Variations of Sensible and Latent Heat Fluxes from a Great Lakes Buoy and Associated Synoptic Weather Patterns

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ABSTRACT

An investigation of sensible and latent heat fluxes and their relation to synoptic weather events was performed using hourly meteorological measurements from National Data Buoy Center buoy 45003, located in northern Lake Huron, during April–November of 1984. Two temporal heat flux regimes were found to exist over Lake Huron. The first period extended from April through July and was characterized by periods of modest negative (downward) heat fluxes. The second regime was marked by periods of large positive (upward) heat fluxes and occurred from August through November. This later period accounted for 95%–100% of both the total positive sensible and latent heat fluxes. In addition, a comparison of the seasonal evolution of sensible and latent heat fluxes showed the transition from the negative to the positive flux regime occurred 10–20 days earlier for latent heat flux than for sensible heat flux. A notable, statistically significant increase of the surface heat flux variability from the negative to positive flux regimes with a general decrease in the near-surface atmospheric stability during the positive flux regime was found. During both flux regimes, the magnitude of surface sensible and latent heat fluxes remained coupled to transient synoptic-scale weather events. On average, the occurrences of minimum (maximum) heat fluxes preceded time periods of low (high) sea level pressure by 0–3 h during the negative flux regime. For the positive flux regime, maximum (minimum) surface heat fluxes followed the passage of low (high) pressure by approximately 24 h. In addition, maximum (minimum) sensible and latent heat fluxes preceded synoptic high (low) pressure by approximately 16 h. Typical synoptic surface weather patterns were identified for both significant positive and negative heat flux events, time periods when the atmosphere–lake heat exchange was maximized.

1. Introduction

Sensible and latent heat fluxes represent the turbulent exchange of heat between the surface and overlying atmosphere. The calculation of representative heat fluxes is a critical component for simulating and examining the global moisture and surface heat budgets. In general, the numbers of investigations of heat fluxes over oceanic regions largely outweigh studies performed in association with inland water bodies (e.g., Laurentian Great Lakes). A large amount of the global and oceanic research has focused on the derivation of appropriate methods to estimate fluxes from readily available data (e.g., Large and Pond 1982). Recent studies addressing the scientific issues of climate change and variability have discussed the need to quantitatively measure and better understand surface–atmosphere exchange processes (e.g., Bates et al. 1995; Betts et al. 1996). In addition, having reliable measurements of the magnitude and variability of surface sensible and latent heat fluxes is important for the development of regional climate models and the verification of regional climate simulations because of the significance of local processes on the kind and intensity of weather experienced in a region.

The existing research on Great Lakes surface heat fluxes has primarily focused on the regional water and energy balances used to examine changes in lake levels, water supply, and the Great Lakes basin hydrologic cycle (e.g., Croley 1989). For these purposes, monthly average values are generally adequate, and examination of short-term (e.g., daily or hourly) fluctuations of heat fluxes over extended periods has not been necessary. Specific meteorological events (e.g., cyclones, cold-air outbreaks) can often cause the largest magnitudes of heat exchange between the atmosphere and Great Lakes (i.e., positive or negative) and lead to large temporal variability of heat fluxes. As examples, Kristovich and Laird (1998) showed that total heat fluxes varied between approximately 100 and 700 W m^{-2} during five cold-air outbreaks over Lake Michigan. These variations, in turn, affected the rate at which clouds formed

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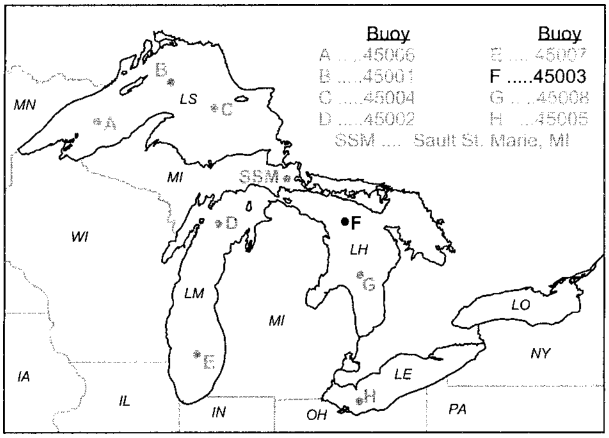

FIG. 1. Map of National Data Buoy Center buoy locations in the Great Lakes region. Buoy 45003 (location F) measurements are used for this investigation.

over the lake. Miner et al. (2000) found latent heat fluxes fluctuated between about 50 and 450 W m^{-2} during a 2-day period as a cyclone passed over Lake Huron, significantly affecting cyclone intensity and movement. The current article examines the seasonal and short-term fluctuations of surface heat fluxes measured by a moored buoy over an 8-month period and the synoptic-scale meteorological conditions associated with the largest-magnitude flux events.

2. Data and surface heat flux calculations

The National Data Buoy Center (NDBC) has maintained instrumented buoys in the Great Lakes since 1979 with the introduction of buoy 45001 in central Lake Superior. During 1980 and 1981, several additional buoys were deployed in each of the Great Lakes except Lake Ontario. Figure 1 shows the locations of the eight NDBC buoys currently sited in the Great Lakes. Each of the buoys in the Great Lakes carries a payload of instruments that routinely measure air temperature (4-m height), wind speed and direction (5-m height), sea level pressure, and lake surface temperature (1.0-m depth). Wind speeds are reported to the nearest knot (0.5 m s^{-1}), directions to the nearest 10°. These measurements are recorded hourly using an 8-min averaging period. Gilhousen (1987) evaluated measurements from NDBC buoys and found the uncertainties of wind speed, wind direction, air and lake temperatures, and sea level pressure were less than $\pm$1.0 m s^{-1}, $\pm$11°, $\pm$1.0°C, and $\pm$1.0 hPa, respectively.

