MICROMETEOROLOGY AND ENERGY BALANCE OF A SMALL BOREAL LAKE

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INTRODUCTION

In the boreal zone, lakes cover approximately 7% of the total land area and it is well known that the lakes affect the climate in a local and global scale (e.g. Long et al. 2007, Dutra et al. 2010). Nonetheless, lakes have either been neglected in numerical prediction models or parameterized crudely. As the grid scale of models is becoming finer, it is possible to include also water body effects. This has induced a need for energy flux measurements at lakes for the use in both model parameterizations and validation. Knowledge on energy fluxes also benefit limnological studies and research on carbon cycles.

Lakes and vegetated surfaces exchange energy with the atmosphere in the form of radiation and turbulent heat fluxes. During the last decade, the energy balance of vegetated surfaces, especially forests, have been intensively investigated by means of nascent flux tower networks based on the usage of the eddy covariance (EC) technique. Research on lakes using EC, on the other hand, is scarce and has mainly concentrated on larger lakes (Anderson et al. 1999, Eugester et al. 2003, Jonsson et al. 2008, Rouse et al. 2008, Liu et al. 2010) though most of the lakes are smaller. Lake dynamics differ, in a micrometeorological sense, from one another due to different size characteristics and water clarity. Furthermore they differ drastically from vegetated surfaces as they have a low albedo, smooth and continuously wet surface and are able to store significant amounts of heat. Consequently, measurements from a vast lake selection are needed, and our aim is to 1) provide detailed information on the thermal structure of a small boreal lake over several years and 2) to determine the energy closure of the lake with its components and their driving factors.

METHODS

The study site Lake Valkea-Kotinen (61°24′N, 25°03′E, 156 m a.s.l.) is a typical small boreal humic lake. The lake is 0.041 km² in size and extends 460 m in the NNW–SSE direction and 130 m in the SWW-NEE direction. The mean and maximum depths are 2.5 m and 6.5 m, and the lake is surrounded by tall pristine forest providing a wind shelter for the lake. Furthermore, the site is characterized by brown water with a high extinction coefficient (6.3 m⁻¹, Arst et al. 2008) and a large amount of dissolved organic carbon (13.3-13.7 mg l⁻¹, Huotari et al. 2009). The lake acts as a CO₂ source since the annual flux is observed to be about 36 g C m⁻² (Huotari et al. 2009). Moreover, Lake Valkea-Kotinen has a strong summertime thermal stratification that is followed by a fall turnover.
The EC measurement setup was installed on a raft on the lake together with complementary meteorological instrumentation in 2005-2008. The EC setup was designed to measure the turbulent flux of sensible ($H$) and latent heat ($LE$) in addition to the momentum flux. The system consisted of a Metek ultrasonic anemometer (USA-1, Metek GmbH, Elmshorn, Germany), which measured the three wind components and virtual temperature, coupled with a closed-path IR gas analyzer (LI-7000, Li-Cor Inc., Lincoln, Nebraska, USA), which measured the water vapour mixing ratio. Meteorological measurements consisted of net radiation ($R_n$) measurements (MB-1, Astrodata, Tartu, Estonia) and a weather station (Davis Instruments Corp., Hayward, CA, USA). In addition to the raft, continuous water temperature profile measurements were conducted close to the raft with a 14 thermistor string (Vemco, Halifax, NS, Canada) attached to a buoy. The change in heat storage ($\Delta Q$) was calculated from the time derivative of the water temperature, and the hourly thermocline depth was determined by fitting a third order polynomial to the temperature data and finding the maximum change of the fit. The thermocline depth and $\Delta Q$ were available around the year whereas the other fluxes measured on the raft were only measured during the open-water periods April/May–October. All data were averaged to match a one-hour resolution. The net radiation measurements were lost in 2005 and $LE$ data in 2008 before August due to measurement malfunctions.

The net radiation, change in heat storage and the turbulent fluxes of heat form the surface energy balance of a lake as

$$R_n - \Delta Q = H + LE,$$

where additional energy flux components such as heat storage to the sediments and net flux of heat through the lake outlet/inlet have been neglected due to their minor importance. All terms have units of W m$^{-2}$ and $R_n$ is defined positive when directed downwards whereas $H$ and $LE$ are positive when directed upwards. $\Delta Q$ is positive when the lake gains heat. The energy balance residual ($Res$, W m$^{-2}$) and closure ($EBC$, %) are

$$Res = R_n - \Delta Q - H - LE,$$

$$EBC = \frac{H + LE}{R_n - \Delta Q}.$$

We evaluated the terms from monthly ensemble average diurnal courses by calculating the cumulative sum of each course. This method was chosen due to a random error in $\Delta Q$ and occasional gaps in the turbulent heat fluxes when atmospheric mixing was weak. All in all, the closure could be assessed for two open-water periods, namely, 2006 and 2007.

