P3.3 **Influences of Upwind Lakes on the Wintertime Lake-Effect Boundary Layer**

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1. Introduction

Some of the most intense lake-effect storms occur when an upwind lake has previously modified the air crossing one of the Great Lakes. Lakes Erie and Ontario, for example, are responsible for some of the most intense local lake-effect storms in the region, and are most often downwind of Lakes Huron, Michigan, and Superior. Cloud bands that continuously extend over two or more lakes may be referred to as Lake-to-Lake (L2L) Bands. Despite prior snow band research, lake-to-lake bands are relatively unknown phenomena. Little quantified information is available on how the modified boundary layer from an upwind lake (i.e., thermodynamic properties, mesoscale circulations) influences boundary layer convective development and precipitation over a downwind lake.

An example case study is presented which describes the impact of Lake Superior on boundary layer growth and lake-effect snow over Lake Michigan on 16 January 2000. Initial results of an observational study to examine common locations and frequencies of occurrence of lake-to-lake band formation over the Great Lakes are also presented.

2. Background

It has long been recognized that intense lake-effect storms may result when mesoscale bands of clouds, heat, and moisture traverse from one lake to another (e.g., Holroyd 1971, Baker 1976). Four processes have been identified as potentially important in such cases: 1) Downwind propagation of a heat and moisture plume (e.g., Niziol *et al*. 1995, Ballentine *et al*. 1998), often reaching the downwind shore as an elevated mixed layer (Agee and Gilbert 1989, Chang and Braham 1991, Mann 1999, Rose 2000), 2) Extension of lake-induced circulations to a downwind lake (e.g., Niziol *et al*. 1995, Sousounis and Mann 2000, Rose 2000), 3) Long wavelength gravity waves initiated by the upwind lake (Yuen and Young 1986), and 4) internal microphysical and radiational processes sustaining the band's inland propagation (e.g., Byrd *et al*. 1995). However, no general mechanism for L2L bands has been determined, and observational studies of such systems are quite limited. An incomplete understanding of this preconditioned and modulated environment may pose forecasting difficulties during lake-effect events affecting the lower peninsula of Michigan, northern Indiana and northeastern Illinois and the Eastern Lakes. Furthermore, it is unsure what, when, where and how individual atmospheric parameters dominate or offset each other while modifying downstream lake-effects.

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3. 16 January 2000 Simulations

The objective of this study is to investigate the impact of Lake Superior on the growth of the boundary layer and lake-effect snow development over Lake Michigan for the case of 16 January 2000. Northwest to northerly wind flow on this date moved plumes of heat and moisture from Lake Superior over northern parts of Lake Michigan. Figure 1 shows GOES visible satellite images, which show well-defined wind-parallel cloud streets blowing north to south off Lake Superior, crossing the upper peninsula of Michigan and continuing over Lake Michigan. The widespread nature of these L2L bands makes this an ideal case study for examination of associated processes.

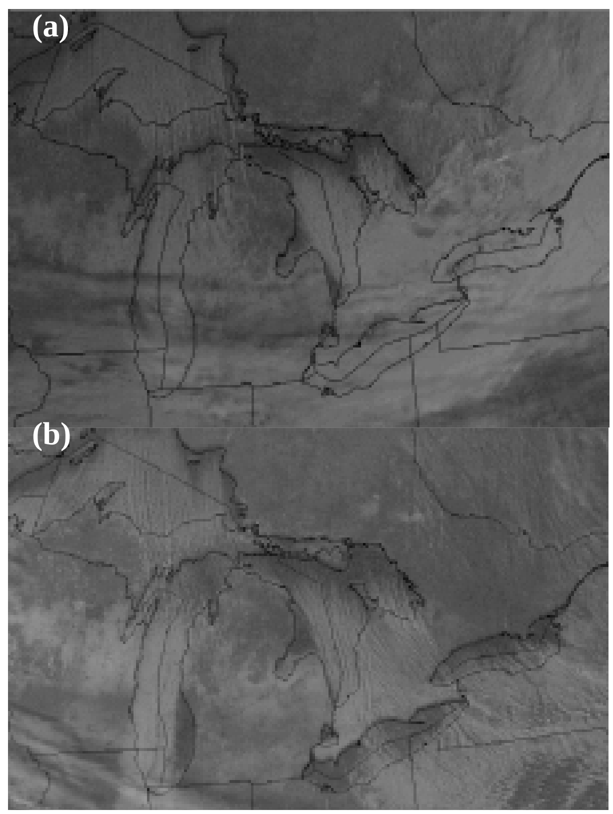

Figure 1: GOES visible satellite images for 16 January 2000. (a) 1445 UTC, (b) 2045 UTC.

