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SURFACE HEAT FLUXES OVER LAKE ERIE PACK ICE FIELDS

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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. It is necessary to understand how the transfer of heat from the lakes to the overlying atmosphere is influenced by different pack ice concentrations and arrangements because this transfer directly affects the development and intensity of lake-effect snowstorms and extratropical cyclones. 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.

Most of the ice on the Great Lakes is pack ice, which is not attached to the shore. Pack ice cover can be highly variable, especially in mid-lake regions where high winds, precipitation, and changing air masses can lead to rapid changes in ice-cover configuration and thickness. Lake Erie possesses the most extensive long-term average peak ice coverage (90%) of all the Great Lakes. Lake Erie ice cover typically reaches maximum areal extent in late February or early March (Assel 1999). The GLICAF experiment was carried out during late February to coincide with the climatological peak in ice coverage on Lake Erie.

While nearly all published work on lake-effect boundary layer development has been on ice-free lake cases, several studies have illustrated the atmospheric response to variations in lake-surface characteristics. Data collected during the Lake-Induced Convection Experiment (Lake-ICE, Kristovich et al. 2000) were used in numerous studies to document the development of lake-effect boundary layers and subsequent mesoscale circulations above ice-free lake regions (e.g., Young et al. 2000, Schroeder 2002, Kristovich et al. 2003). One study from this experiment suggested that local variations in lake-surface temperature influenced observed spatial variations in surface heat fluxes over ice-free Lake Michigan (Kristovich et al. 2001). A more recent investigation noted that ice-cover was present during many lake-effect events, with some events occurring when ice concentrations exceeded 80% over the entire lake (Laird and Kristovich 2004). This unexpected result demonstrates that the response of the atmospheric boundary layer to lake surfaces possessing substantial pack ice cover is not well understood.

Research involving the boundary-layer response over ice-covered water has generally been confined to Arctic regions. Several of these investigations examined the surface heat fluxes and associated atmospheric circulations found above Arctic leads (e.g., Alam and Curry 1995, Pinto et al. 1995, Zulauf and Krueger 2003). A key difficulty in applying the results from Arctic lead studies is that the environmental conditions (e.g., lake-air temperature difference and near-surface static stability, thickness and stability of ice fields) during these investigations differed from typical mid-winter conditions found in the Great Lakes region. The main goal of the GLICAF field experiment was to obtain unprecedented observations of the boundary layer response to lakes covered by pack ice of varied concentrations. This paper describes initial findings from one of the GLICAF cases during 26 February 2004.

2. DATA AND METHODS

During the GLICAF field project, 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. Observations of ice cover were collected by a downward-directed video camera that gave a visual image of surface conditions from 500 m above the lake surface (ALS). Surface temperature measurements were obtained by a downward-pointing radiometer (Heimann KT-19.85). These additional measurements are used in this study to distinguish between areas of ice cover and open water. Figure 1 illustrates the close correspondence between the digital image information and Heimann temperature observations during a flight segment on 26 February 2004. In this example, surface temperatures dropped suddenly from around 0°C to -1.25°C as the aircraft flew across a transition from open water to ice. For this study, the Heimann radiometer observations are used to infer surface ice conditions.

The data used in the current study were collected over Lake Erie during 26 February 2004. Vertical sensible and latent heat fluxes were calculated from observations of vertical motion, potential temperature,

