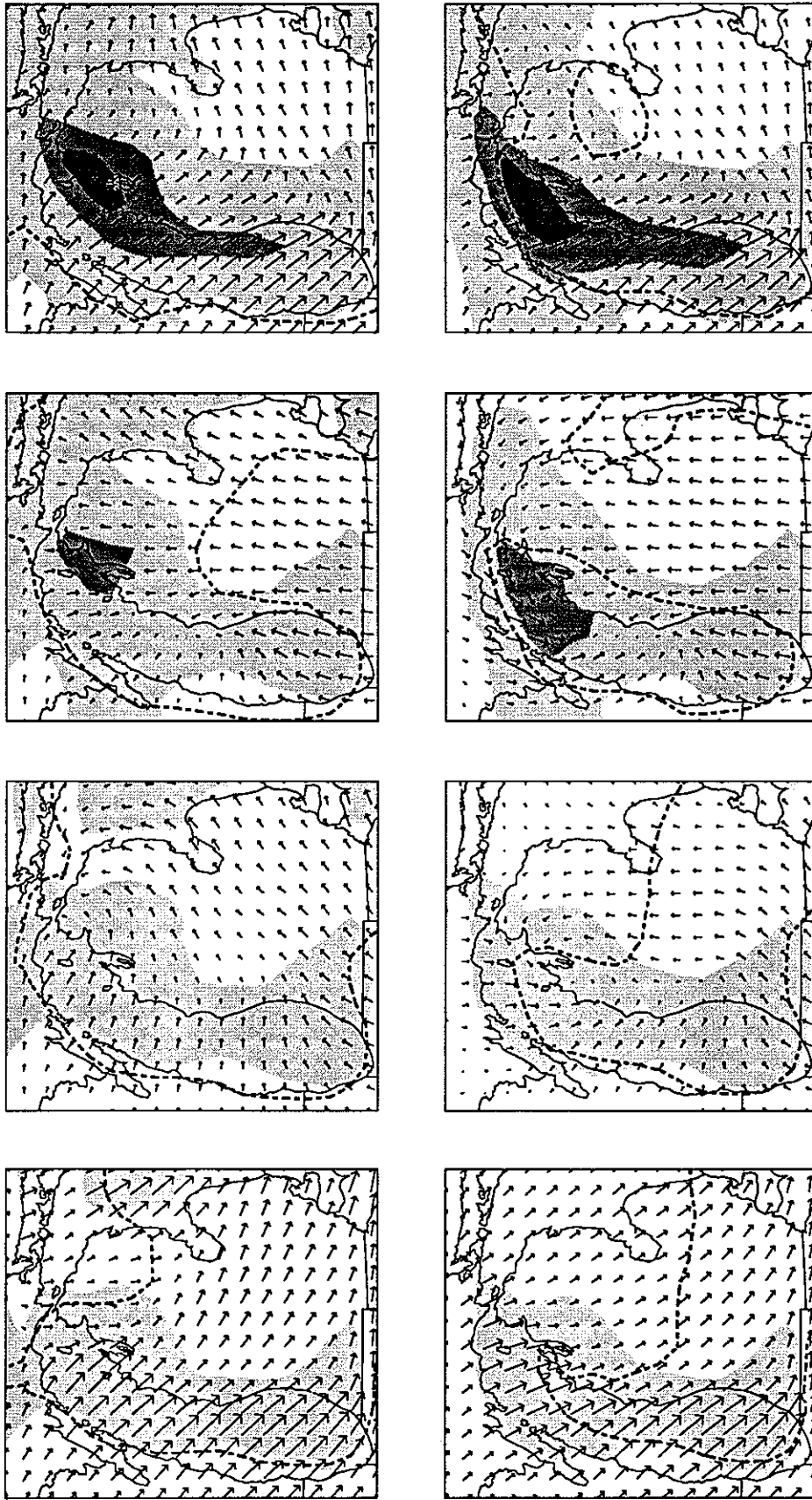


Figure 5. Surface winds (vectors), accumulated precipitation (shading), and -4°C surface isotherm (dashed curve) for WL (upper row) and for ML (lower row) simulations valid at 12h (left column), 24 h (middle left column), 36 h (middle right column), and 48 h (right column). Vectors of length equal to the grid separation distance indicate 10 ms^{-1} winds. Precipitation shading indicates levels of 10 mm (light), 70 mm (medium), and 130 mm (dark) liquid water equivalent.