Data used for this investigation were collected in 1984 by buoy 45003 [6-m Naval Oceanographic and Meteorological Automated Device (NOMAD) buoy], located in northern Lake Huron. This dataset was chosen because atmospheric humidity data were obtained during the time period in addition to the collection of standard variables. The NDBC buoys have typically not been equipped with humidity sensors, due in part to the difficulty in obtaining reliable measurements of boundary layer moisture from unattended instruments over open waters for extended time periods (e.g., Breaker et al. 1998). However, from April through November of 1984 special hourly humidity measurements were made at buoy 45003 and archived by NDBC. The collection of a full suite of meteorological measurements allowed for the derivation of hourly sensible and latent heat fluxes over the April–November 1984 time period. Figures 2a,b show the time series of lake surface, air, and dewpoint temperatures over the 8-month period. The seasonal variations and short-term temporal fluctuations in the temperatures and heat fluxes will be examined and discussed in sections 3 and 4.

The humidity measurements were obtained using a Vaisala, Inc., HMP 111A sensor. Subsequent testing by NDBC of the relative humidity measurement accuracy associated with the Vaisala humidity sensor has shown measurement uncertainty of $\pm$4.8% RH in the 0%–80% range and $\pm$5.8% RH in the 80%–100% range (Meindl 1987; Michelena 1987). The larger uncertainty for relative humidities above 80% RH suggests that the largest potential errors could occur for negative and small positive latent heat fluxes. Applying $\pm$6% uncertainties to the relative humidity measurements suggested that the potential error would produce a mean difference in our presented latent heat fluxes of $\pm$3.1 W m^{-2} with a standard deviation of $\pm$4.7 W m^{-2}. This small potential error in latent heat fluxes does not significantly affect the conclusions of this study given our focus on surface heat flux temporal variability and synoptic weather patterns associated with large-magnitude heat flux events.

In addition, laboratory and field tests have suggested that similar Vaisala humidity sensors may have recovered slowly (e.g., 36–48 h) following periods of saturation in fog and continued to record high humidity values not representative of the environment (e.g., Muller and Beekman 1987). The time series and temporal variability of atmospheric variables at buoy 45003 and a nearby shoreline site [Sault St. Marie, Michigan (SSM); see Fig. 1] were examined to determine the validity of the humidity measurements following time periods of saturation at buoy 45003. There were only 11 occurrences of time periods with RH $>$95% for at least 24 h. We found that the humidity data from buoy 45003 were physically consistent and meaningfully correlated with temporal changes in atmospheric variables at buoy 45003 (e.g., pressure, temperature, and winds) and in the region (i.e., SSM: humidity, pressure, temperature, and winds). Therefore, we have chosen to use all measured data in our analyses and not to remove data directly following periods of saturation.

Surface heat fluxes were calculated from the hourly buoy measurements using the method described by Quinn (1979) and Croley (1989). The method applies the Monin and Obukhov (1954) similarity hypothesis to field measurements in the atmospheric surface layer, a region in which turbulent fluxes are taken as approximately constant with height. The equations for sensible and latent heat flux are

$$H_S = -C_p \rho k U_* \theta_* \quad \text{and} \tag{1}$$

$$H_L = EL_v = -L_v \rho k U_* q_*, \tag{2}$$

where H_S is sensible heat flux, H_L is latent heat flux, E is vapor flux, L_v is latent heat of vaporization, C_p is specific heat at constant pressure for dry air, k is von Kármán's constant, ρ is air density, U_* is friction velocity, θ_* is scaling temperature, and q_* is scaling specific humidity.

The friction velocity, scaling temperature, and scaling specific humidity are estimated by

$$U_* = Uk[\ln(z/z_0) - S_1]^{-1}, \tag{3}$$

$$\theta_* = (\theta_a - \theta_w)[\ln(z/z_0) - S_2]^{-1}, \quad \text{and} \tag{4}$$

$$q_* = (q_a - q_w)[\ln(z/z_0) - S_2]^{-1}, \tag{5}$$

where U is the wind speed at the reference height, z is the reference height (4.5 m was used to account for wind and temperature measurements collected at 5.0 and 4.0 m above the lake surface, respectively), z_0 is the roughness length, S_1 and S_2 are stability-dependent parameters, θ_a and q_a are the potential temperature and specific humidity at the reference height, θ_w is the potential temperature of the water surface, and q_w is the saturation specific humidity at the temperature of the water surface.

Following Panofsky (1963) and Paulson (1970), the stability dependence of S_1 and S_2 are defined by

$$\begin{aligned} S_1 &= 2\ln\{[1 + (1 - a_1 z/L_M)^{1/4}]/2\} \\ &\quad + \ln\{[1 + (1 - a_1 z/L_M)^{1/2}]/2\} \\ &\quad - 2\tan^{-1}(1 - a_1 z/L_M)^{1/4} + \pi/2 \\ &\qquad\qquad z/L_M \le 0 && \text{(6a)} \\ &= -a_2 z/L_M \qquad 0 < z/L_M < 1 && \text{(6b)} \\ &= -a_2[1 + \ln(z/L_M)] \qquad z/L_M \ge 1 && \text{(6c)} \end{aligned}$$

$$\begin{aligned} S_2 &= 2\ln\{[1 + (1 - a_3 z/L_M)^{1/2}]/2\} \\ &\qquad\qquad z/L_M \le 0 && \text{(7a)} \\ &= -a_2 z/L_M \qquad 0 < z/L_M < 1 && \text{(7b)} \\ &= -a_2[1 + \ln(z/L_M)] \qquad z/L_M \ge 1, && \text{(7c)} \end{aligned}$$