Figure 2 shows a surface analysis for 1500 UTC. A high-pressure center was located over Winnipeg, Canada, associated with the cold arctic air. A cold front marking the leading edge of the cold air originated from a low center located north of Ottawa, Canada, and extended through central Pennsylvania and across the northern border of Kentucky. By 2100 UCT, the high had moved northeast of International Falls, MN. The cold front was no longer analyzed, but the associated trough had moved further south, stretching from Washington, DC, to Memphis, TN.

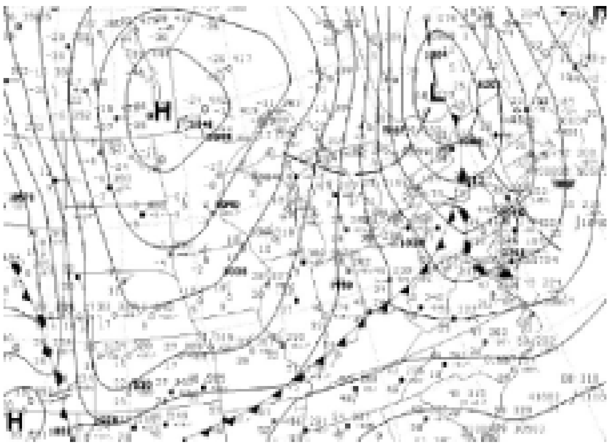

Figure 2: NCEP surface analysis for 16 January 2000 valid at 1500 UTC.

Simulations

Numerical simulations are made with and without Lake Superior to investigate the significance and implications of the preconditioning of the boundary layer due to the fetch across Lake Superior on boundary layer development and evolution over Lake Michigan.

The Advanced Regional Prediction System (ARPS) – developed by the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma (Xue *et al*. 2000, 2001) – was applied to the 16 January 2000 case. Three grids were employed, as shown in Fig. 3. The outer grid encompassed a domain of 1620 km on a side with a horizontal grid spacing of 18 km. The domain was centered over Lake Michigan, stretching from the southern tip of Hudson Bay to Kentucky and the eastern Dakotas to Lake Ontario. The second grid covered an area of 846 x 846 km with a horizontal grid spacing of 6 km centered on the Lake Michigan coastline just east of Green Bay, and encompassed the Lakes Superior, Michigan and Huron. The fine scale domain spanned nearly 316 km on a side, with a 2 km spacing, centered over the northern end of Green Bay, including southeastern Lake Superior, much of Upper Michigan, northern Lake Michigan and the Wisconsin and Lower Michigan coastal areas.

Simulations were performed using the explicit bulk water microphysical parameterization of Tao and Simpson (1993) and for the outer grids, the convective parameterization scheme due to Kain and Fritsch (1993). Land processes were modeled using a force-restore surface energy balance parameterization based on Noilhan and Planton (1989) and Pleim and Xiu (1995). Turbulence processes were simulated as described by Xue *et al*. (2001) based on the TKE parameterization of Sun and Chang (1986). For simulations without Lake Superior, the Lake grid surface values were replaced with land values interpolated from nearby land sites, making these locations much colder and rougher than their corresponding water values. Initialization and outer boundary conditions were based on the 40 km Eta Model Data Analysis (EDAS) fields archived at the National Center for Atmospheric Research.

Figure 3: ARPS simulation domains. (1) Regional [91x91 grid, 18km horizontal spacing], (2) Subregional [142x142 grid, 6km spacing], and ng].