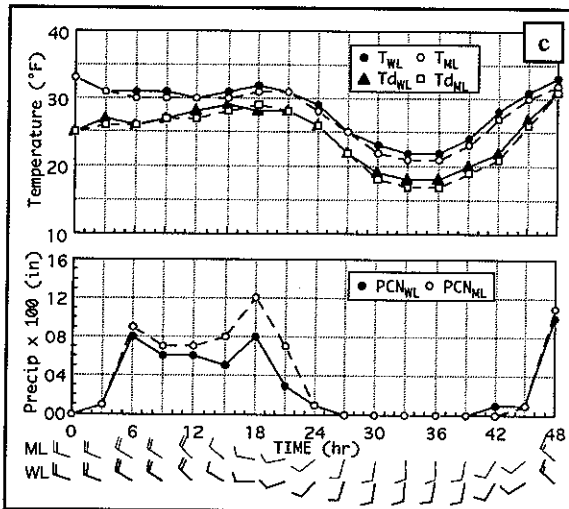
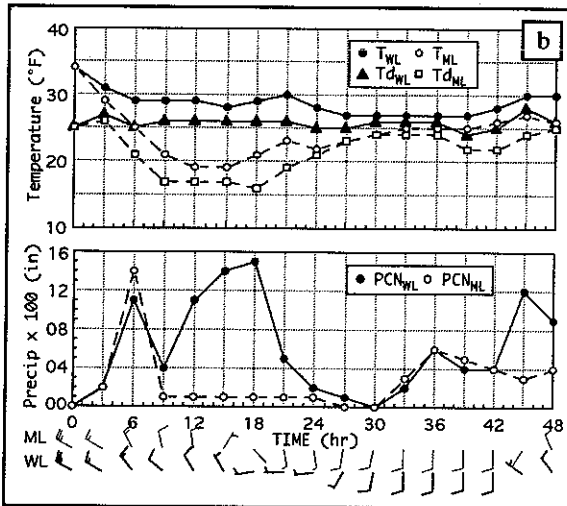
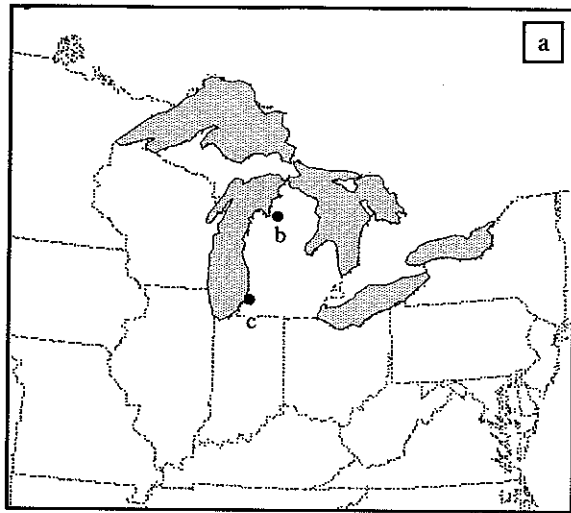


Figure 6. Time series for selected points as shown from WL and ML simulations. a) Locations of points. b) Time series plots for point b. c) Time series plots for point c. Precipitation values are three hourly totals.

Altered surface winds and perhaps other changes in boundary layer stability and moisture likely caused a shift in the convergence zones and hence in the regions of significant precipitation. This shifting effect suggests that Lakes Superior and Huron may have a bigger impact than does Lake Michigan on LESs along northwestern coastal Michigan. This result is consistent with satellite observations that show elongated LES cloud bands beginning over Lake Superior and extending southeastward over parts of lower Michigan. Similar phenomena occur with respect to Lakes Huron and Erie (Robert Ballentine, personal communication). However, because the model resolution (30 km) for these simulations was too coarse to simulate explicitly individual snow bands (10-15 km), it is difficult to confirm that the enhanced precipitation total just onshore in northwest lower Michigan is the result of elongated long snowbands. Another possible explanation for the enhanced precipitation that is consistent with the relatively coarse model resolution is that the air, which passed over Lake Michigan, was pre-moistened and de-stabilized by passage over Lake Superior.

A possible explanation for the reduced snowfall amounts along southwestern lake shore regions in the WL simulation may be that subtle changes in wind direction (e.g., more westerly), resulting from the lake aggregate heat and moisture farther to the north and east, shortened the fetch, enhanced divergence, and hence reduced the precipitation.

SUMMARY AND CONCLUSIONS

Results from a numerical simulation over the Great Lakes region that included only Lake Michigan (ML) were compared with those from existing simulations over the Great Lakes that included all the Lakes (WL) and none of the Lakes (NL). The comparisons indicate that the lake aggregate (e.g., Lakes Superior and Huron, in this case) have a significant effect on lake-effect wind, temperature, and snow patterns in lower Michigan, especially along the western shore, when the synoptic-scale flow is northwesterly. Specifically, snowfall was augmented along the northwestern shores of lower Michigan, and reduced along the southwestern shores. The lake-aggregate effect apparently was the primary reason for snowfall accumulation onshore in the northwestern part, as the ML simulation produced most of the snow offshore. For most of the 48 h period, significant WL-ML differences existed directly over and in the immediate vicinity of Lake Michigan, a point that

underscores the significant impacts of the lake aggregate on local Michigan weather.

It is concluded that the lake-aggregate effect can play a significant role in altering LESs in Michigan when the synoptic scale flow is northwesterly for prolonged (e.g., > 6 h) periods of time. This slowly evolving effect can pose a significant hazard to residents and motorists along the northwestern shores of lower Michigan, because the effect is one that is not currently incorporated into LES forecasts.

While the modeling study suggests significant lake aggregate impacts, the effect may be more intense than the model shows. Because of the coarse model resolution, and because of the observed precipitation totals along the western shores of lower Michigan, the model likely underrepresented the intensity of the precipitation at certain locations, and hence may have underrepresented the effects of the lake aggregate on LESs in that area.

While the lake-aggregate effects on LESs in Michigan may be significant, they may be equaled or exceeded by lake-aggregate effects on LESs adjacent to some of the other Great Lakes. It is anticipated that the lake aggregate should have a very significant effect on LESs along the shores of Lakes Erie and Ontario because these lakes are downwind (east) of the other three major Great Lakes. Simulations that include only Lake Erie and only Lake Ontario are planned in order to examine the lake-aggregate effects on LESs in these regions.

ACKNOWLEDGMENTS

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