Net Ecosystem Exchange (NEE) of CO₂, H₂O, and Energy
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Oct 29, 2014

Two permanent flux stations in western Lake Erie - PERMS1 at the Toledo City Crib (CB) and PERMS2 at the NOAA #2 Light buoy (LI) – were installed with our Lake Erie Center Sensor Network and have been operating since September 2011. A mobile flux station (MoFS) was constructed for use on the Lake Erie Center boat and has successfully completed four intensive field campaigns since November 2011. As planned, wireless accesses to both of the two permanent stations were completed before the end of May 2012, and high-frequency data were collected, including during the winter when the lake surface was frozen (Fig. 1). Both of the permanent stations have been working reliability. Data are downloaded every five minutes via spread spectrum radios and are then automatically stored on a server. The project webpage is: http://research.eeescience.utoledo.edu/lees/LESensorN/index.html.

Fig. 1. Two permanent flux stations in western Lake Erie - Crib (CB) and Light buoy (LI) – were installed with our Lake Erie Center Sensor Network and have been operating since September 1, 2011. The sensors work year-round, including winters (right middle) and data are downloaded every five minutes via spread spectrum radios and then automatically stored on our server. A mobile flux station (right upper) was constructed for use on the Lake Erie Center boat and has successfully completed four intensive field campaigns since November 1, 2011.

At PERMS1, a YSI 6600 water quality sonde program was incorporated into the EC system in spring 2012, with wireless networking with half-hourly water quality data recorded continuously. We also incorporated a YSI instrument into the Crib intake system at PERMS2.

Raw data from the EC systems are processed offline, with half-hourly CO₂ fluxes, latent heat flux (LE) and sensible heat flux (H) calculated with EdiRe (University of Edinburgh, v1.5.0.32, http://www.geos.ed.ac.uk/abs/research/).
micromet/EdiRe) following the workflow described by Chu et al. (2014). Briefly, the raw data have been quality checked, and spikes were removed. The diagnostic signals from the CSAT3 and LI7500A were used to flag periods of any instrument malfunction. Raw sonic temperatures were corrected using fluctuations of water vapor concentration. A 30-min blocking average without detrending was used (Moncrieff et al., 2004), and a Webb–Pearman–Leuning (WPL) correction was applied to correct for air density fluctuation. We set range checks for each of the physical variables, including CO$_2$ (12–22 mmol m$^{-3}$) and H$_2$O concentrations (35–2765 mmol m$^{-3}$), $H$ (-200–900 W m$^{-2}$), $LE$ (-200–900 W m$^{-2}$) and $F_c$ (CO$_2$ flux) (-50–50 µmol m$^{-2}$ s$^{-1}$). We also adopted a seven-day moving window to the time series of half-hourly fluxes in order to detect and filter out erroneous flux (>6 times standard deviation of each window). Finally, the footprint for each half-hourly flux was calculated and used to omit periods with <80% of the measured fluxes originated within measurement fetch. Based on that process, the appropriate flux results for net ecosystem exchange of CO$_2$, H$_2$O, and energy in relation to measured microclimate data are reported.

Observations were recorded for 32 months at the Crib site and 31 months at the Light site, as detailed in this report (Fig. 2). According to interpretations of our data on an annual perspective, both western Lake Erie monitoring sites showed that the Lake system acts as a small carbon sink. NEE (net on-site vertical fluxes of C) were -16 and -74 gC m$^{-2}$ month$^{-1}$ at the Crib and Light sites, respectively, during the ice-free (spring-summer-fall) season. There were four and five CO$_2$ uptake months in the Crib and Light site, respectively, and July was the maximum CO$_2$ uptake month at both sites, with -28 and -72 gC m$^{-2}$ month$^{-1}$. Methane flux at both Lake sites was less than that for the wetland site, but higher than measured at the cropland site. The hourly values of the average diurnal courses of sensible heat ($H$) varied from $-1$ W m$^{-2}$ to +30 W m$^{-2}$. The diurnal variation of latent heat flux ($LE$) at the Crib site did not show obvious diurnal courses, and that site showed no day or night variations. The maximum values (largest +130-150 W m$^{-2}$ from April to July) were observed from the afternoon to the next morning, whereas the minimum (smallest 0-30 W m$^{-2}$ ) occurred from late afternoon to the early morning. From June through August, sensible heat flux ($H$) in the lake was higher than for the other months, > 100 W m$^{-2}$ throughout most of the day, while the minimum occurred from November through March, from near 0 to < 50 W m$^{-2}$. Variation of $LE$ at the Light site did not show an obvious diurnal course, but was higher at night from June to October than during the daytime;
Fig. 2 Mean daily wind speed ($U$, m s$^{-1}$, a) air temperature ($T_a$, °C, b), relative humidity (RH, %, c), vapor pressure deficit (VPD, kPa, d), photosynthetically active radiation (PAR, mol m$^{-2}$ d$^{-1}$, e), and rainfall (mm, f) at ~16 m above the water surface for the Crib and Light sites in Lake Erie from 2011 to 2014.

