14.7 NUMERICAL SIMULATION OF CONVECTIVE EVOLUTION ACROSS LAKE MICHIGAN DURING A WIDESPREAD LAKE-EFFECT SNOW EVENT

by
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1. INTRODUCTION

Lake-effect snowstorms generally form in convective boundary layers as cold air flows over relatively warm lakes in fall and winter. This study presents simulations of the evolution of the thermodynamic and microphysical boundary layer structure and mesoscale convective patterns across Lake Michigan for an intense lake-effect event observed during the Lake-Induced Convection Experiment (Lake-ICE, Kristovich *et al.,* 2000) on 13 January 1998. Kristovich *et al.* (2003) recently published an observational study of this case.

2. DATA COLLECTION ON 13 JAN 1998

Lake-ICE observations used in this study included three National Center for Atmospheric Research (NCAR) Integrated Sounding System (ISS) sites located in Michigan and Wisconsin, two aircraft (NCAR Electra and the University of Wyoming King Air) deployed over Lake Michigan, and the NCAR Electra Doppler Radar (ELDORA). Observations from the 00 and 12 UTC NWS rawinsondes at Green Bay, WI, were also used. On 13 January 1998, the Electra flew repeatedly across Lake Michigan nearly parallel to the wind direction within the convective mixed-layer at an altitude of approximately 550-600 m above the lake surface (ALS). The King Air conducted four stacks of level flight segments approximately perpendicular to the Electra flight. The box on the satellite image shown in Fig. 1 shows the area of aircraft operations.

3. SYNOPTIC CONDITIONS AND MESOSCALE STRUCTURE

A succession of cold fronts and surface pressure troughs moved through the Great Lakes region from 9 to 13 January, followed by surges of cold air and lake-effect snow storms. West-northwest winds and low-level cold-air advection were present over the western Great Lakes during the day on 13 Jan. At 14 UTC, during Lake-ICE flight operations, surface temperatures were about –18º to – 26ºC upwind and –10º to – 13ºC downwind of Lake Michigan. Lake surface temperatures were 2º to 5º C, resulting in surface lake-air temperature differences of approximately 15º to 30º C. Wind speeds near 8 m s^{-1} were observed 120 m above the lake surface by Lake-ICE aircraft.

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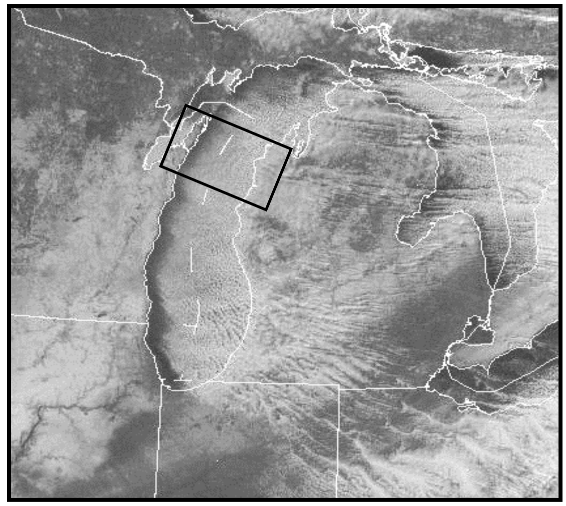

Fig. 1 Visible satellite image for 13 January 1998 showing lake-effect clouds over Lake Michigan. The dark box encloses the region of aircraft operations.

This synoptic environment gave rise to conditions suitable for lake-effect storms. The GOES-8 imagery for 13 January 1998, 1502 UTC, shown in Fig. 1, indicates the presence of clouds to within about 15 km of the western shore of Lake Michigan. Linear cloud features are visible in the southeastern portions of the lake, as confirmed by observations near the southeastern shore (Miles 2002). Satellite and Eldora observations over the northern half of the lake did not indicate clear mesoscale structures, though some regions appeared to have cellular structures. Over the eastern shore the cloud patterns became more linear.