Simulation Results

Model simulations for the 6 km grid show that flow over Lake Superior resulted in rapid warming of the near-surface air (Fig.4a), such that air reaching the northern edge of Lake Michigan was as much as 5° C warmer at –15°C, than if the Lake was not present. Surface winds, shown in Fig.4b, are much stronger and more northerly over Lake Superior at the surface (consistent with 850 mb winds) than if the lake was not present. In addition, air reaching Lake Michigan arrived with higher humidity with Lake Superior present. As shown in Fig. 4c, dewpoint temperatures at the northern coast of Lake Michigan are –18 to –19°C with Lake Superior present, but are –22 to –24°C without Lake Superior. Potential temperatures show a similar impact, Fig. 4d, (252-253 K without Lake Superior and 257 K or more with the lake). The effects of heating over Lake Michigan are more pronounced in the no-Lake Superior run due to colder air over the adjacent land areas (especially over Wisconsin), and is shown by enhanced bulging of the isentropes northward over Lake Michigan.

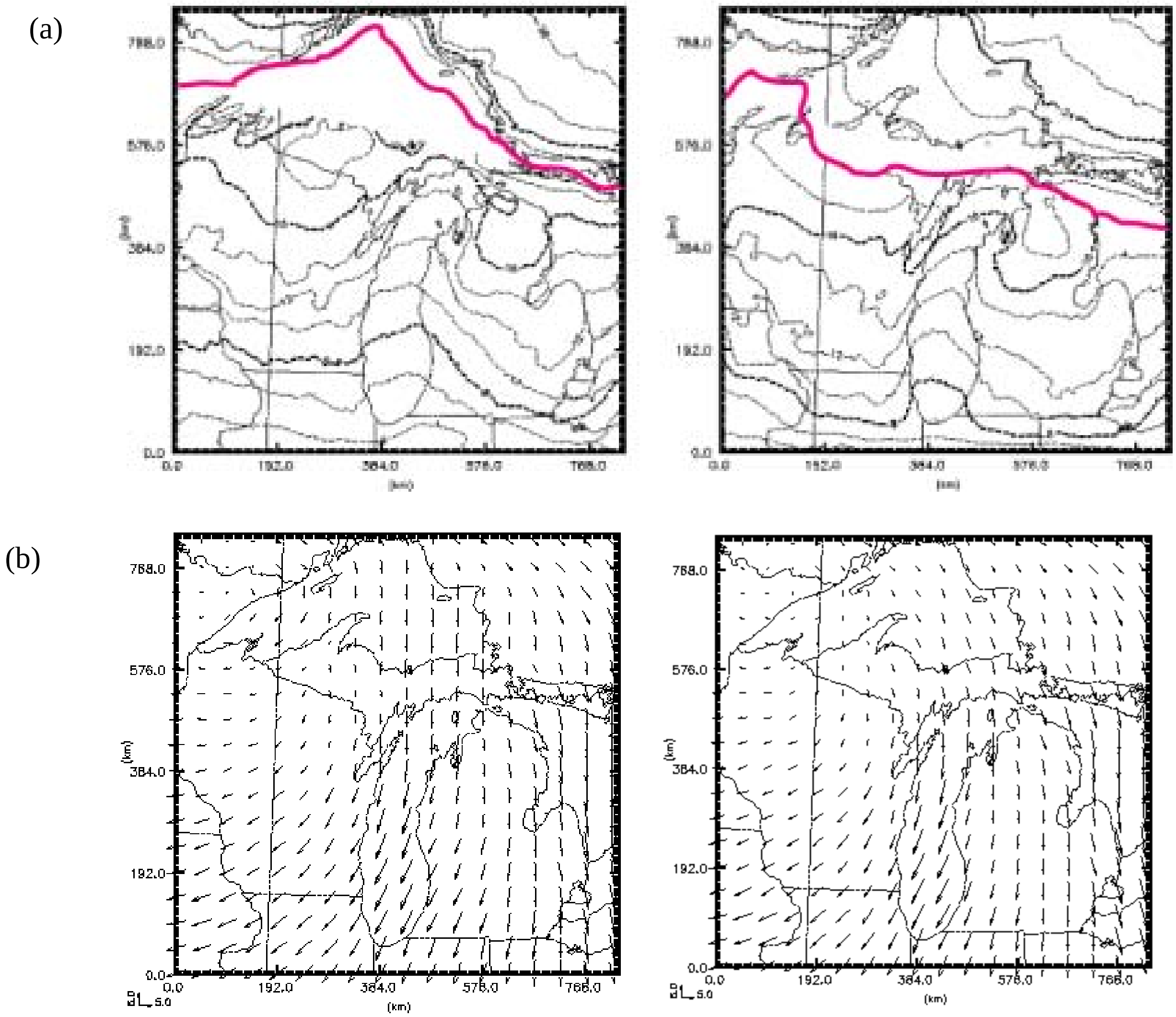

Figure 4: Surface conditions for the 6km model domain valid at 2100 UCT. Left Column–with Lake Superior, Right Column--without Lake Superior. (a) Surface temperature [°C] –20C highlighted; (b) Surface wind [m/s].

The differences in properties of boundary layer air reaching Lake Michigan and subsequent development over the Lake are illustrated in a series of South - North cross-sections from the 2 km grid, taken at about y = 400, near the center of Lake Michigan, Figure 5. Note that the wind direction in these figures is from right to left. The relatively short 60-80km