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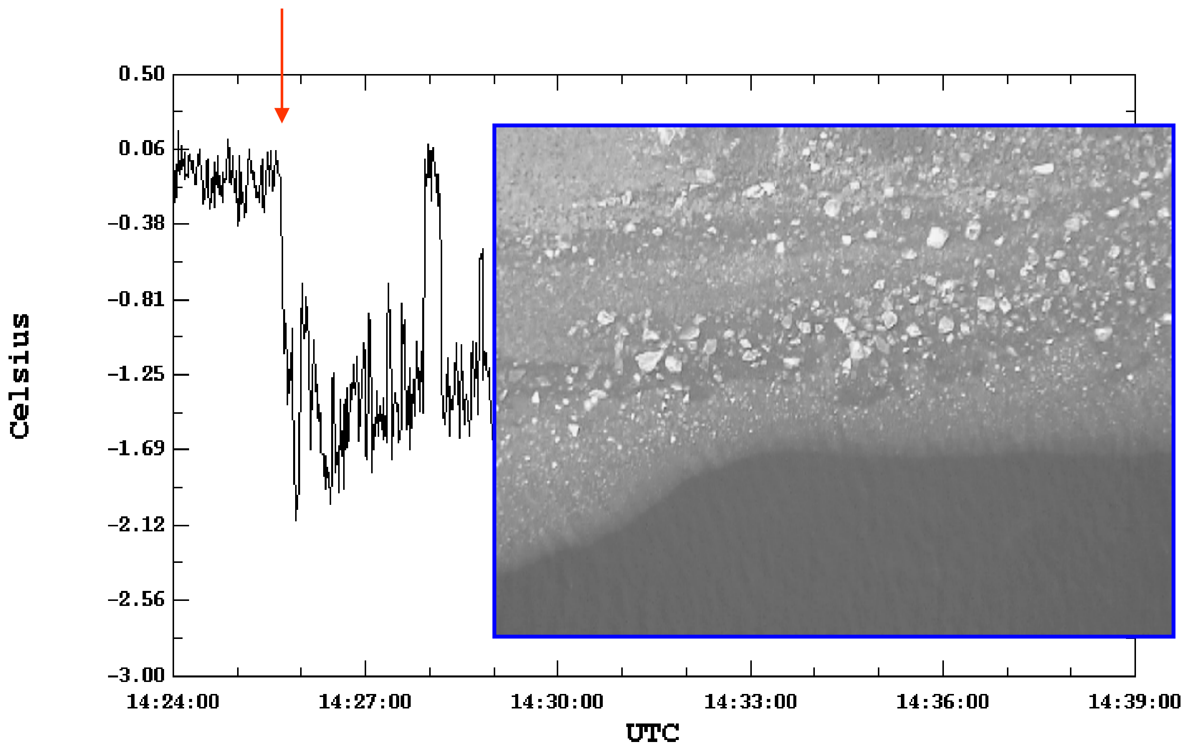

Figure 1. Example of changes in Heimann radiometric temperature when the aircraft flew over a water-ice boundary. The plot is of Heimann radiometric temperature as a function of time on 26 February 2004. The red arrow shows the time of the inset video image. In the video image, the aircraft is flying from bottom to top.

and specific humidity using eddy correlation techniques. Perturbations in potential temperature and moisture were calculated from 25 Hz data through the use of a moving average scheme with a 1-km cutoff length scale to sufficiently capture the turbulent fluctuations of these variables (Sun et al. 1996). Perturbations in vertical motion were determined by subtracting pass-mean vertical motion from the observed values.

Flight operations on 26 February 2004 were characterized by four two-altitude flight stacks and spiral soundings to about 2 km ALS at the endpoints of each stack. Each flight stack was composed of two flux-observing legs (hereafter referred to as "flux legs") conducted at approximately 45 m ALS and a flight leg flown at 500 m ALS to obtain video observations of ice conditions. Flight legs were oriented approximately perpendicular to the mean boundary layer wind direction. The present study focuses on the first two flight stacks from 26 February, as changes in boundary layer conditions during the course of the day (discussed below) warranted the separate treatment of flight stacks from the second half of the flight day. The flux legs considered in this study ranged from 42 to 75 km in length.

3. SYNOPTIC AND MESOSCALE OVERVIEW

During the morning of 26 February 2004, regional weather conditions were dominated by a surface 1039 mb high-pressure system located just to the east of Hudson Bay in Quebec, Canada. The associated anticyclonic flow around the high-pressure system generally 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. Flux-leg temperatures from the passes considered in this study 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).