Visual observations from the Electra aircraft of the convective structure over Lake Michigan are shown in Fig. 2. Over the lake, the clouds formed nearly overcast conditions with individual convective clouds protruding without clear organization, Fig. 2a. At the western end of the lake, near the Wisconsin shore, skies were clear and streaks of steam were visible elongated with the wind, rising to form steam devils, Fig. 2b. Further out over the lake these rising plumes fed into the clouds, which rose abruptly, forming a wall-like appearance, Fig. 2c.

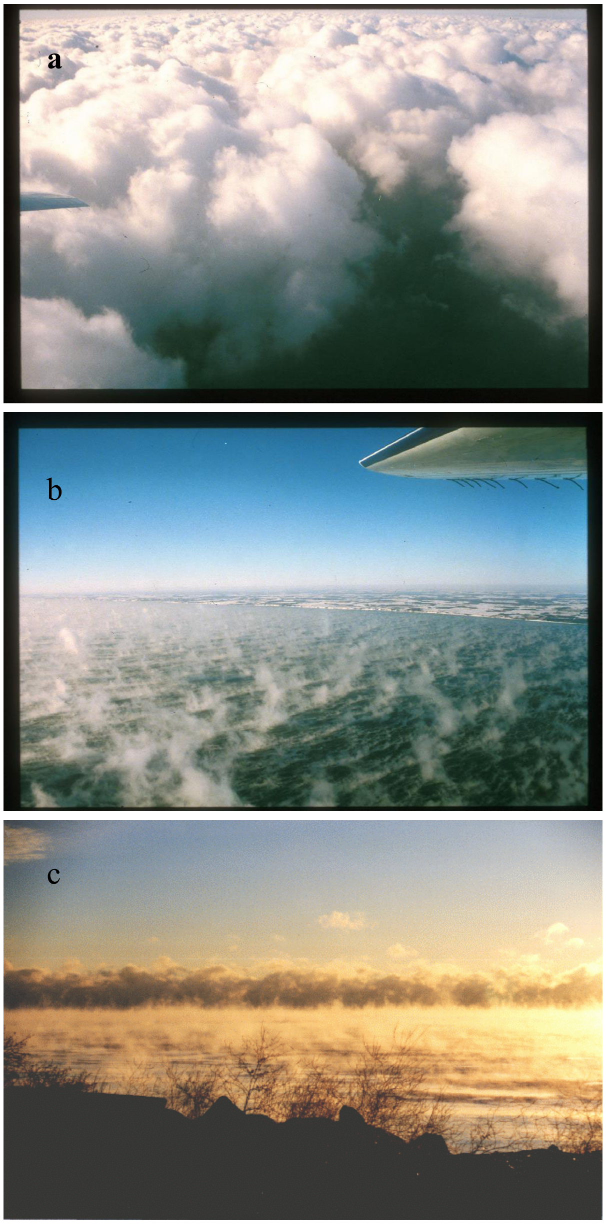

Fig. 2. Photographic observations of lake-effect clouds on 13 January 1998. a) Cloud deck as seen from above, b) View of Wisconsin shore and streaks of steam from Lake Michigan (Both taken from the NCAR Electra by David Rogers of NCAR). c) Steam rising from Lake Michigan and wall of clouds further off shore (Photo by Shane Mayer from the U. of Wisconsin Volume Imaging Lidar located near Sheboygan Wisconsin).

4. Model Description

Simulations were made using the Advanced Regional Prediction System (ARPS) developed by the Center for Analysis and Prediction of Storms at the University of Oklahoma (Xue *et al.* 2000, 2001). The dynamic model is based on the fully compressible equations of motion and permits interactive nesting of multiple grids of differing resolution. The equations are solved in a terrain-following coordinate system. Precipitation processes are simulated using the explicit bulk-water microphysical parameterization of Tao and Simpson (1993) and/or a convective parameterization scheme (Kain and Fritsch, 1990, 1993). Radiation-cloud interaction processes are treated through the long- and short-wave radiation package described by Tao *et al.* (1996). Land surface processes in the ARPS model are treated by a force-restore, surface energy balance parameterization, based on the work of Noilhan and Planton (1989) and Pleim and Xiu (1995) which distinguishes between land and water surfaces and permits multiple land surface types in a model domain.

