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OBSERVED MESOSCALE VARIATIONS IN THERMODYNAMIC PROPERTIES AND SURFACE FLUXES OVER ICE-COVERED LAKE ERIE

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1. BACKGROUND

The presence of substantial pack ice cover on the Great Lakes modifies the local and large-scale atmospheric response to the lakes. While it is known that ice cover inhibits wintertime convection, cases of significant lake-effect snow development in such conditions have been documented (R. LaPlante, Cleveland NWSFO 2003, personal communication; Laird and Kristovich 2004). Several examples of significant lake-effect snow events downwind of nearly ice-covered Lake Erie are provided on the National Weather Service Buffalo forecasting office website (T. Niziol, Buffalo NWSFO, personal communication, 2002). Cordeira and Laird (2005) examined the evolution of snowfall regions and ice cover conditions for two lake-effect events over the eastern Great Lakes. These observations suggest that substantial sensible and latent heat fluxes can still occur over Great Lakes that are covered with high concentrations of ice and significant snowfall can occur in association with small regions of low ice concentration (percent of unit area of lake covered by ice).

The relationship between ice cover on the lakes and the atmospheric boundary layer response has received little attention in the scientific literature. In order to predict how ice cover influences the development of lake-effect snowstorms and the modification of extratropical cyclones, it is necessary to quantify how the transfer of heat from the lakes to the overlying atmosphere is influenced by different pack ice concentrations and arrangements. The Great Lakes Ice Cover – Atmospheric Flux (GLICAF) experiment was conducted in February 2004 to quantify the surface-atmosphere exchanges that occur over mid-latitude ice-covered lakes.

This paper describes initial findings from one of the GLICAF cases, 26 February 2004. The primary objectives of this presentation are to discuss the relationships between atmospheric thermodynamic properties, surface heat fluxes, and underlying lake-surface conditions and to explore reasons for their observed mesoscale variability.

2. DATA AND METHODS

During the GLICAF study, observations of surface pack ice concentration and turbulent surface heat fluxes (sensible and latent) were obtained over regions of variable ice concentration by the University of Wyoming King Air. The King Air was equipped with sensors for measuring atmospheric state, motion, radiation, and microphysical properties (standard instrumentation can be found at http://flights.uwyo.edu). Aircraft observations were averaged to 25 Hz, or about 3 m flight distance.

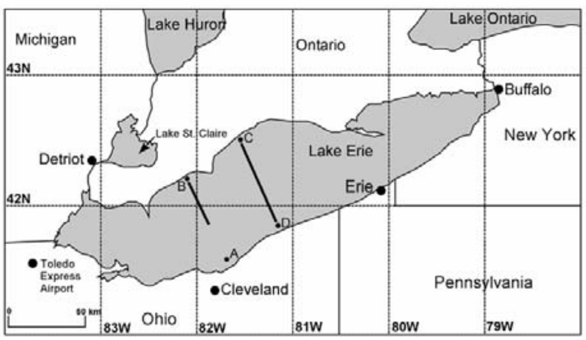

Figure 1. Locations of flight stacks AB and CD on 26 February 2004. The gap in the southern portion of stack AB reflects a region of low clouds. Data from this region are not included in the present study.

The data used in the current study were collected on 26 February 2004. Vertical sensible and latent heat fluxes were calculated from observations of vertical motion, potential temperature, and specific humidity using eddy correlation techniques. Perturbations in potential temperature, moisture, and vertical motion were calculated from 25 Hz data through the use of a moving average scheme with a 30 s (2.4 km) cutoff length scale to sufficiently capture the turbulent fluctuations of these variables. For the present investigation, downward-pointing radiometer (Heimann KT-19.85) observations are used to infer surface ice conditions. Comparisons between observations taken by a downward-directed video camera and Heimann

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KT-19.85 surface temperature measurements showed a close correspondence (Gerbush 2005).

Figure 1 shows locations of two flight stacks conducted by the UW King Air during the morning hours of 26 February 2004. Each flight stack was composed of two flux-observing legs (hereafter referred to as “flux legs”) conducted at approximately 45 m above the lake surface (ALS) and a flight leg flown at 500 m ALS to obtain high-resolution digital imagery of ice conditions. Flight legs were oriented approximately perpendicular to the mean boundary layer wind direction. The flux legs considered in this study ranged from 42 to 75 km in length.