distance across northern Michigan is not sufficient in this case to destroy the Lake Superior-effected boundary layer or decouple it from the surface layer, as proposed in the west-northwesterly wind case studied by Chang and Braham (1991). A cross section of potential temperature, Fig.5a, reveals that air reaching Lake Michigan after passing over Lake Superior is several degrees warmer, and the boundary layer is nearly 50% deeper than if Lake Superior were not present. The turbulent kinetic energy of air reaching northern Michigan is very small with no Lake Superior. TKE < 1 m2s-2 is generated by the small topography of northern Michigan. With Lake Superior, the air arrives with a deep layer of TKE > 1 m2s-2. As the air flows down the length of Lake Michigan, TKE values extend one and a half times the height above the surface for the with-lake simulation as comparable values for the no-lake simulation as the air reaches the Lake Michigan shore. Thus, boundary layer growth and turbulence intensification over Lake Michigan is more rapid with Lake Superior. The temperature cross section in Fig.5c shows the much greater penetration of the cold arctic air in the no-Lake Superior case. –22°C air appears below 0.5 km reaching out over the northern edge of Lake Michigan, until it encounters the growing Lake Michigan-effected boundary layer. The –22°C air only appears weakly aloft, above the Lake Superior boundary layer in the With-Lake case. Snow concentrations greater than 0.15 g kg-1, not shown, are obtained over Lake Michigan in the simulation with Lake Superior, but without Lake Superior, values do not exceed 0.5 g kg-1 until impacted by effects of topography along the southern shore.