CONCLUSIONS

The lake water temperature profile and the thermocline depth are shown in figure 1. The water has an opposite temperature gradient during winter and a thermocline with a positive temperature gradient develops around May, a few weeks after ice break-up. The thermocline deepens towards fall until the lake experiences a total turnover around October. The thermocline was observed to be thermally driven as the weak winds (1.2 m s$^{-1}$) did not seem to be strong enough for mechanically induced mixing. Furthermore, the thermocline depth had a diurnal cycle with a 0.5 m amplitude in midsummer.

The ensemble average monthly diurnal courses of $R_n$, $\Delta Q$, $H$ and $LE$ are represented in figure 2. The data record is the longest available for small lakes. Net radiation and the change in heat storage peak at noon and have their minimum during night. The fluxes range from -91 W m$^{-2}$ to +523 W m$^{-2}$ and -209 W m$^{-2}$ to 283 W m$^{-2}$, respectively, and the seasonal maximum is during summer. The sensible heat has much lower values as it ranges from -45 W m$^{-2}$ to +32 W m$^{-2}$. 
The diurnal maximum is observed in early morning whereas the maximum is in late afternoon. The latent heat flux, on the other hand, has an opposite phase and larger values ranging up to +116 W m$^{-2}$. Significant nocturnal evaporation with an average value of 16 W m$^{-2}$ is observed. It is enabled by the heat release from the lake, i.e. negative $\Delta Q$. Moreover, the sensible heat flux is observed to be governed by the air–water temperature difference ($r^2 = 0.57$), and the latent heat flux is driven by the air–water vapour pressure deficit ($r^2 = 0.70$). Wind speed was found not to be as important a factor as it is at larger lakes (Blanken et al. 2000). The seasonal and diurnal variation of the energy fluxes generally corroborates observations from other boreal lakes (Venäläinen et al. 1999, Spence et al. 2003, Rouse et al. 2003) though the turbulent fluxes are on average smaller probably due to weaker winds caused by a small fetch and wind sheltering.

The monthly energy balance closure in W m$^{-2}$ and per cents is shown in figure 3. The average EBC for the open-water periods of 2006 and 2007 is 82% and 72%, which corresponds to residuals of 16 W m$^{-2}$ and 23 W m$^{-2}$. The closure would have been 4%–units worse if only the water above the thermocline had been taken into account in calculating $\Delta Q$. Furthermore, the hourly residual did not correlate with any environmental variable nor show any seasonal variation. Only flux data for times when the wind was blowing from NNW were used to ensure maximal source area coincidence. As there is no specific reason for the underestimation of $H$ and $LE$ (or overestimation of $R_n$ and $\Delta Q$), several factors are suspected to cause the unclosed energy balance and its variation: EC is generally known to underestimate the turbulent fluxes for an unknown reason, advection was not taken into account, random noise in $\Delta Q$ is apparent and the source areas of the four fluxes do not totally coincide. Anyhow, our average EBC is in correspondence with the more abridged research from other lakes. Eugster et al. (2003) got a 10 W m$^{-2}$ residual from 2 days of EC data at Lake Soppensee, Switzerland. Jonsson et al. (2008), on the other hand, found periods with "a good" and "a poor" EBC for a four month period of measurements at Lake Merasjärvi, Sweden, using the EC method but they did not provide explicit numbers. To the contrary, Blanken et al. (2000) plotted $R_n - \Delta Q$ against $H + LE$ and made a linear regression and forced it through the origin and got a slope of 0.96. They used EC data from 49 days measured at Great Slave Lake,
Canada. Liu et al. (2009) provide 5 months energy flux data measured by EC over Ross Barnett Reservoir, Mississippi, but the closure was not calculated. From the available monthly mean values, the closure can be estimated to be about 80%. Furthermore, the energy balance is observed to be unclosed also at terrestrial sites as Wilson et al. (2002) observed an average 80% closure at 22 sites.

Figure 2: The monthly ensemble average diurnal course of $R_n$ – net radiation, $\Delta Q$ – change in heat storage, $H$ – sensible heat flux and $LE$ – latent heat flux. The y-axis shows the local time of day, the x-axis the months April-October of 2005-2008 and the colorbar shows the flux magnitude in W m$^{-2}$. Note that $R_n$ and $\Delta Q$ as well as $H$ and $LE$ have a common colorbar.

Figure 3: Monthly energy balance for Lake Valkea-Kotinen during the open-water periods of 2006 and 2007. The closure (%) on the left and the residual (W m$^{-2}$, grey) on the right axis. The closure could not be calculated for some months due to wind direction restrictions. See text for further details.
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REFERENCES


