P5.1 LAKE MICHIGAN SURFACE TEMPERATURE VARIATIONS AND IMPACTS ON CONVECTIVE INTENSITY

David A. R. Kristovich [1,2], Mark R. Hjelmfelt [3], Maria C. Peters[1], and Michael S. Timlin[2]

[1] Atmospheric Environment Section, Illinois State Water Survey
[2] Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign
[3] Institute for Atmospheric Sciences, South Dakota School of Mines And Technology, Rapid City, SD

1. INTRODUCTION

Surface heat and moisture fluxes are a fundamental driving force for the development of convective boundary layers and lake-effect snow storms over the Great Lakes (e.g., Lenschow 1973). For example, Kristovich and Laird (1998) found that mesoscale variations in lake surface temperature and estimated surface fluxes resulted in significant changes in the location of the upwind cloud edge in several lake-effect events.

Hjelmfelt (1990) studied the morphology of lake effect snowstorms over Lake Michigan and found that they tended to fall into well-defined convective structure regimes. The morphology was primarily determined by the wind velocity and the lake-air temperature difference. Numerical simulation studies described in that paper indicated, that near regime boundaries, changes in water surface temperature of two to three degrees could lead to changes in regime or appreciable changes in precipitation (eg. Hjelmfelt, 1990; Table 2, Fig. 7). For example, a west wind of 6 m s^{-1}, a stable boundary layer upwind of the lake ($d\theta/dz = 8^oC\ km^{-1}$), and an upwind air temperature 18 degrees colder than the lake gave a broad area of convection over the lake; however if the lake was 2 degrees warmer ($\Delta T=20^oC$), a land breeze with a shore-parallel band was obtained. Similarly, some marginal land-breeze cases producing only a trace of precipitation were greatly strengthened by an additional temperature contrast of 2-3 degrees and resulted in appreciable snowfall rates.

Currently, satellite-derived analyses of lake surface temperature distributions, provided by the National Oceanic and Atmospheric Administration Great Lakes CoastWatch program (Schwab et al. 1992), are the best available operational dataset of water surface temperature fields. Schwab et al. (1999) showed that data provided through CoastWatch had a mean difference of less than 0.5^oC with coincident in-situ observations from buoys. *However, frequent cloudiness over the Great Lakes region in winter can result in long time periods where satellite estimates of surface temperature are not available for large portions of the lake. This, in turn, can result in derived temperature analyses of the Great Lakes that become less representative of actual water temperature distributions with time, potentially producing significant uncertainty in the results of scientific investigations of resultant mesoscale atmospheric circulations.*

This presentation will describe 1) a comparison of Lake Michigan surface temperature analyses derived from AVHRR satellite observations with those obtained by low-flying aircraft during the Lake-Induced Convection Experiment (Lake-ICE, Kristovich et al. 2000), (2) observations of over-lake variations of heat and moisture fluxes, and (3) numerical simulations of convective structure response to varying lake surface temperatures.

2. ANALYSIS METHODOLOGY

Satellite-derived lake surface temperature observations (Schwab et al. 1992) were provided for this study by the CoastWatch program. In short, CoastWatch composites lake surface temperature observations from cloud-free portions of the lake into a daily lake surface temperature map. During cloudy time periods, the temperature maps may represent conditions observed many days earlier. An example lake surface temperature map is given in Figure 1, left panel.

Aircraft data were collected by the National Center for Atmospheric Research Electra and the University of Wyoming King Air. As part of Lake-ICE research flights, the aircraft were often at altitudes appropriate for remote sensing of the lake surface temperature. Lake surface temperatures were obtained from both aircraft with Heimann KT 19.85 pyrometers. Because of the strong effects of liquid water and atmospheric vapor content on these observations, all aircraft data used in this study met these criteria: 1) flight altitude was less than 250 m above the lake, 2) the roll and pitch angles of the aircraft were less than 3.5^o, and 3) in situ instrumentation did not detect more than 50 cm^{-3} cloud particles (as measured by FSSP). Flight altitudes were somewhat high for surface heat flux estimates, but should be adequate for determination of their spatial trends.