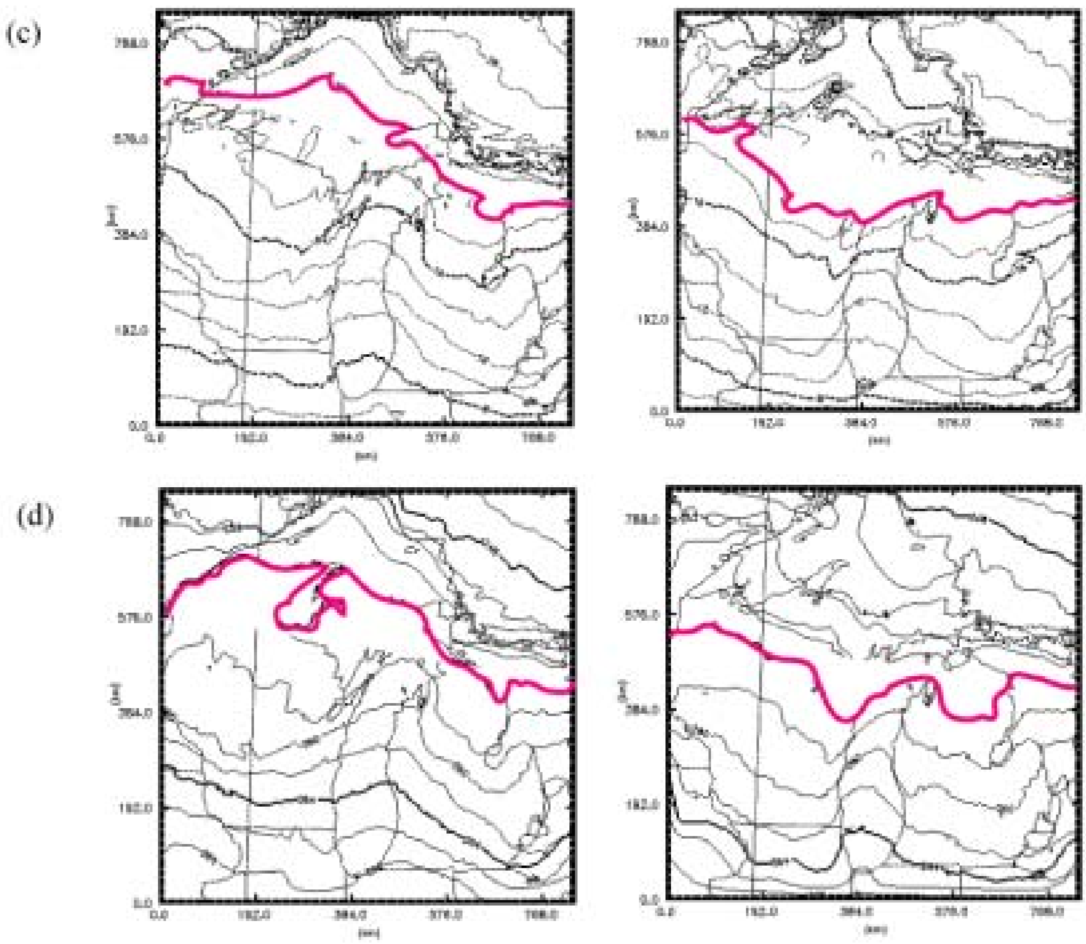

Figure 4 (continued): Surface conditions for the 6km model domain valid at 2100 UCT. (c) Dewpoint temperatures [°C] –20C highlighted; (d) Potential temperature [K] 258K highlighted.

In summary, simulations with and without Lake Superior indicate that the warm cloudy boundary layer over Lake Superior crosses northern Michigan and arrives at the northern shore of Lake Michigan warmer, moister, and deeper than without Lake Superior. This results in rapid initial boundary layer development and initiation and intensification of clouds and precipitation over Lake Michigan. However, as the air passes over Lake Michigan, differences in boundary layer height, vertical velocities, and cloud amounts decrease, as fluxes from Lake Michigan dominate. Values remain higher in the Lake Superior case all the way to the downwind shore, including precipitation and simulated reflectivities. This is consistent with the recently published work of Mann *et al*. (2002) who looked at potential Lake Superior influences on lake-effect cases on the downwind Michigan shore.

4. Climatology of L2L bands

An observational study was also made of the frequency of occurrence of, and environmental conditions favorable for lake-to-lake cloud bands over the Great Lakes. The study is based on analysis of two years of winter data (2000-01 and 2002-03) which examined and recorded the daytime development and positioning of lake-effect cloud bands from animations of GOES (Geostationary Operational Environmental Satellite) visible satellite images to identify occurrences of L2L bands. This study, which is currently being expanded to a five-year period, documents the frequency of L2L bands originating from each of the Great Lakes. Lake-effect bands were defined as those that clearly originated over an upwind lake for which the upwind shore was visible. For a band to be classified as L2L, it had to extend continuously over two or more lakes. Figure 6 gives the frequency and common locations of cloud bands originating over Lake Superior (top) and Lake Huron (bottom).

Initial results found that lake-to-lake bands most commonly originated over Lakes Superior or Huron, but were observed originating from any of the Great Lakes. Bands between the eastern lakes (Ontario and Erie) were quite rare. In addition, lake-effect bands extending