3. FLUX AND ICE CONCENTRATION RELATIONSHIPS

During the morning of 26 February 2004, regional weather conditions were dominated by a surface high-pressure system (1039 hPa) located just to the east of Hudson Bay in Quebec, Canada. The associated anticyclonic flow around the high-pressure system resulted in winds from the ENE between the surface and 850 hPa over Lake Erie. Flux-leg wind speeds ranged from 3 – 7 m s^{-1}. Cloud cover was sparse, though high-level cirrus clouds occasionally drifted over the study area. Patches of dense fog were also present, particularly along the southern shore of Lake Erie. Observations collected in fog regions were removed from this analysis (Fig. 1). Flux-leg air temperatures from flight stacks AB and CD ranged from -3.5 to -1°C. Weak positive heat fluxes were anticipated as a result of small positive lake-air temperature differences (generally 0° to 2°C).

On 26 February 2004, the National Ice Center analysis indicated that a large percentage of Lake Erie was covered with ice. The central basin, where GLICAF measurements were collected, possessed ice concentrations above 90%, except for areas of open water along the northern and southern shores of the lake. Radiometric surface temperatures ranged from -2°C in regions of ice cover to near 0°C in areas of open water. Pass-mean turbulent sensible and latent heat fluxes were found to be consistently positive despite extensive ice cover, small differences between flux-leg air temperatures and lake-surface temperatures, and relatively light wind speeds. Pass-mean sensible and latent heat fluxes ranged from 1 to 6 Wm^{-2}.

UW King Air measurements indicate that there was a close correspondence between lake-surface temperature and air temperature along the flux legs. For example, Figure 2 shows measured flight-level temperature and water vapor content at 45 m ALS, and estimated values for the surface based on Heimann radiometric surface temperature observations. Note the strong correspondence between the spatial trends in lake-surface temperature and air temperature, suggesting an important thermal link between the surface and the boundary layer. A general correspondence was observed for atmospheric vapor content, but the correlation was lower than for temperature.

In order to examine the relationship between spatial heat flux patterns and lake-surface conditions, each flux leg was divided into segments ranging from 5 s (400 m) to 60 s (4.8 km). In each segment, the percentage of Heimann radiometric surface temperature observations below -0.5°C was used to provide a proxy for ice concentration. Additionally, turbulent sensible and latent heat fluxes were calculated for each segment. Figure 3 shows sensible and latent heat fluxes for 30 s intervals plotted as a function of the percentage of Heimann radiometric temperature observations below -0.5°C for flight stack CD.

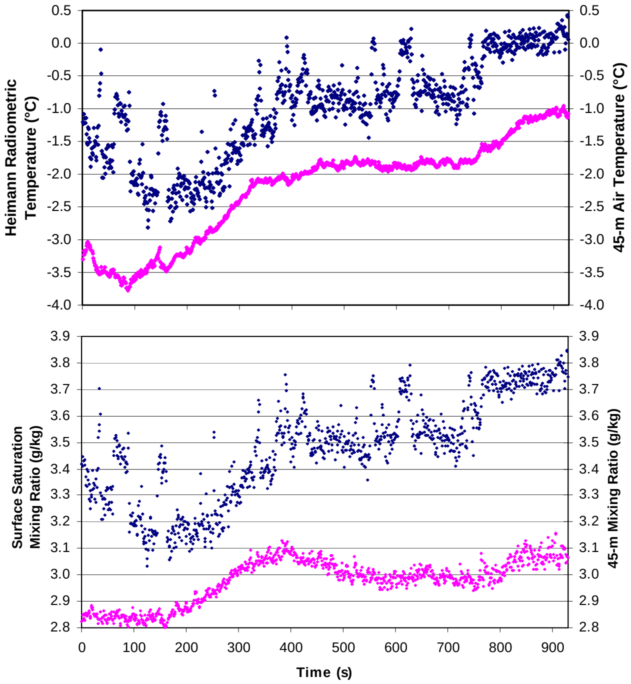

Figure 2. ***(top)*** *Surface temperature observations by the Heimann KT 19.85 radiometer (blue) and flight-level temperature observations (pink) taken at 45-m height during flight leg CD2.* ***(bottom)*** *Estimated surface mixing ratios assuming saturated conditions at temperatures observed by the Heimann radiometer (blue) and flight-level mixing ratio (pink).*

The data presented in Figure 3 suggest that turbulent fluxes of heat and moisture were generally greater over portions of the lake characterized by larger percentages of open water. Likewise, areas of particularly high ice concentrations had a tendency to possess weaker surface fluxes, indicating that the modification of the atmospheric boundary layer was strongly influenced by the ice-cover conditions on the lake surface.