where L_M is the Monin–Obukhov length,

$$L_M = -U_*^3 C_p \rho \gamma/(kgH_S) \tag{8}$$

and the roughness length is given using the Charnock (1955) relationship,

$$z_0 = a_4 U_*^2/g. \tag{9}$$

The quantities a_1, a_2, a_3, and a_4 are empirical coefficients; γ is the absolute temperature of near-surface air; and g is the gravitational acceleration rate. From observations collected during the International Field Year on the Great Lakes (IFYGL), Quinn (1979) acquired values of $a_1 = 16$, $a_2 = 5.2$, $a_3 = 16$, and $a_4 = 0.0101$ for large lakes. A value of $k = 0.41$ was deemed appropriate based on a review by Hicks (1976). These values are used for this investigation, and the methods are consistent with approaches used for several other investigations of Great Lakes surface fluxes (e.g., Quinn 1979; Croley 1989; Lofgren and Zhu 2000). Note from Eqs. (6) and (7) that the friction velocity, scaling temperature, and scaling specific humidity [i.e., Eqs. (3)–(5)] are functions of the stability parameter z/L_M, where unstable conditions are denoted by $z/L_M < 0$, $z/L_M = 0$ represents neutral conditions, $0 < z/L_M < 1$ denotes stable conditions, and $z/L_M \ge 1$ corresponds to strongly stable conditions. Equations (1)–(9) are solved iteratively to determine H_S and H_L from the buoy measurements of wind speed, water temperature, air temperature, and dewpoint temperature. The solutions were found to converge rapidly within 7–8 iterations.

3. Spring-to-autumn seasonal variation

The seasonal evolution of evaporation (i.e., latent heat flux) from the Great Lakes has been discussed in previous investigations (e.g., Schertzer 1978; Pinsak and Rodgers 1981; Croley 1989) using buoy observations and model calculations. However, the authors are not aware of any investigations discussing variations of sensible heat fluxes estimated from overlake in situ measurements. Lofgren and Zhu (2000) recently used satellite-derived lake temperature and surface meteorological data from 1992–95 in the region to provide spatial distributions, over each of the Great Lakes, of estimated latent and sensible heat fluxes on a monthly climatological basis. Several studies have estimated sensible and latent heat fluxes as residual quantities of the energy balance equation rather than direct measurement (eddy correlation method) or using Monin–Obukhov similarity theory to estimate heat fluxes (e.g., Pinsak and Rodgers 1981). Weekly and monthly evaporation estimates presented by Quinn (1979) showed two evaporation regimes existed over Lake Ontario during the 1972–73 IFYGL field season. The first, a low-evaporation regime, occurred between April and July, and the second regime, a high-evaporation period, existed between August and December. Quinn (1979) found the second regime accounted for nearly 98% of the total seasonal evaporation. In an earlier IFYGL investigation using daily evaporation estimates, Phillips (1978) found that 70% of the yearly evaporation occurred on less than 25% of the days during the year and 33% of the total occurred on only 35 days. In this section, seasonal variations of sensible and latent heat fluxes estimated from buoy measurements are examined and average fluxes are compared with results from previous investigations.

Figure 3 shows the seasonal variation of sensible and latent heat fluxes obtained from hourly buoy 45003 mea-