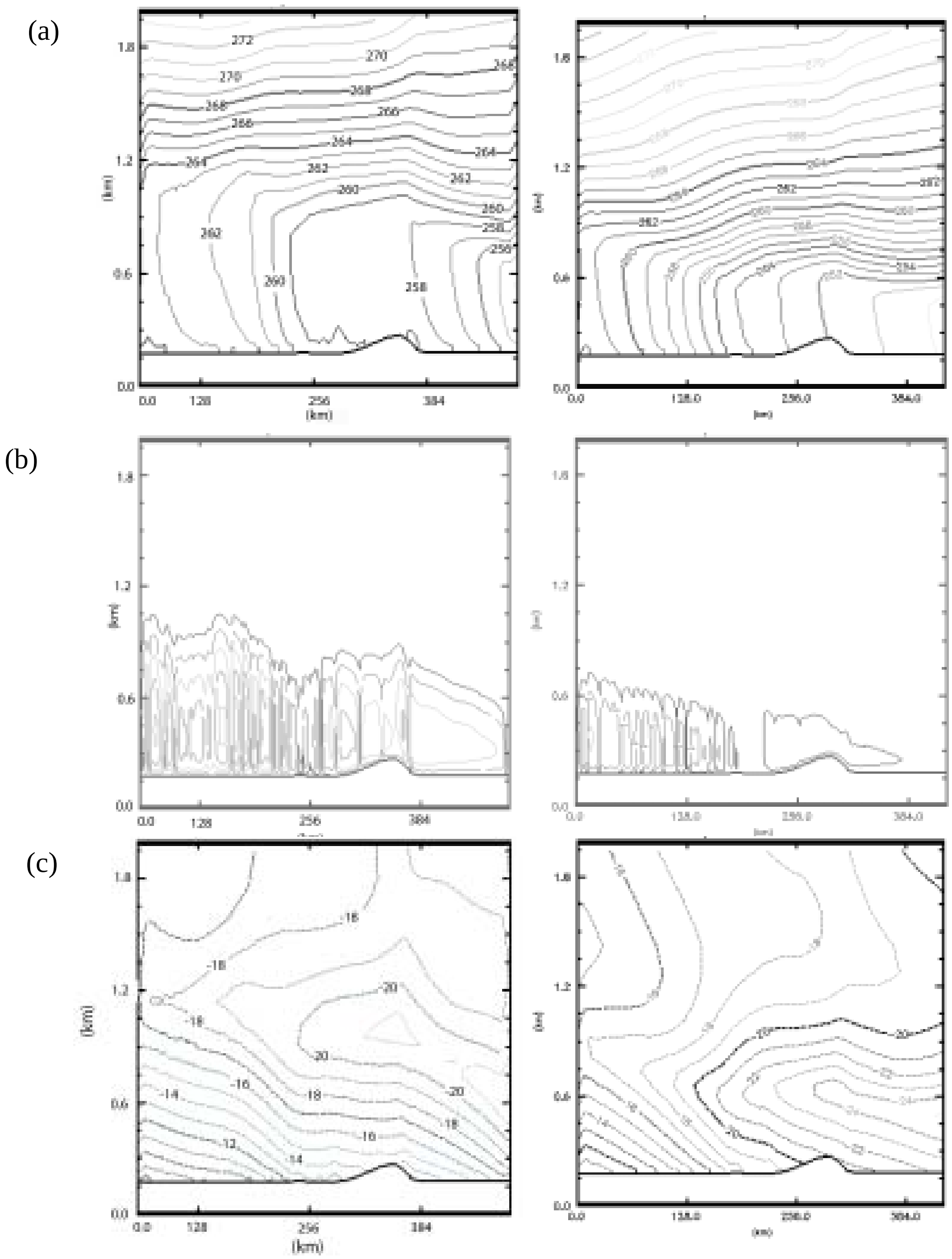

Figure 5. South-North cross sections down the center of Lake Michigan from the 2km model valid at 2100 UTC: Left Column–with Lake Superior, Right Column--without Lake Superior. (a) Potential temperature [K]; (b) Turbulent kinetic energy [m^2/s^2]; (c) Temperature [°C]. Winds are blowing right-to-left. Lake Superior is at the extreme right, the raised portion of the lower boundary indicates the higher topography of northern Michigan, and the left two-thirds of the grid is over Lake Michigan (the southern shore is just off the left edge of the figure).