5. Model Setup

For the present study, multiple grids were used (Fig. 3). The outermost grid, with horizontal spacing of 15 km, (Grid 1), covers the entire Upper-Midwest region. Nested within this grid was a higher resolution, 5 km grid, covering the Lakes Michigan and Superior and surrounding states (Grid 2). A fine grid of 1.67 km covered most of Lake Michigan and parts of the states of Wisconsin and Michigan (Grid 3). Finally, high resolution simulations of convective structure were made with an interactively nested grid with 0.55 km spacing covering a rectangular area over Lake Michigan and including both the upwind Wisconsin and downwind Michigan shores (Grid 4). The outer two grids were nested in a one-way, non-interacting manner. The two inner grids were interactively nested, respectively, within the 5 km model.

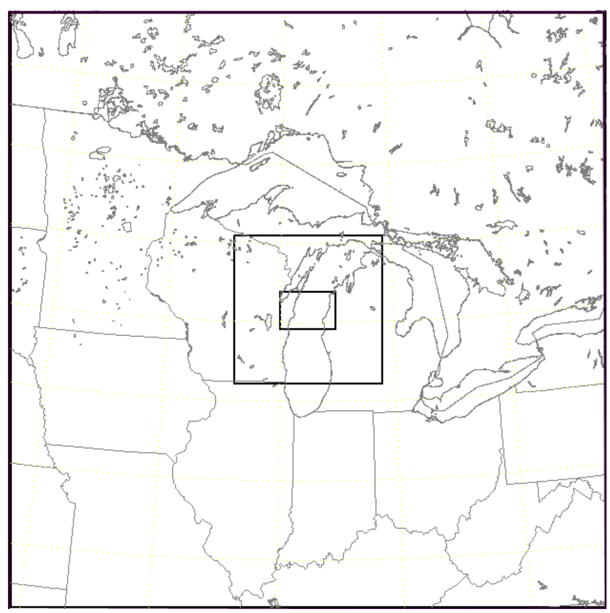

Fig. 3 Model domains for Grids 1, 2, and 3. Domain 4 was centered N-S within Grid 3, and extended from shore-to-shore across Lake Michigan.

The Kain and Fritsch (1990) cumulus parameterization scheme and the explicit microphysical parameterization scheme of Tao and Simpson (1993) were used together for Grids 1 and 2. Only the explicit precipitation scheme was adopted in Grids 3 and 4.

Data for land cover was derived from the 1-km Global Land Cover Characterization dataset (Loveland *et al*., 2000) modified to accommodate the ARPS land surface categories. Soil textures were extracted from the Penn State CONUS-SOIL database, a 1-km national-scale product (Miller and White, 1998). Soil moisture and soil and surface temperature values were obtained from the GCIP-derived, National Center for Environmental Prediction, Eta Data Analysis System (EDAS) archived at NCAR. Terrain was derived from 1-km resolution USGS Digital Elevation Model data. Satellite-derived lake surface temperatures were obtained from the Great Lakes Environmental Research Laboratory (Schwab *et al.* 1999).

The 40km resolution EDAS gridded atmospheric analyses archived at the National Center for Atmospheric Research provided initial fields for Grid 1 and Grid 2, and also gave lateral boundary conditions for Grid 1 (updated every 3 hrs.). *The Eta analysis fields did not provide proper low-level atmospheric or surface temperatures over much of Minnesota and Wisconsin, being in some areas greater than 10 degrees Celsius too warm.* Thus, the ARPS Data Assimilation System was used to replace the surface temperatures and temperatures in the lowest atmospheric levels with data from surface observations in these areas.