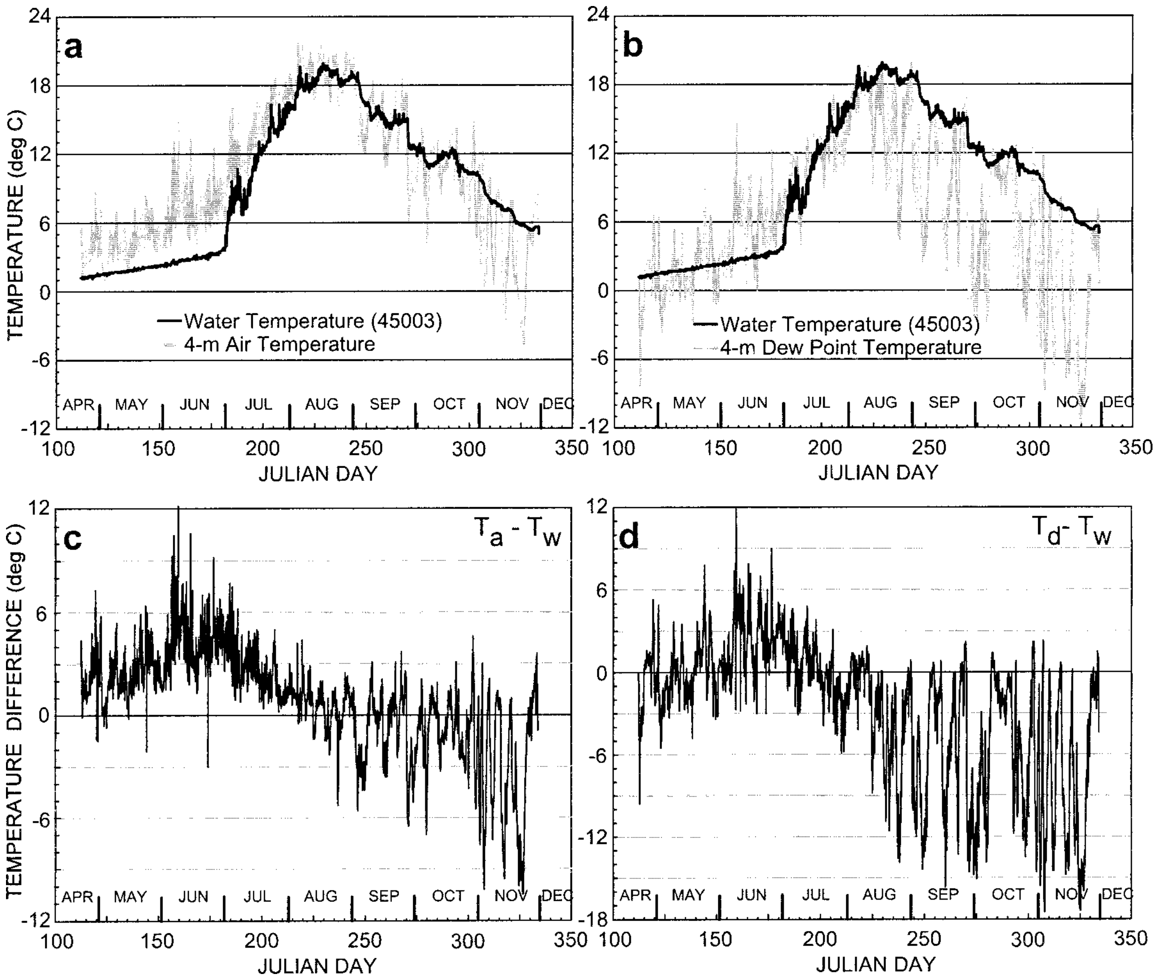

FIG. 2. Time series of hourly (a), (b) lake water (0.5-m depth), (a) air, and (b) dewpoint temperatures measured by buoy 45003 during 1984. The (c) air–lake temperature difference and (d) dewpoint–lake temperature difference are also shown.

surements during 1984. Similar to the evaporation regimes found by Phillips (1978) and Quinn (1979) over Lake Ontario, two heat flux regimes existed over Lake Huron. In general, the first period extended from April through July and was characterized by negative (atmosphere to surface) sensible and latent heat fluxes. Table 1 shows that 76.6% and 83.2% of total negative sensible and latent heat fluxes, respectively, occurred between April and July. The second regime was marked by large positive (surface to atmosphere) heat fluxes and occurred from August through November. This later period accounted for 95%–100% of both the total positive sensible and latent heat fluxes.

Figure 3 shows that the transition from the negative flux regime to the positive flux regime occurred 10–20 days earlier for latent heat flux than for sensible heat flux. The difference in timing of the flux-regime transitions is a direct result of disparity in the seasonal cycles and variations of air, lake, and dewpoint temperatures. Figures 2c,d show dewpoint temperatures commonly became cooler than lake water temperatures during early August of 1984 and air temperatures regularly became cooler than lake temperatures near the end of August of 1984. These conditions allowed for a change in the direction of the vertical gradients of temperature and moisture above the lake surface and a shift in the near-surface atmospheric stability from stable to unstable conditions. In part, this change to unstable conditions allowed large positive heat fluxes (i.e., greater exchange from the surface to the overlying atmosphere) to occur. The 1984 data show that consistent positive moisture fluxes occurred prior to the period of predominant positive sensible heat fluxes, allowing the beginning of the primary seasonal evaporation period to precede the occurrence of peak lake surface temperatures. For example, Table 1 shows that positive H_S in August (i.e., period of peak 1984 lake temperature) made up only 2.9% of the total season positive H_S, whereas August positive H_L accounted for 13.9% of the total season positive H_L.

To gain additional insight into the representativeness of these flux measurements, we compare our results with two previous investigations of monthly mean surface fluxes for