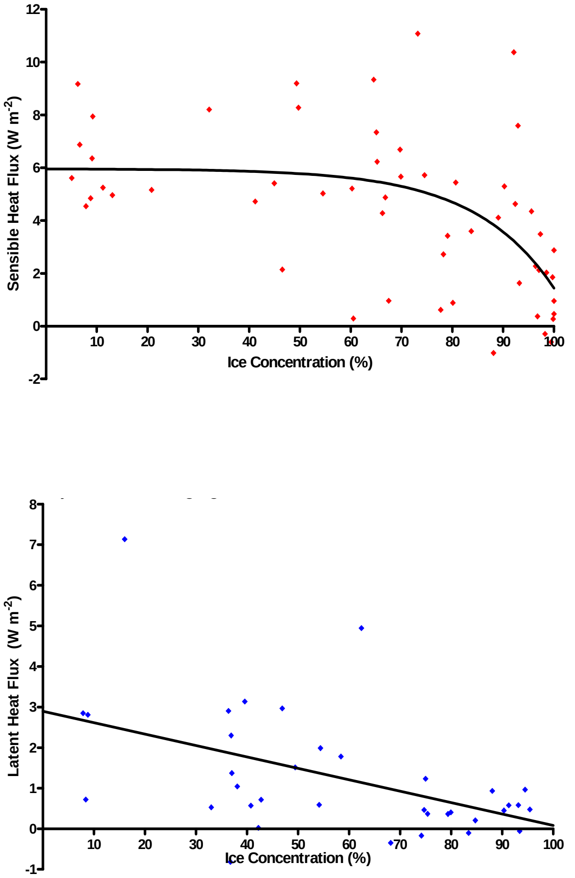

Figure 3. Surface sensible heat flux (red) and latent heat flux (blue), averaged over 30-second time intervals, during a pass in flight stack CD on 26 February 2004.

4. MESOSCALE VARIATIONS IN THERMODYNAMIC VARIABLES AND SURFACE FLUXES

Lake-surface pack ice concentrations, atmospheric thermodynamic characteristics, and surface heat fluxes varied significantly across Lake Erie during the morning of 26 February 2004. For example, Figure 2 indicates cold air temperatures and lower water vapor contents near the beginning of flight leg CD2, which corresponds to the southern portions of Lake Erie. Similar mesoscale variations were observed for the other flight legs in stacks AB and CD.

The reason for this variation is illustrated in Figure 4. As the morning progressed, the land areas around Lake Erie warmed more quickly than the lake. Air warmed by the nearby land areas would have been advected to the northern portions of the flight stacks. In addition, pack ice cover increased from north to south over the lake. These factors combined to produce the observed warmer temperatures in the northern sections of flight stacks AB and CD. Southern portions of the flight stacks sampled air that had moved along a much larger over-lake fetch, over regions where ice concentrations were considerably larger than further north. This resulted in a local cold-pool of air in the southern portions of the flight stacks.

The observed variations in surface ice and atmospheric conditions had a noticeable impact on surface heat flux magnitudes. Most of the surface flux observations over portions of the lake with high ice concentrations (right-hand sides of the two panels in Figure 3) were over southern regions of Lake Erie. Because of the higher ice concentrations, surface fluxes were generally lower over these regions. However, since air temperatures were lower in southern regions, surface sensible heat fluxes appeared to be highly sensitive to small variations in surface ice concentrations. Note in Figure 3 (top), for example, that surface sensible heat fluxes increased to near open-water values as ice concentrations decreased from near 100% to 80%. A similar response was not observed for latent heat fluxes, which will be discussed in the presentation. To fully understand the interchanges between surface, air, and turbulent flux exchange processes, further detailed observational and numerical modeling investigations must be conducted.