A comparison of pyrometer observations from the two aircraft was carried out for the 5 Dec. 1997 case, when the aircraft flew side by side across portions of Lake Michigan. These pyrometer observations generally indicated cloud top temperatures. Temporal (spatial) variations were in excellent agreement. However, the Electra observations had to be corrected by $+3.1^o$ C to account for an offset between the aircraft and to bring these observations more inline with aircraft and sounding observations of cloud-top

Author address: Dr. David A.R. Kristovich, Atmospheric Environment Section, Illinois State Water Survey, Champaign, Illinois 61820; e-mail: dkristo@uiuc.edu

temperatures. Further intercomparisons on other days of the project gave results consistent with this analysis.

Two dates were chosen for lake surface temperature comparisons based on availability of adequate aircraft data. The 20 December 1997 case is illustrated in this abstract, and the 19-20 January 1998 cases will also be shown in the presentation. The lake was covered by clouds during much of December 1997 and January 1998, limiting satellite observations of the lake surface. Weak lake-effect convective patterns were observed on 20 December 1997 with relatively cool air flowing from northwest-to-southeast across Lake Michigan in the vicinity of the aircraft observations. Lake-effect convection on the 19-20 January cases was more complex, with organized convective bands in several locations and with different orientations over the lake.

3. SURFACE TEMPERATURE COMPARISON

Figure 1 gives AVHRR-derived lake surface temperatures (left panel, from CoastWatch) and aircraft-derived lake surface temperatures from both aircraft (right panel), for December 20, 1997. Despite the presence of clouds over the lakes during most of December 1997, limiting updates of satellite-derived lake surface temperatures, surface temperature observations agreed quite well. Generally, aircraft-observed surface temperatures were within about 2^{o}C of those from satellite.

Despite the good statistical agreement in temperature observations, however, significant regional differences were visible. For example, on the 19-20 January case (not shown), satellite-derived temperatures were 2-3^{o}C warmer in the southeastern-most and northern-most portions of the aircraft observations. Time series animations of CoastWatch data revealed that this region was largely cloud covered or otherwise unavailable for over 10 days before, and over 5 days after, the aircraft operations. Once clear skies were present over that portion of the lake, the satellite-derived surface temperatures dropped quickly in this region, possibly because of updated observations. Other regions of differences in estimated surface temperatures greater than 1.5^{o}C were noted on both dates.

From a boundary layer standpoint, regional variations in lake surface temperature may be more important to mesoscale circulation patterns than random temperature differences throughout the observation region. On 20 December 1997, for example, lake surface – air temperature differences generally ranged from 6-7^{o}C. A 1-2^{o}C error in lake surface temperature can give rise to as much as a 20-30% difference in estimated regional surface heat and moisture fluxes for such conditions.

4. SURFACE FLUX OBSERVATIONS

The 20 December 1997 case was chosen for a detailed examination of heat flux measurements from aircraft due to the relatively simple west-to-east growth of the convective boundary layer in the locations of aircraft flights on this day. Figure 2 gives lake-air temperature differences, sensible heat fluxes, lake-air mixing ratio differences, and latent heat fluxes along the NW-SE flight passes shown in Figure 1b. These data were taken at a single height level, about 195 m above the lake surface.

Across most of Lake Michigan, there is a general decrease in air-lake temperature and mixing ratio differences from NW to SE. This is due primarily to increasing atmospheric temperature and moisture across the lake (not shown), since lake surface temperatures were nearly steady or increasing across the lake. Local variations in lake surface temperature gave rise to lower lake-air temperature differences near the NW end of the flight leg, and locally higher differences near the SE end.

Correspondingly, surface sensible and latent heat fluxes decreased slowly from NW to SE along the flight path by approximately 20-40% and 10-30% for sensible and latent heat fluxes, respectively. These trends are similar to those observed in the lake-effect event studied in Chang and Braham (1991). Increases in wind speed from about 5 to 8 m s^{-1} across the lake (not shown) may have partially offset the effects of the large cross-lake decreases in lake-air temperature and mixing ratio differences.