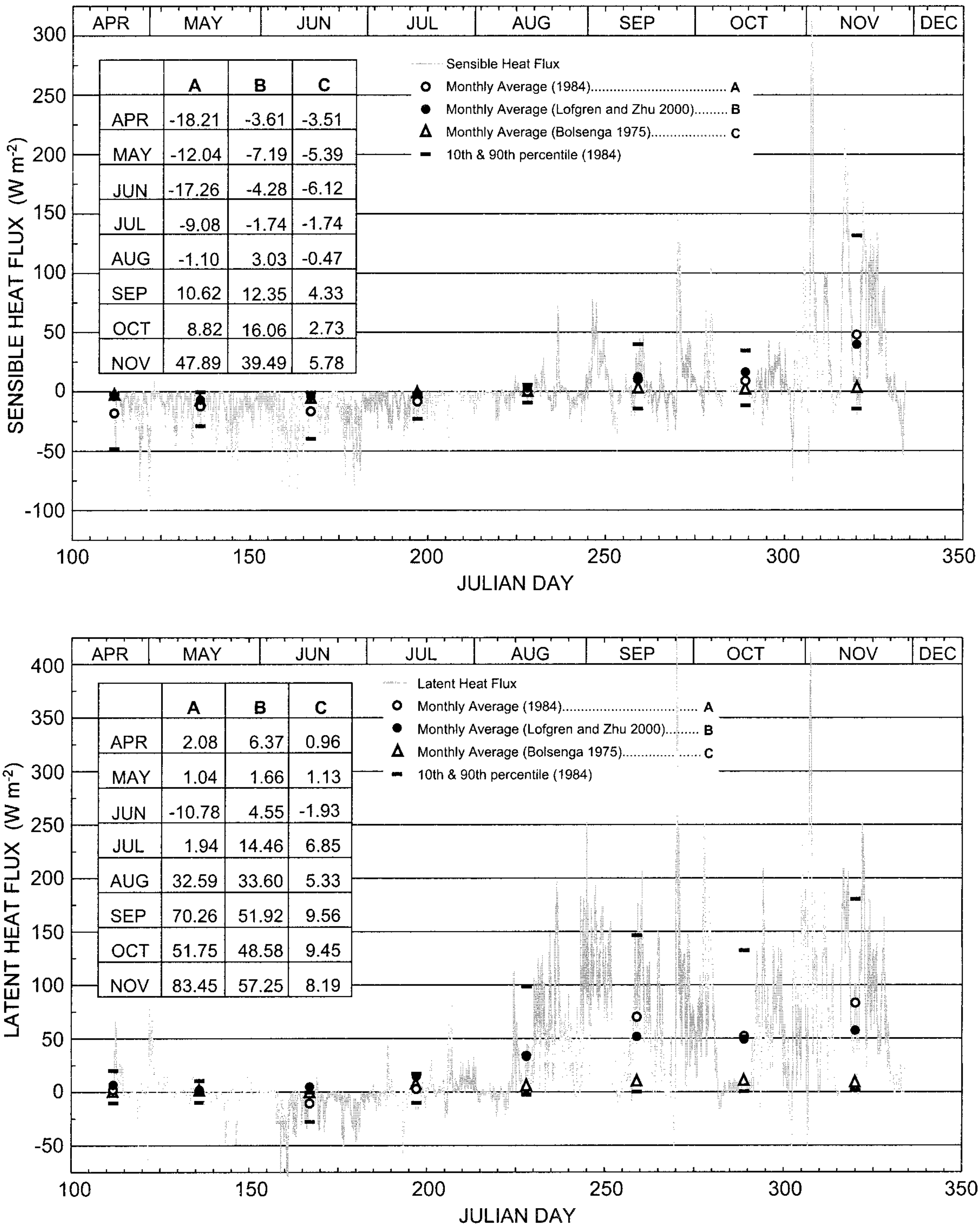

FIG. 3. (top) Sensible and (bottom) latent surface heat fluxes during 1984. Monthly averages (open circle) are shown for 1984 along with 10th and 90th percentiles. In addition, Lake Huron monthly mean fluxes are shown from Lofgren and Zhu (2000; filled circle) and Bolsenga (1974; open triangle).

Lake Huron. Bolsenga (1975) estimated monthly evaporation and sensible heat flux for Lake Huron as residuals from the energy budget equation and using a mass transfer method. The estimates from Bolsenga (1975) are shown in Fig. 3 (column C and open triangles). It is immediately noticeable that the magnitude of these estimates is much less than the monthly mean heat fluxes found in the current investigation (column A and open circles). However, the

TABLE 1. Percentage of total 1984 season positive or negative heat flux.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
SHF < 0	10.4	21.1	29.2	15.9	5.7	6.7	5.2	5.7
LHF < 0	6.5	14.0	49.3	13.4	4.9	4.1	5.8	1.9
SHF > 0	0.0	0.0	0.0	0.0	2.9	19.0	15.9	62.2
LHF > 0	0.9	1.7	0.0	2.0	13.9	28.5	21.9	31.1

flux direction [i.e., upward (positive) or downward (negative)] and seasonal variation of the heat fluxes agree reasonably well with our estimates calculated using different methods and datasets.

The spatially averaged monthly mean heat fluxes over Lake Huron determined by Lofgren and Zhu (2000) are also indicated in Fig. 3 (column B and solid circles). These monthly heat flux estimates compare more favorably with the monthly values determined in the current study. Although the monthly mean heat fluxes from Lofgren and Zhu (2000) are similar, a direct comparison of the results is not possible given the differences in the data, procedures, and time periods used to calculate average heat fluxes over Lake Huron. For example, the heat flux estimates found by Lofgren and Zhu (2000) contain a potentially large uncertainty caused by their use of an empirical method (Phillips and Irbe 1978) to estimate overwater meteorological conditions from data collected at stations surrounding the Great Lakes (B. M. Lofgren 2000, personal communication). In addition, a direct comparison of the heat fluxes is precluded because of climatic variations in Great Lakes water temperatures (e.g., McCormick and Fahnenstiel 1999), air temperatures (e.g., Bolsenga and Norton 1993), humidity, wind speeds, and frequency and intensity of synoptic systems in the region (e.g., Zishka and Smith 1980; Angel and Isard 1998) between 1984 and the 1992–95 period used by Lofgren and Zhu (2000).

Although the seasonal evolution of monthly mean fluxes has been examined previously, these investigations failed to provide information pertaining to the variability of fluxes or the seasonal evolution of shorter-term surface flux variability. This information is critical for investigations examining the impact that the Great Lakes may have on regional climate change and variability (e.g., Lofgren 1997; Kunkel et al. 2001). Available observations from a single year are not sufficient to examine climate changes, but the seasonal and monthly variability can supply vital data useful for verification of surface–atmosphere exchange processes within regional climate models. Figure 2 shows the variability of both air and dewpoint temperatures increased following the transition from the negative to positive flux regime. With the annual cycle removed, the variances for the period prior to the transition were 1.6° and 2.6°C^2 for air and dewpoint temperatures, respectively. The variances for the period following the transition were 5.2° and 17.1°C^2 for air and dewpoint temperatures, respectively. The differences in variances of the two periods were found to be statistically significant at the 99% confidence level for both air and dewpoint temperatures. This difference in variability is also evident in the surface sensible and latent heat fluxes.

Figure 3 shows the 10th and 90th percentile of hourly fluxes for each month (horizontal dashes). During the early negative flux regime, the range in fluxes about the monthly mean is very small. For example, during one of the larger negative flux events on 8–9 June, sensible and latent heat fluxes increased from −89.3 to −7.5 and −78.3 to −4.0 W m^{-2}, respectively. A noticeably larger increase in variability about the monthly mean heat fluxes is evident during the later positive flux regime. For example, sensible and latent heat fluxes increased from −25.7 to 145.0 and −30.0 to 428.0 W m^{-2}, respectively, during a 12-h time period on 25–26 September 1984. During another event on 1–2 November 1984, sensible and latent heat fluxes increased from −60.0 to 324.0 W m^{-2} and −60.0 to 411.0 W m^{-2}, respectively, during a 17-h time period. This increased variability under generally unstable near-surface conditions suggests either the transfer of surface heat and moisture with the atmosphere became appreciably coupled to transient synoptic-scale weather events (e.g., cyclones) or synoptic-scale weather events became more intense or frequent. These possibilities will be examined and discussed in section 4.