6. RESULTS

A 3-dimensional plot of cloud water and cloud ice for the 0.55 km grid is shown in Fig. 4. The figure depicts a pattern very consistent with the visual observations shown in Fig. 2, including evidence of shallow surface-layer streaks near the western shore, rising abruptly to form a disorganized cloudy region over the lake. Evidence for more banded clouds over the eastern shore is also seen, in agreement with the satellite photo shown in Fig. 1. The 0.55 km grid dictates the minimum scale of the clouds in the simulations, and thus is not quantitatively accurate.

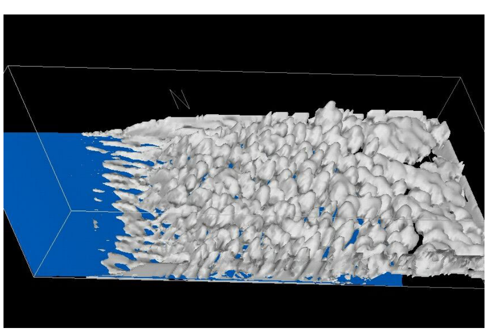

Fig. 4 Three-dimensional depiction of the model cloud outline for total water content of 0.1 g/kg from the 0.55 km model.

7. CBL DEVELOPMENT

The growth and development of the CBL was rapid over the 90 to 100-km cross-lake fetch. Boundary layer temperatures increased 8-10ºC below 900 hPa and moisture contents approached saturation with respect to ice near the downwind shore. The well-mixed layer (nearly constant equivalent potential temperature) increased in depth, with height of the CBL top increasing from about 200-400 m ALS near the upwind shore, to about 900 m ALS at the downwind shore. A comprehensive view of the evolution of CBL growth is provided by a vertical cross section of potential temperature (θ), Fig. 5a. A corresponding cross-section derived from Lake-ICE aircraft and rawinsonde observations, and NWS observations at Green Bay, WI is shown in Fig. 5b.

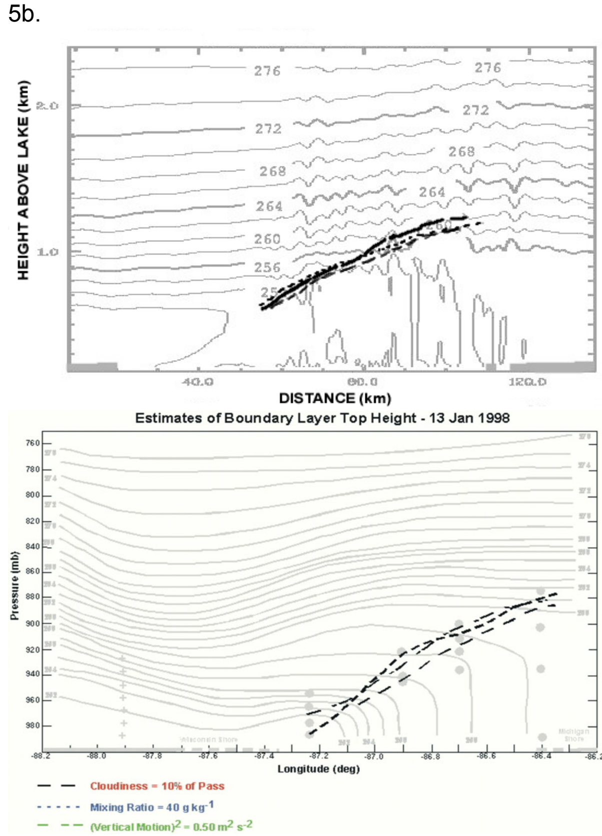

Fig. 5 Profiles of potential temperature and estimated boundary layer height across the lake a) Simulated, b) Observed (from Kristovich et al., 2003). Thick gray lines at bottom indicate areas over land.

The observed boundary layer-mean θ increased by about 7 K across the lake. Also shown are several estimates of CBL top height increases across Lake Michigan, based on locations of lake-effect cloud tops, delineation of the height of rapidly decreasing vapor (estimated by mixing ratios of 0.40 g kg^{-1}), and where turbulence rapidly decreased with height (estimated as turbulent motions of 0.50 m^2 s^{-1}). These estimates are in close agreement. Comparison of the model results and the observations show that the profiles are quite similar and suggest that the model is capturing the physics.