5. NUMERICAL SENSITIVITY EXPERIMENTS

Kristovich et al (1999) studied an earlier lake effect snow event over Lake Michigan on 17 December 1983. They found that as the wind speed changed with little measurable change in air-lake temperature contrast, the structure of the observed convection changed from predominately non-roll like (cellular), to roll convection with a strengthening of the boundary layer winds, to a mixture as the winds abated to an intermediate value. Cooper et al. (2000) simulated this case using sounding data from aircraft and rawinsondes for atmospheric profiles and an estimated lake temperature in the region of the observed convection of 4^{o}C based on satellite and near-shore water measurements. Simulations with atmospheric temperature and wind profiles corresponding to each of the above situations produced convective patterns similar to that observed for the respective case.

We have extended the simulations of Cooper et al to consider the effects of errors in the lake surface temperature estimates. For example, simulations were made of the third period, with mixed rolls and cells, keeping the atmospheric conditions fixed but varying the lake surface temperatures. With a lake surface temperature of 4^{o}C (Fig. 3, middle), the model produced irregular pieces of linear vertical velocity elements with maximum updrafts greater than 1.0 m s^{-1}. For a lake surface temperature of 1^{o}C (Fig. 3, left), the linearity was somewhat enhanced, but the updrafts had about half the magnitude. With a lake temperature of 7^{o}C (Fig. 3, right), the pattern was much more broken up (more non-roll in character). Updrafts exceeded 1.5 m s^{-1}. These results are expected, since theory predicts that the determination of roll and non-roll structure is related to the ratio of heat flux to shear (e.g., Kristovich 1993). Thus, varying the heat flux as done here should give similar results to proportional changes in shear, as observed in Kristovich et al. (1999) and modeled in Cooper et al. (2000).

6. SUMMARY AND CONCLUSIONS

CoastWatch Great Lakes surface temperature distribution analyses are the best dataset available operationally. However, scientific analyses must cautiously use these data, because they cannot be updated when clouds cover the lakes, leading to potentially significant uncertainty in temperature fields. Aircraft observations of lake surface temperatures were compared to CoastWatch satellite-derived lake surface temperature fields for two cases of wintertime lake-effect snow storm events. Despite the large number of days with cloud cover limiting satellite observations, the overall agreement was quite good (generally within about 2^{o}C). However, mesoscale regions of surface temperature differences above 1.5^{o}C were noted. Such differences on weak lake-effect dates may influence boundary layer structure and mesoscale circulations. Aircraft-observed sensible and latent heat fluxes, derived by eddy-correlation techniques, showed the expected cross-lake decreases. However, these observations indicated regional variations in fluxes which were partially accounted for by lake surface temperature variations. Numerical simulations indicated that even quantitatively small errors in lake surface temperature can result in important changes in lake-effect convective intensity and morphology, in some cases. Mesoscale predictons of wintertime clouds and precipitation in the Great Lakes may be affected by limitations in observations of lake temperatures.