4. Relation of synoptic-scale weather events to daily fluctuation

The heat and moisture exchanges of the Great Lakes with the overlying atmosphere have a large impact on the development and evolution of meteorological systems and atmospheric conditions (e.g., stability, inland temperatures) in the region, especially in areas downwind of each of the Great Lakes (e.g., Baker 1976; Scott and Huff 1996). Research investigations have shown that the track, intensity, and development of synoptic and meso-α-scale (200–2000 km; Orlanski 1975) circulations can be altered by the presence of the Great Lakes (e.g., Sousounis 1997; Miner et al. 2000). Surface heat and moisture fluxes from the Great Lakes are also critical to the development of numerous local mesoscale circulations, such as lake breezes (e.g., Ryznar and Touma 1981; Laird et al. 2001) and lake-effect snowstorms (e.g., Braham 1983). In general, the relationship between lake surface heat fluxes and synoptic or mesoscale weather events has been examined previously only during individual case-study investigations. An examination and discussion of the relationship between synoptic weather events and the magnitude and fluctuation of surface heat fluxes for the time period of April–November of 1984 is presented in the section.

Figure 4 shows the time series of sea level pressure, sensible heat flux, and latent heat flux at buoy 45003. Sea level pressure is used as a surrogate for the examination of the timing and intensity of transient syn-

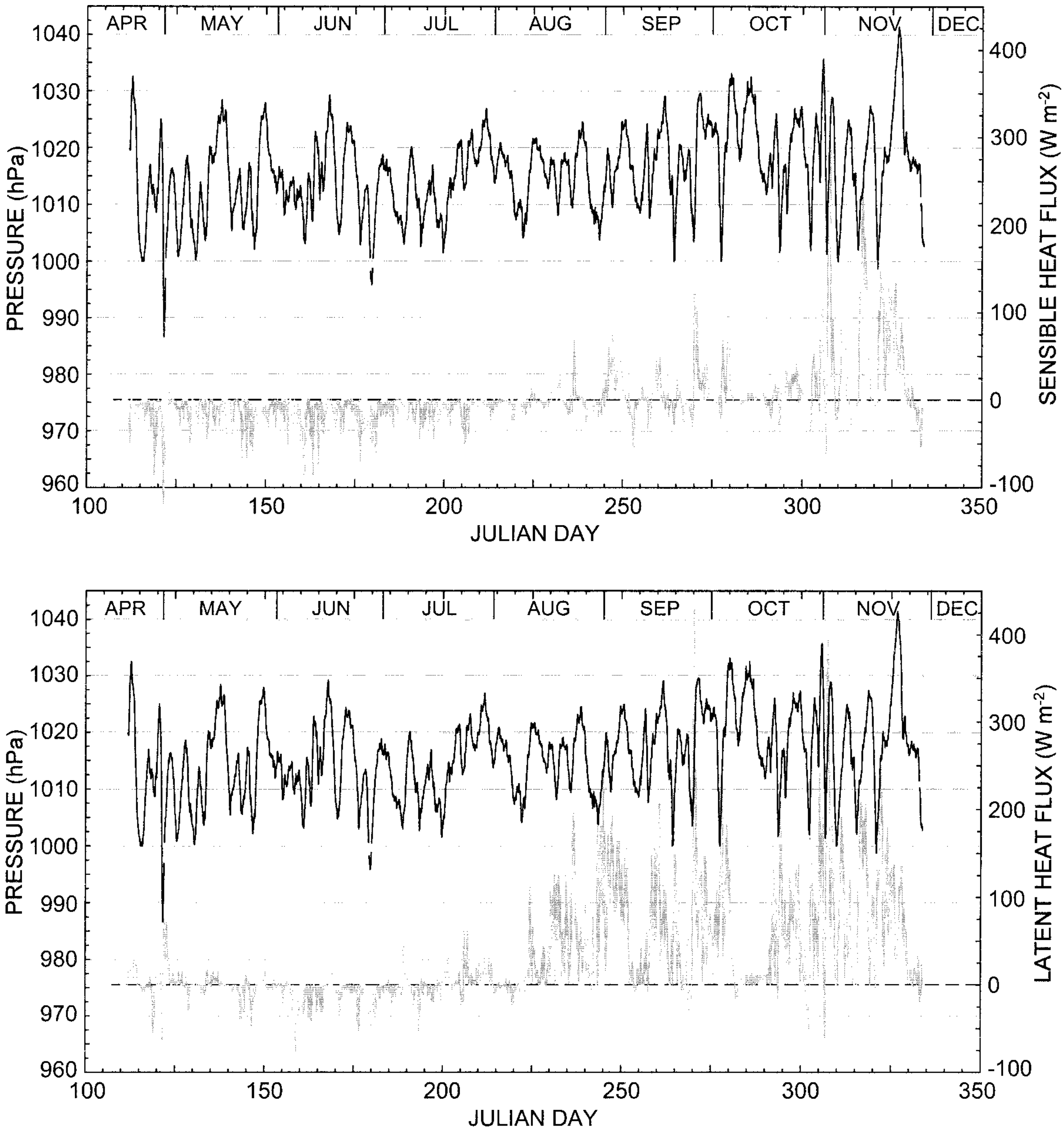

FIG. 4. Time series of hourly (top), (bottom) sea level pressure (dark lines), (top) sensible heat flux (gray line) and (bottom) latent heat flux (gray line) for 1984.

optic-scale weather events. The variance of sea level pressure increased from 48.5 during the negative flux regime to 52.5 hPa^2 for the positive flux period, suggesting only minor increases in the frequency and intensity of synoptic-scale systems. This finding is consistent with the small increase in both frequency and intensity of Great Lakes cyclones between the time periods of April–July and August–November presented by Angel and Isard (1998).