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5. REFERENCES

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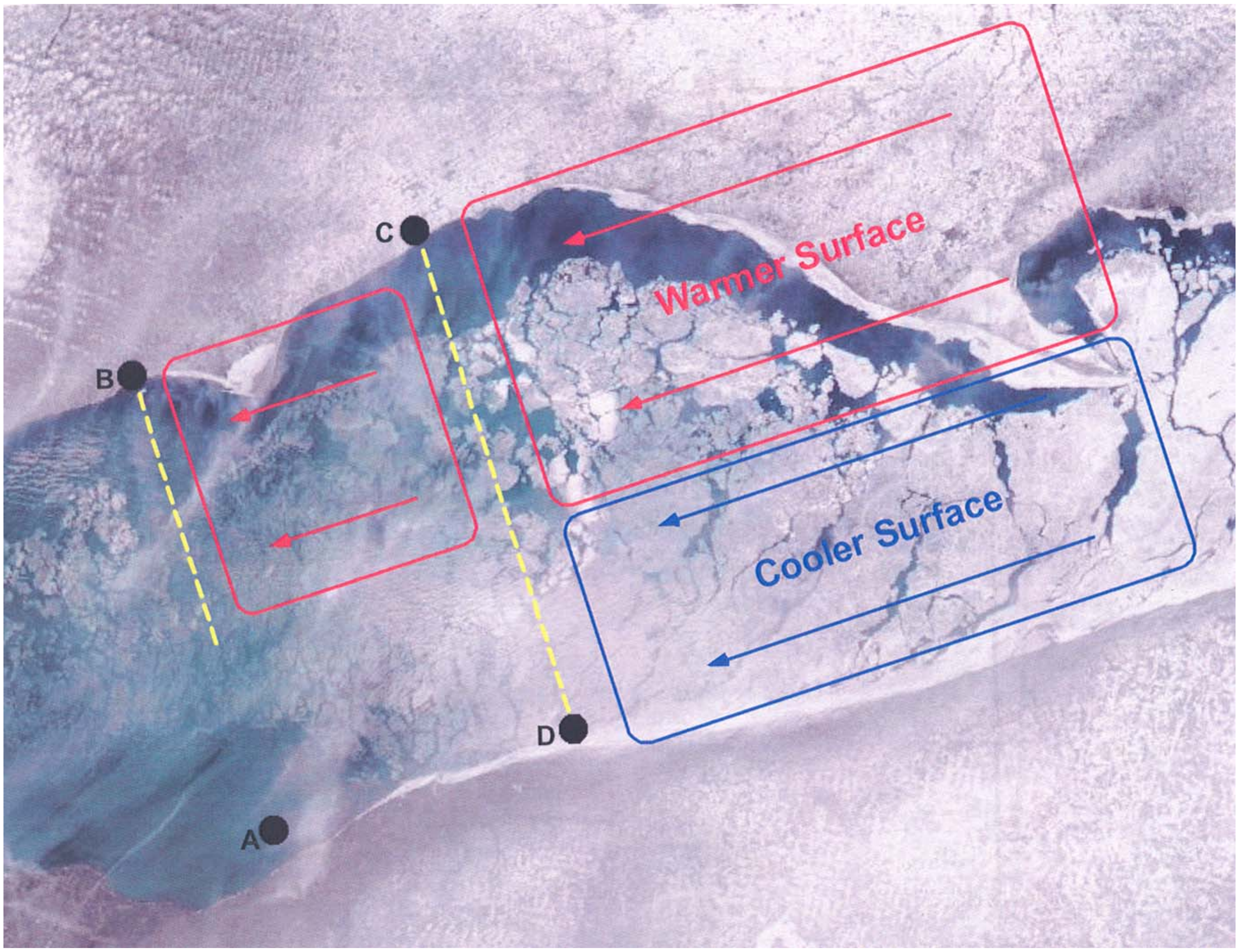

Figure 4. MODIS satellite visible-wavelength image of Lake Erie on 26 February 2004. Flight stacks AB and CD (yellow, dashed lines) are indicated. Regions of warmer and colder surface conditions are also illustrated.