The monthly combined half-hourly data in 2012 were used to describe the daily variation of energy fluxes among months, and between CB and LI. At the Crib site, sensible heat ($H$) was lowest in the afternoon (15:00-17:00) and peaked in the early morning (7:00-9:00) from July–November (Fig. 3). Hourly values of the average diurnal courses varied from −1 W m$^{-2}$ (July 2012) to +30 W m$^{-2}$ (September, 2012). The diurnal amplitude of $H$ was largest in spring and in early fall (29 W m$^{-2}$ in September), whereas it was smaller in July and August (20 W m$^{-2}$). Liu et al. (2009) found the same shape and magnitude of diurnal courses of $H$ for a large open-water
surface (136 km$^2$) in Mississippi, USA. Venäläinen et al. (1999) also found similar diurnal courses of $H$ for two lakes in Sweden. Nordbo et al. (2011) found the same shape in a small boreal lake in Finland, but the minimum value was much lower than our results.

The diurnal variation of latent heat ($LE$) at the Crib site did not show obvious diurnal courses, and the site did not have day or night variations (Fig. 3). Maximum values (largest +130-150 W m$^{-2}$ from April to July, 2012) were observed from the afternoon to the next morning whereas the minimum (smallest 0-30 W m$^{-2}$ from January to March) was from late afternoon to the early morning. Liu et al. (2012) likewise found similar diurnal courses and magnitudes of $LE$ for a large open-water surface in Mississippi. However, different diurnal courses were described by Nordbo et al (2011), notably an obvious day and night variation in $LE$ due to effects from the terrestrial surroundings of their small lake.

![Diagram showing diurnal variation of latent heat (LE) and sensible heat (H) for different months.](image-url)
At the Light site, $H$ was at its minimum in the afternoon (15:00-17:00) and peaked in the early morning (7:00-9:00) from August–November (Fig. 3). The hourly values of the average diurnal courses varied from $-4 \text{ W m}^{-2}$ (April 2012) to $+31 \text{ W m}^{-2}$ (September 2012). In June through August, $H$ values for the lake were highest than in other months, with $> 100 \text{ W m}^{-2}$ during most of the day; the minimum monthly values occurred in November through March, with $< 50 \text{ W m}^{-2}$ or near zero.

The diurnal variation of $LE$ in the Light site did not show an obvious diurnal...
course, but from June to October was higher at night than during the day (Fig. 4). The maximum values (largest +150-180 W m⁻² from April to August, 2012) were observed from the afternoon to next morning, whereas the minimum (smallest -10-0 W m⁻² from November, 2011 to March, 2012) occurred from late afternoon to early morning. The maximum values were larger, ~30 W m⁻², for the Light site than at the Crib site, and the minimum LE was lower for the Light site than at the Crib site. This means that that the LE variation amplitude was higher at the Light site.

The energy fluxes, LE and H, showed different seasonal changes from each other (Fig. 5). The annual variation of LE showed an obvious one-peak change in both years, which was different from its diurnal change without a sinusoidal dynamic. LE was lower (near zero) from December through February during the two winters. In both years, at the beginning of March, LE switched to a positive value and continued to increase, reaching a maximum in July, August, and September, and then gradually decreased. The maximum LE appeared in late-July with 22.73 and 20.81 MJ m⁻² d⁻¹ in the first and second years, respectively. LE obviously decreased after mid-September and became extremely low when the weather turned cold after November and ice formed in January. The maximum value for LE occurred during late-July, producing an annual two-year mean of 21.77 MJ m⁻² d⁻¹. These differences appear to be due to energy limitation in Lake Erie, whereas the terrestrial ecosystems were often water limited.

![Figure 5](image_url)

**Fig. 5** Seasonal patterns of daily CO₂ (C, g C m⁻² d⁻¹), latent (LE, W m⁻²) and sensible (H, W m⁻²) heat fluxes for western Lake Erie from 2011 through 2013.
Fig. 6 Seasonal patterns of daily CO₂ (C, g C m⁻² d⁻¹), latent (LE, W m⁻²) and sensible (H, W m⁻²) heat fluxes for western Lake Erie from 2011 through 2013.

Monthly C revealed that Lake Erie served as a carbon sink in the summer and as a carbon source in winter (Fig. 6). Uptake C was 43.8 in 2012 and 14.6 g C m⁻² in 2013 (May-Sept). Annual LE variation showed a single-peak curve change, with annual cumulative evaporation in 2012 = 740 (CB) and 640 mm (LI), and in 2013 = 710 and 650 mm, compared to annual rainfall in 2012 = 670 and 2013 = 710 mm. This indicates that the present lake ecosystem ET returned approximately 90% of the annual rainfall to the atmosphere, as an important local atmospheric moisture source that would affect vegetation distribution and productivity, climate, and water resources across multiple spatial-temporal scales (Xiao et al., 2013). Blanken et al. (2000) measured a cumulative evaporation of 485 mm over the ice-free season (June 22 to December 31) from the Canadian high-latitude Great Slave Lake, which was slightly less than our measurement of 515 mm for Lake Erie, during the same season, likely due to differences in latitude and climate. H lacked seasonal patterns, matching the daily trends, and was ~1/4 of the annual LE.

As a conclusion from our observations, from an annual perspective, western Lake Erie acted as a carbon source, but as a small carbon sink in summers. Lake evaporation was much lower than in terrestrial ecosystems, and significantly lower than models have predicted (by 1/7; e.g., Croley 2005: Recent Great Lakes evaporation model estimates. http://www.glerl.noaa.gov/pubs/fulltext/2005/ 20050015.pdf ). Lake latent heat showed an obvious seasonal pattern, with greater energy than the sensible heat values. Turbulent energy totaled <40% of the global solar radiation; thus water heat storage contributed >1/2 of the input energy.
References