Figure 5 shows the relationship between sea level pressure and surface heat fluxes during the negative and positive flux regimes using a lagged cross-correlation analysis. Correlation coefficients were determined by shifting the time series of both sensible and latent heat fluxes relative to the time series of sea level pressure from 48 h preceding through 48 h following the coincident time period. Correlation coefficients for a lag number of 0 h represent values for coincident heat fluxes and pressure. The magnitude of the cross-correlation coefficient provides a useful measure of the proportion of variability in the heat fluxes that is associated with sea level pressure variations. The maximum correlation coefficients for the negative flux regime (at 0 to −3–h lag) show that the hourly sea level pressure measure-

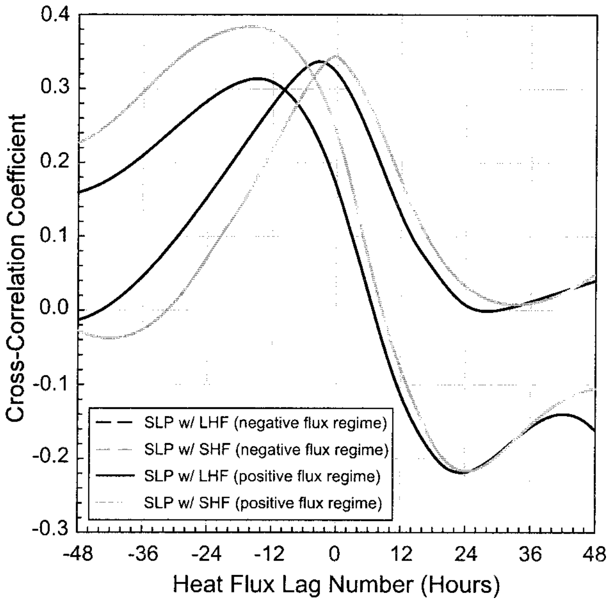

FIG. 5. Lag cross-correlation analysis of sensible (SHF) and latent (LHF) heat fluxes with sea level pressure (SLP) for negative and positive flux regimes. The regime transition date used was 1 Aug 1984. A negative lag number (*x* axis) corresponds to heat fluxes preceding SLP and positive values correspond to heat fluxes following SLP.

ments are associated with about 11%–13% of the variability in latent and sensible heat fluxes. The maximum correlation coefficients for the positive flux regime (at −16 h lag) show that the hourly sea level pressure measurements are related to about 10%–15% of the variability in the surface fluxes. This result suggests that the magnitude of surface heat and moisture fluxes remained coupled to transient synoptic-scale weather events (as identified by sea level pressure) despite a statistically significant increase of the surface heat flux variability from the negative to positive flux regimes and a general decrease in the near-surface atmospheric stability during the positive flux regime.

The lag time (i.e., number of hours) corresponding to extreme values of correlation coefficients provides important information about the temporal relationship between local extremes of heat fluxes and sea level pressure. Figure 5 shows the occurrences of minimum (maximum) heat fluxes preceded time periods of low (high) sea level pressure by 0–3 h during the negative flux regime from April through July. For the positive flux regime from August through November, maximum (minimum) sensible and latent heat fluxes preceded synoptic high (low) pressure by an average of approximately 16 h. In addition, maximum (minimum) surface fluxes followed the passage of low (high) pressure by about 24 h. The qualitative timing of extreme lake flux events relative to the passage of synoptic-scale high and low pressure can be demonstrated easily by examining the position of transient centers of synoptic high and low pressure relative to Lake Huron during extreme flux events.

An examination of large negative flux events in 1984 showed only 24 days experienced sensible heat flux values ≤ -50 W m^{-2}, 19 days during the early-season negative flux regime and 5 days during the autumn and winter positive flux regime. In general, during each event, a low pressure center and cold front were located within approximately 500 km northwest or west of the Great Lakes region and high pressure was located along the east coast of the United States, with strong southerly flow and a region of warm-air advection positioned over the Great Lakes. An example of the synoptic surface weather pattern that often existed during large negative flux events is illustrated in Fig. 6a. This case occurred during the negative flux regime. On 8 June 1984, a center of low pressure was located over western Lake Superior and surface high pressure was positioned over the southeastern United States. This synoptic configuration resulted in strong, warm southerly flow over Lake Huron and the eastern Great Lakes due to a strong surface pressure gradient. During the afternoon (1800–2000 UTC), the most intense negative fluxes ($H_S = -89$ W m^{-2}, $H_L = -78$ W m^{-2}) at the site of buoy 45003 occurred as wind speeds increased to 8.5 m s^{-1} and lake–air temperature differences decreased to −7.0°C.

An inspection of large positive flux events in 1984 showed only 14 days experienced sensible heat flux values ≥ 100 W m^{-2}, with all 14 occurring during the autumn and winter positive flux regime. The mean sensible and latent heat fluxes during these time periods were 150 and 203 W m^{-2}. In general, during each event, a low pressure center was located northeast or east of the Great Lakes region with a cold front situated along the East Coast. In addition, a high pressure center was located over the central United States, producing strong northwesterly flow and cold-air advection over the Great Lakes. An example of the typical synoptic surface weather pattern that existed during large positive flux events is illustrated in Fig. 6b. On 16 November 1984, a center of low pressure was positioned over Quebec, Canada, with a surface cold front located along the East and Gulf Coasts of the United States. In addition, a surface high pressure center was located over Kansas and Missouri, resulting in a strong, cold northwesterly flow over the Great Lakes. During the evening (2000–2300 UTC) on 16 November, large positive surface heat fluxes ($H_S = 162$ W m^{-2}, $H_L = 252$ W m^{-2}) occurred at the location of buoy 45003 as wind speeds increased to nearly 13.0 m s^{-1} and air temperatures of 0.5°C overlaid lake waters having temperatures of approximately 6.5°C. Precipitation was located in the vicinity of both the low pressure center and over the Great Lakes; the latter was associated with lake-effect snow showers downwind of Lakes Michigan, Huron, and Erie.