Analyses of surface and aircraft observations provide evidence of a lake-induced secondary circulation during the second half of the study day. The finding of a lake breeze is somewhat surprising given that positive surface heat fluxes were present over the lake throughout the day. Indications of a lake-breeze circulation were first evident during the late morning (around 1500 UTC) of 26 February 2004 along the southern shore of Lake Erie, where several surface stations in the vicinity of the flight stacks began reporting onshore breezes. Aircraft wind data show that during the final two flux legs, onshore flow became established close to the endpoints of the passes near the northern and southern shores of Lake Erie.

Furthermore, the presence of negative half-minute mean vertical motions and lower atmospheric moisture near the center of the lake during the flux legs later in the day suggest that subsidence may have been established. The present investigation focuses only on the first two flight stacks when no lake breeze was observed. Future analyses will address the relationships between surface fluxes and ice cover during flight stacks flown in lake-breeze conditions on 26 February 2004.

4. SURFACE CONDITON – SURFACE FLUX RELATIONSHIPS

On 26 February 2004, the National Ice Center ice concentration (percent of unit area of lake covered by ice) 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 just above 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}.

Measurements indicate that there was a close correspondence between lake-surface temperature and air temperature along the flux legs. An example of this is illustrated in Figure 2, which shows a strong agreement between the spatial trends in lake-surface temperature and air temperature. This finding suggests that flux-leg air temperatures were strongly related to the underlying lake-surface conditions.

In order to examine the relationship between spatial flux patterns and lake-surface conditions, each flux leg was divided into 5-km segments. In each segment, the percentage of Heimann radiometric temperature observations above 0°C (representing open water) was used to provide a proxy for ice concentration. Additionally, turbulent sensible and latent fluxes were calculated for each 5-km segment. Figure 3 shows sensible and latent heat fluxes plotted as a function of the percentage of Heimann radiometric temperature observations above 0°C for 16 different 5-km segments over Lake Erie.

The data presented in Figure 3 suggest that turbulent fluxes of heat and moisture were generally greater over portions of the lake characterized by a larger percentage 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.