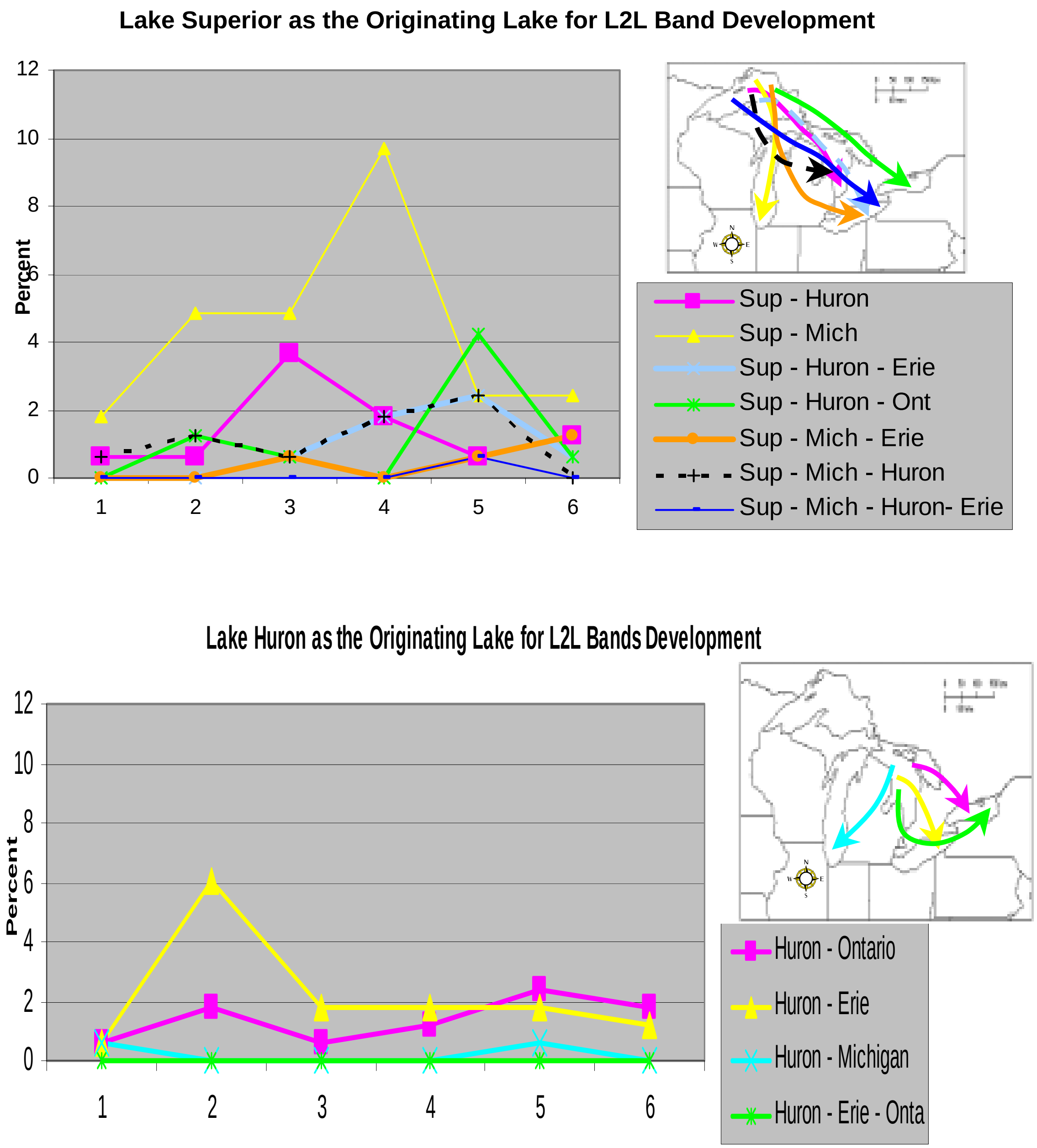

Figure 6: Frequencies of L2L bands originating from Lake Superior (top) and Lake Huron (bottom). The vertical axis on the graph to the left denotes the percentage of days over a two year period with each type of lake to lake band.

over more than one downwind lake (lake-to-lake-to-lake bands) occurred rather frequently when Lake Superior was the originating lake, but were observed from both Lakes Michigan and Huron.

5. Summary

Lake-to-lake, L2L, bands can significantly impact boundary layer growth and precipitation development over the downwind lake. All of the lakes downwind of Superior experience L2L bands with some frequency. Therefore, it is important that further studies be performed to better understand the conditions suitable for L2L bands between the different lakes, the environmental conditions governing the resulting impacts, and the processes involved in the interactions between L2L bands and the developing boundary layer over the downwind lake.

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