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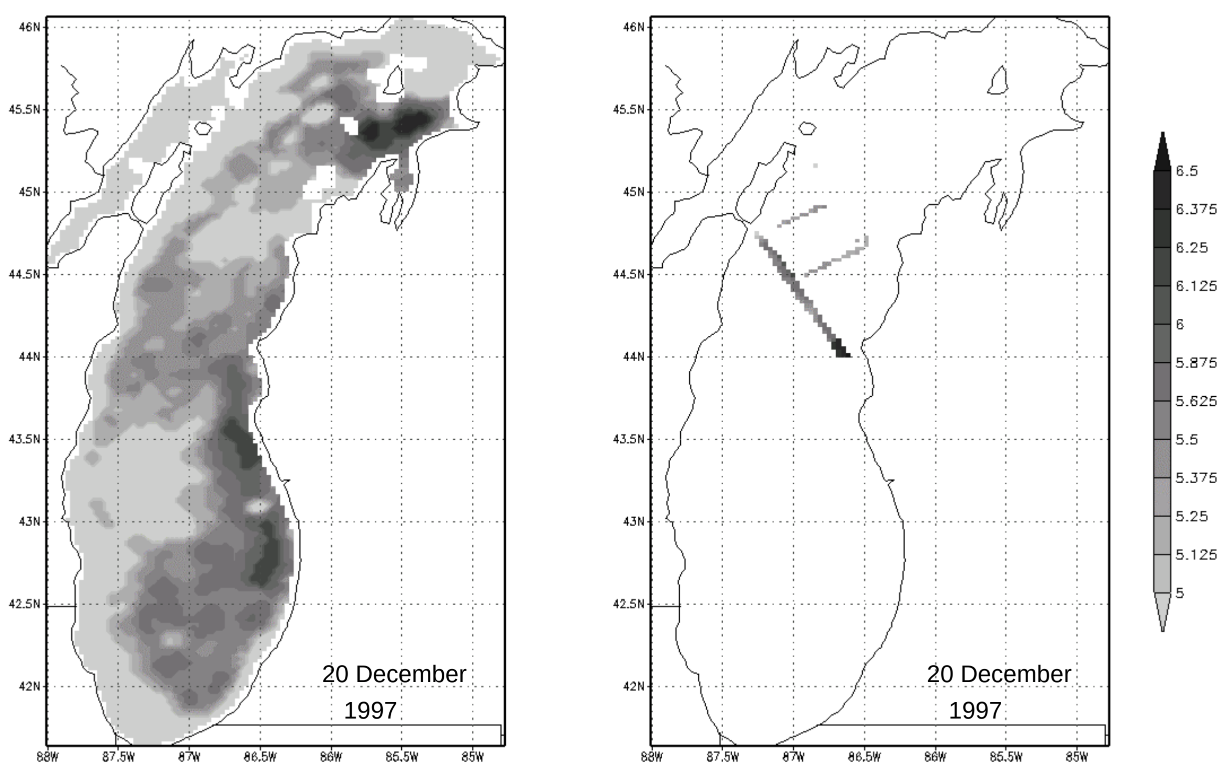

Figure 1. Lake surface temperatures from satellite (CoastWatch, panel 1a) and aircraft (Lake-ICE, panel 1b) observations.