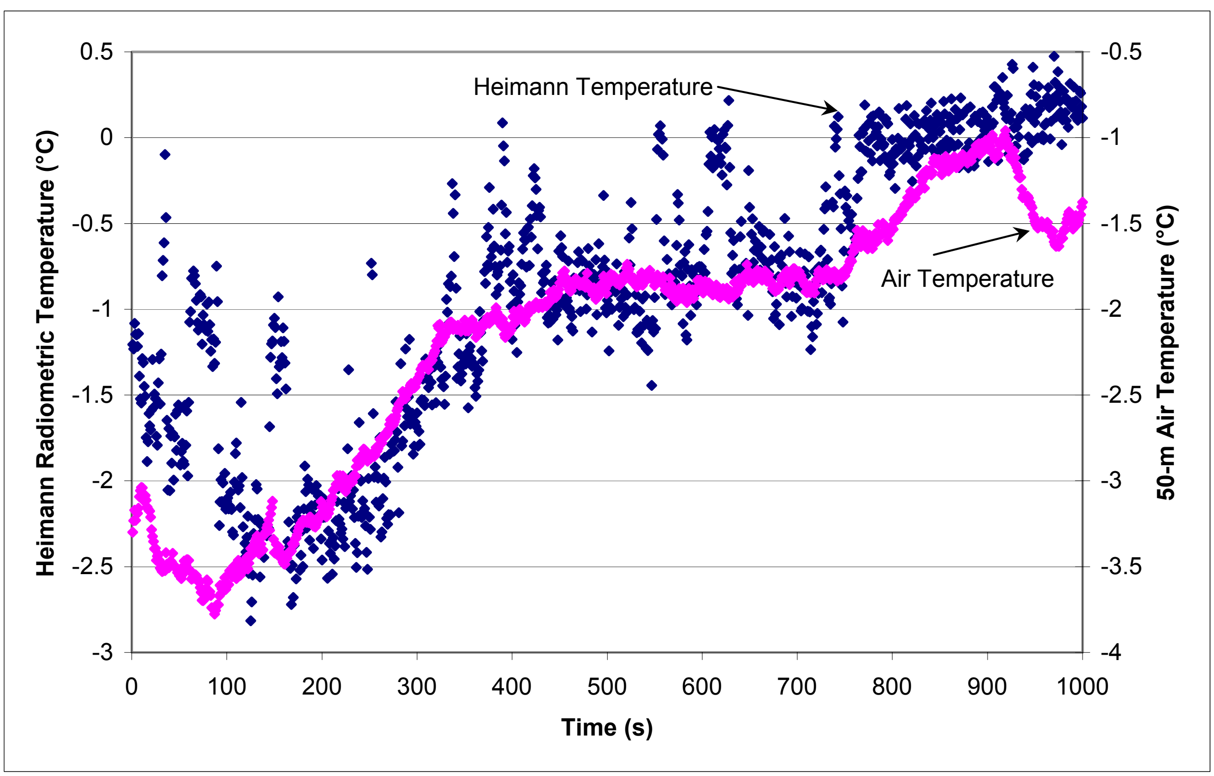

Figure 2. Time series of Heimann radiometric temperature and air temperature from a flux leg on 26 February 2004. Data were collected by the University of Wyoming King Air at an altitude of approximately 45 m.

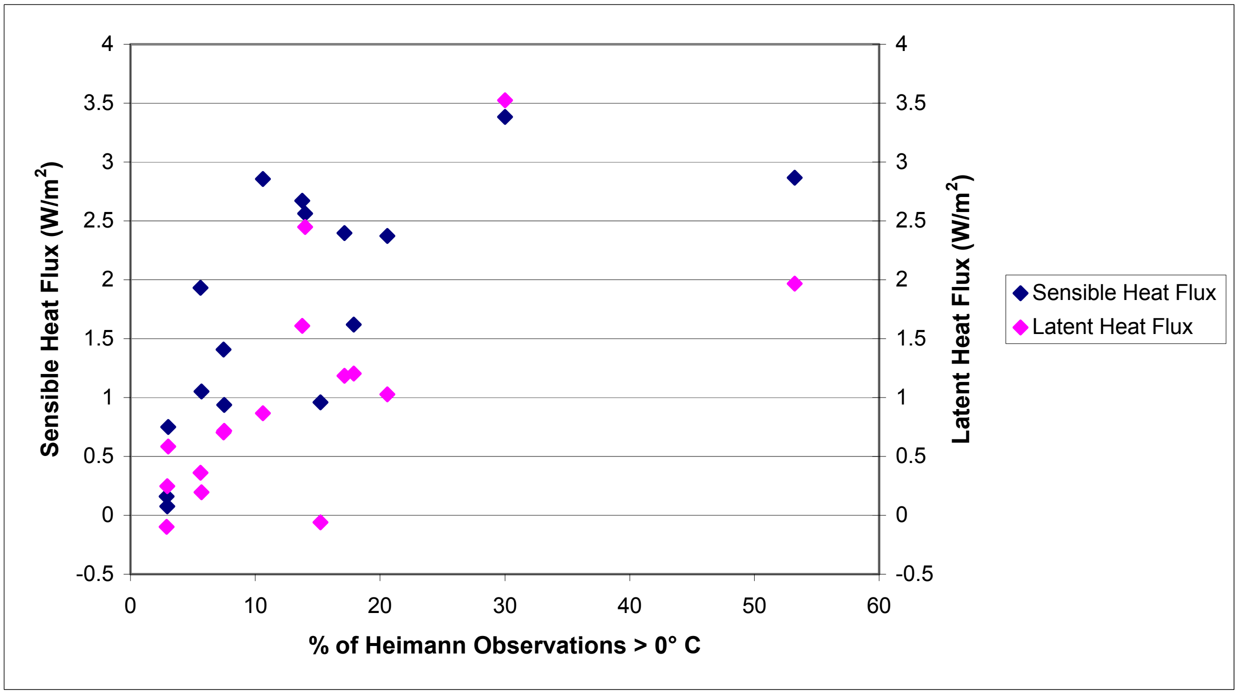

Figure 3. Turbulent sensible and latent heat flux plotted as a function of the percentage of Heimann radiometric temperature observations above 0˚C. Fluxes and Heimann percentages were calculated over 5-km flight segments during two flux legs within a single flight stack on 26 February 2004.