5. Summary

Continuous hourly measurements of wind speed and direction, air temperature, water temperature, humidity,

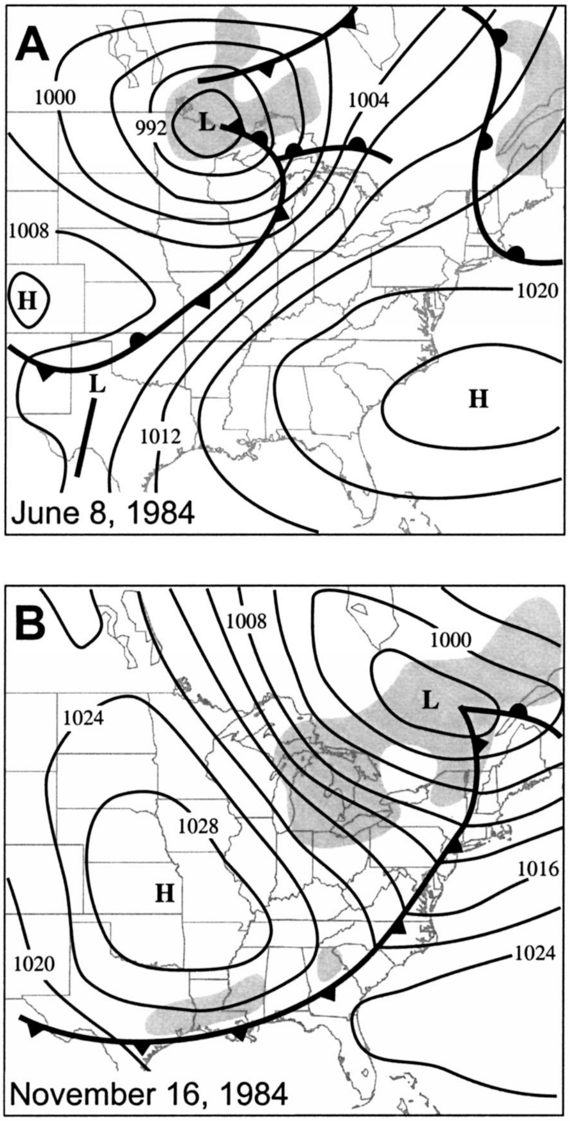

FIG. 6. Surface synoptic maps at 1200 UTC showing example weather pattern for (a) large negative surface heat flux and (b) large positive surface heat flux cases. Shaded region represents locations of surface precipitation. Surface isobars are contoured, and surface frontal locations are designated.

and sea level pressure from NDBC buoy 45003, located in northern Lake Huron, during April–November of 1984 allowed examination of short-term sensible and latent heat flux variations and their relation to synoptic weather events. Similar to the evaporation (i.e., latent heat flux) regimes found by Phillips (1978) and Quinn (1979) over Lake Ontario, two heat flux regimes existed over Lake Huron. In general, the first period extended from April through July and was characterized by periods of negative sensible and latent heat fluxes. The second regime was marked by periods of large positive heat fluxes and occurred from August through November. This later period accounted for 95%–100% of both the total positive sensible and latent heat fluxes. In addition, a comparison of the seasonal evolution of sensible and latent heat fluxes showed the transition from the negative flux regime to the positive flux regime occurred 10–20 days earlier for latent heat flux than for sensible heat flux.

The magnitude of surface heat and moisture fluxes remained coupled to transient synoptic-scale weather events despite a statistically significant increase in the surface heat flux variability from the negative to positive flux regimes. Examination of sea level pressure and heat fluxes at buoy 45003 showed the occurrences of minimum (maximum) heat fluxes preceded time periods of low (high) sea level pressure by 0–3 h during the negative flux regime from April through July. For the positive flux regime, maximum (minimum) sensible and latent heat fluxes preceded synoptic high (low) pressure by approximately 16 h. In addition, maximum (minimum) surface fluxes followed the passage of low (high) pressure by about 24 h.

In general, a low pressure center and cold front located northwest or west of the Great Lakes region and high pressure along the East Coast of the United States with strong southerly flow and warm-air advection over the Great Lakes were present during significant negative heat flux events. On the other hand, during significant positive heat flux events, a low pressure center was located northeast or east of the Great Lakes region with a cold front situated along the East Coast and a high pressure center over the central United States producing strong northwesterly flow and cold-air advection over the Great Lakes.

The results of this investigation provide quantitative information of the magnitude and variability of surface sensible and latent heat fluxes during the annual negative and positive flux regimes over Lake Huron and provide insight into the coupled atmosphere–lake system. Although limited both temporally (i.e., 8-month period) and spatially (i.e., single buoy location), the analyses provide unique, detailed information that can be useful to examine and to verify the surface–atmosphere exchange processes used within recently developed regional climate models [such as the model described by Liang et al. (2001)]. In addition, the synoptic and time series analyses identify the typical synoptic surface weather patterns associated with large-magnitude flux events and the timing of these events relative to the passage of transient surface pressure centers. The linkage between surface processes and synoptic weather patterns demonstrated in this article can provide more quantitative information to future investigations of regional climate variability and climate change, especially if model simulations suggest a change in the synoptic regime or frequency, track, and intensity of midlatitude cyclones in the Great Lakes region.

Future studies of the coupled atmosphere–lake system will need to address the continued lack of surface meteorological data on the Great Lakes, the influence of lake circulations on surface heat fluxes, and difficulty in determining overlake conditions from shoreline and remotely sensed data (e.g., Lofgren and Zhu 2000). These issues suggest the need to increase buoy deployment, with the capability of measuring atmospheric humidity on a continual basis, and to continue improvement of data assimilation and modeling techniques of near-surface conditions in the Great Lakes region for both weather forecasting and climate research purposes.

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