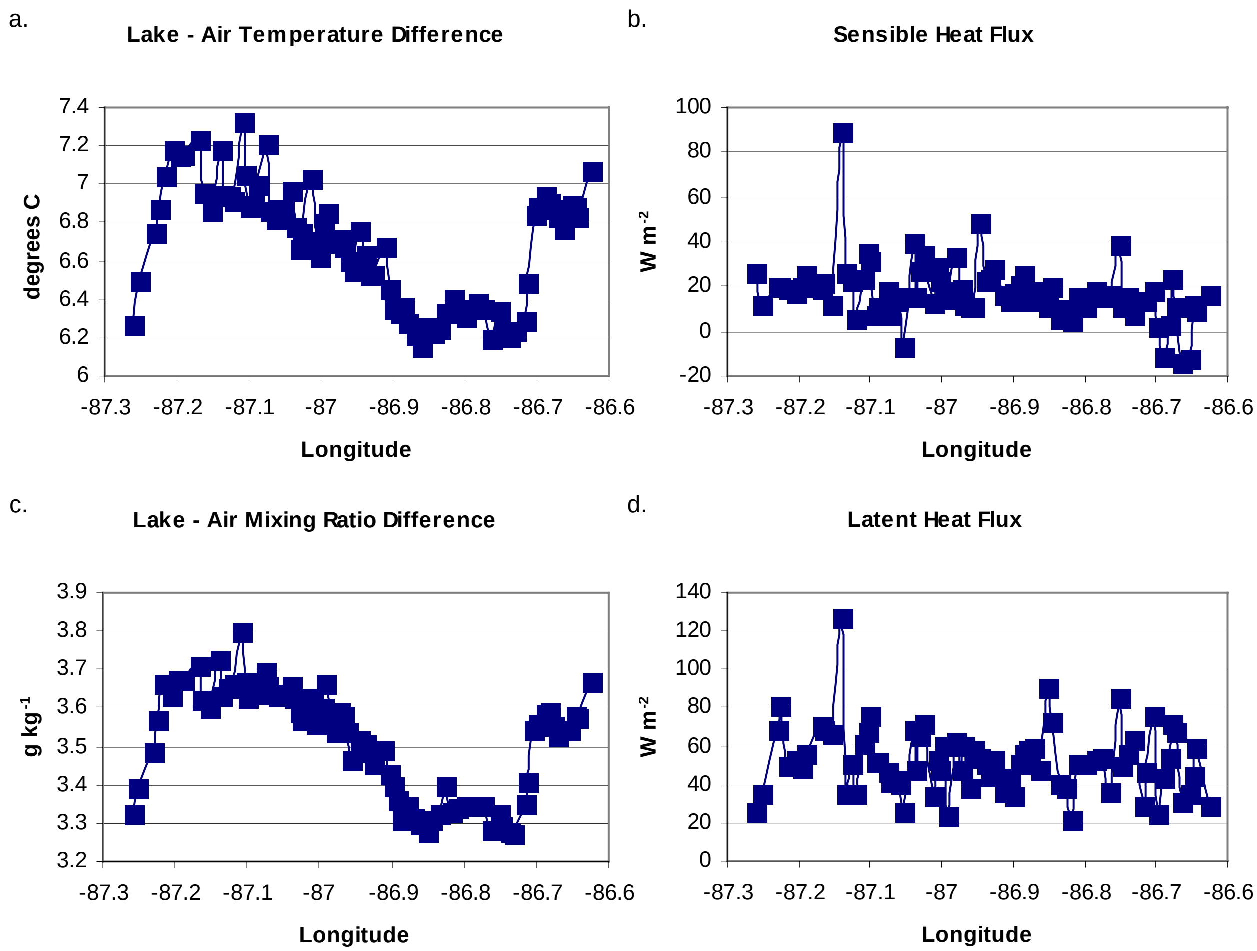

Figure 2. 20 December 1997 observations of lake-air temperature differences (panel 2a), sensible heat fluxes (panel 2b), lake-air mixing ratio differences (panel 2c), and latent heat fluxes (panel 2d). These data were taken along a Northwest-to-Southeast oriented flight track.

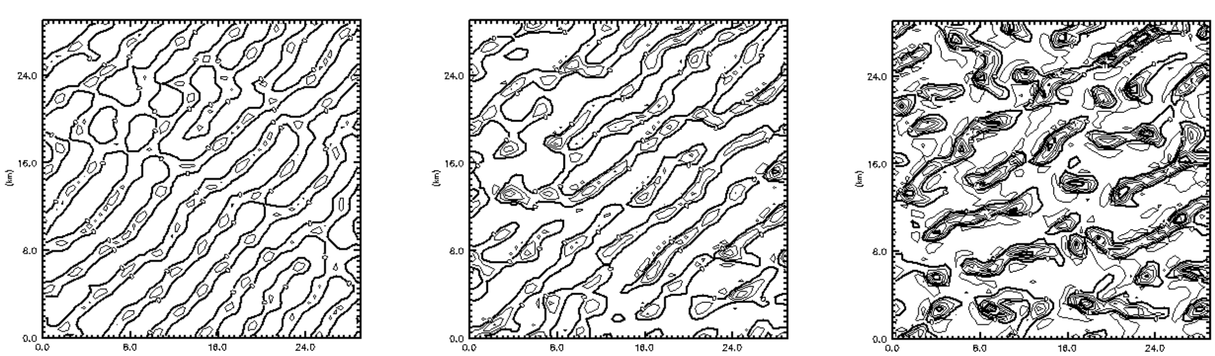

Figure 3. Numerical sensitivity experiments of vertical motion fields observed on 17 December 1983. Contours are every 0.5 m s^{-1}, with a lowest contour value of +0.5 m s^{-1}. Atmospheric conditions were kept constant while lake surface temperatures were varied from (left) 274 K, (middle) 277 K, to (right) 280 K.