5. SUMMARY AND CONCLUSIONS

The primary goal of the Great Lakes Ice Cover – Atmospheric Flux (GLICAF) project is to better understand the relationship between Great Lakes pack ice cover and the associated turbulent fluxes of heat and moisture. Initial findings from aircraft data collected on 26 February 2004 over ice-covered Lake Erie indicate that in this case, patterns in ice cover had a measurable effect on air temperature profiles along flux legs. One possible explanation for the close correspondence between surface temperature and flux-leg air temperature is that surface turbulent heat fluxes were strongly controlled by lake-surface ice-cover conditions. Indeed, comparisons of radiometer estimates of ice concentration to turbulent latent and sensible heat fluxes show that surface heat and moisture fluxes over 5-km flight segments negatively correlate with ice concentration. This finding suggests that the correspondence of air temperature to lake-surface conditions is, at least in part, the result of the spatial patterns of surface heat fluxes relating to the underlying lake-surface ice cover. Future work will attempt to determine the sensitivity of surface fluxes to the spatial variability of ice concentration. Additional analyses will also address the nature of turbulent heat fluxes during the second half of the flight day on 26 February 2004, when a lake-breeze circulation was established.

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6. REFERENCES

Alam, A. and J. A. Curry, 1995: Lead-induced atmospheric circulations. *J. Geophys. Res.*, **100**, 4643–4651.

Assel, R. A., 1999: Great Lakes Ice Cover (chapter 6), *Potential Climate Change Effects on Great Lakes Hydrodynamics and Water Quality.* D. C. L. Lam and W. M. Schertzer, Eds., American Society of Civil Engineers, 6: 1–21.

Kristovich, D. A. R. and 21 coauthors, 2000: The Lake-Induced Convection Experiment and the Snowband Dynamics Project. *Bull. Amer. Meteor. Soc.*, **81**, 519–542.

—, M. C. Peters, and M. S. Timlin, 2001: Spatial variations of surface temperatures and heat fluxes over Lake Michigan. Preprints, *11th Conf. Interactions of Sea and Atmos.*, 142–145.

—, N. F. Laird, and M.R. Hjelmfelt, 2003: Convective evolution across Lake Michigan in a lake-effect snow event. *Mon. Wea. Rev*., **131**, 643–655.

Laird, N .F., and D. A. R. Kristovich, 2004: Comparison of observations with idealized model results for a method to resolve winter lake-effect mesoscale morphology. *Mon. Wea. Rev*., **132**, 1093–1103.

Pinto, J. O., J. A. Curry, and K. L. McInnes, 1995: Atmospheric convective plumes emanating from leads. Part 1: Thermodynamic structure, *J. Geophys. Res.*, **100**, 4621–4631.

Schroeder, J. J., 2002: Observed Changes to a Lake-Induced Convective Boundary Layer in the Vicinity of a Synoptic Cyclone. M.S. Thesis, The University of Illinois, 139 pp.

Sun, J., J. F. Howell, S. K. Esbensen, L. Mahrt, C. M. Greb, R. Grossman, M. A. LeMone, 1996: Scale dependence of air-sea fluxes over the western equatorial Pacific. *J. Atmos. Sci.*, **53**, 2997–3012.

Young, G. S., B. K. Cameron, E. E. Hebble, 2000: Observations of the entrainment zone in a rapidly entraining boundary layer. *J. Atmos. Sci.*, **57**, 3145–3160.

Zulauf, M. A., and S. K. Krueger, 2003: Two-dimensional cloud-resolving modeling of the atmospheric effects of Arctic leads based upon midwinter conditions at the Surface Heat Budget of the Arctic Ocean ice camp. *J. Geophys. Res.*, **108(D10)**.