Surface fluxes were estimated using bulk techniques (e.g., Garratt 1992) for a location over the lake about 10 km from the upwind shore. Using the satellite-derived lake surface temperature of 4.8ºC ,as used in the model, and model grid values for wind speed and temperature at 10 m above the lake surface, a sensible heat rate of 475 W m^{-2}. Bulk estimates using model values at the King Air flight altitude of 120 m above the surface gave surface sensible heat fluxes of about 550 W m^{-2}. The actual fluxes obtained from the surface energy budget calculation at the lake surface were 714 W m^{-2} for the sensible heat flux and 228 W m^{-2} for the latent heat flux.

8. SENSITIVITY ANALYSIS

Cloud-radiation interactions are crucial to the dynamics of stratocumulus fields. In the present, convective case, strong forcing is provided by the surface energy fluxes. However, with a nearly overcast deck, it is not obvious whether the radiation heating effects could be important. A sensitivity test was run in which the atmospheric and cloud radiation scheme was turned off. Eliminating diabatic heating effects due to cloud-radiative interactions did not significantly change the convective structure or intensity.

A horizontal grid spacing of 0.55 km is not small enough to fully resolve the actual scale of vertical motions in this case. Thus the convective scale in the simulations is aliased to a larger size. To test whether this might impact the simulated convective structure, simulations were made using a sounding based on the ISS sounding at Sheboygan, Wisconsin and covering a 50x50 km patch of water with periodic boundary conditions (similar to those in Cooper *et al.* 2000). Model results for horizontal grid intervals of 0.55 km and 0.30 km were compared. The 0.55 km results were found to be very similar to those for the nested grid simulation shown in using Vis5D in Fig. 4. The 0.30 results showed a similar structure, but with a smaller scale, closer to that observed.

It might be expected that the dominant mesoscale convective scale would increase as the CBL grew from west to east. The mean horizontal scale of convective structures was estimated from the simulations by determining central locations of all high-reflectivity regions and then calculating the mean distances between local reflectivity peaks as a function of location across the lake. In general, there was a notable, but irregular increase in convective wavelength for both model results and observations, on average increasing some 15 to 30% from west to east. Kristovich *et al.,* (2003) obtained similar results from analysis of reflectivity spacing along the ELDORA flight track.

While the simulations and observations indicate that the convective wavelength increased roughly 15-30% across Lake Michigan, the CBL top height was estimated to increase by more than 50% (Fig. 5). The specific percentage increases depend on which method is used to estimate CBL top height. These changes in convective wavelength and CBL depth translate into a decrease of the mean aspect ratios (wavelength/depth) of the mesoscale convection by at least 20-25% across the lake. This decrease in aspect ratio is contrary to some previous studies, which indicate increased aspect ratios with convective depth over water (Kelly, 1982; Young *et al.,* 2002). In contrast, Melfi *et al.* (1985) found decreasing aspect ratios and Lohou *et al.* (1998) and Young *et al.* (2002) reported no consistent relationship between aspect ratio and boundary layer depth over land areas. Further simulations are underway to analyze this result and to examine if the decreasing aspect ratio could be the result of the rapid boundary layer growth.

9. SUMMARY AND CONCLUDING REMARKS

Numerical simulations were made of a lake-effect snow event, beginning with Eta model forecast output fields and nesting down to convective scales. Three-dimensional patterns of the simulated convection and boundary layer growth were similar to those observed. Calculated fluxes were higher than those estimated from aircraft observations. Cloud-radiation interactions were found to have a small effect on the simulated clouds and convection. Latent heating in the clouds had a significant effect on the strength of convection but less effect on the convective pattern. A decreasing aspect ratio of the convective horizontal scale to the boundary layer height was obtained, similar to the observations for this case. Possible causes are currently under investigation.

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