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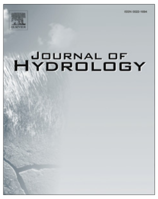

Temporal and spatial variations in radiation and energy balance across a large freshwater lake in China

Wei Wang[a], Wei Xiao[a], Chang Cao[a], Zhiqiu Gao[a,b], Zhenghua Hu[a], Shoudong Liu[a], Shuanghe Shen[c], Linlin Wang[b], Qitao Xiao[a], Jiaping Xu[a], Dong Yang[a], Xuhui Lee[a,d,]*

[a] *Yale-NUIST Center on Atmospheric Environment, Nanjing University of Information Science and Technology, Nanjing 210044, China*
[b] *State Key Laboratory of Atmospheric Boundary Layer Physics and Atmospheric Chemistry, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China*
[c] *Jiangsu Key Laboratory of Agricultural Meteorology, Nanjing University of Information Science and Technology, Nanjing 210044, China*
[d] *School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511, USA*

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ABSTRACT

The surface radiation and energy exchange processes are important drivers of lake evaporation and the associated hydrological cycle. In this paper, we investigated the temporal and spatial variations in evaporation and the associated radiation and energy fluxes across Lake Taihu, China with an eddy covariance mesonet consisting of three lake sites and one land site. The results indicate that on the diurnal scale, water heat storage showed a similar behavior to net radiation with comparable magnitudes and fueled the substantial nighttime evaporation (48% of annual evaporation). Unlike boreal deep lakes, the monthly mean sensible and latent heat flux was tightly coupled with seasonal variations in net radiation at this large (size 2400 km^2), subtropical (30.9–31.6°N) shallow (mean depth 1.9 m) Lake Taihu. On the monthly to annual scales, the radiation and energy fluxes showed little spatial variations across the lake, indicating a lack of sensitivity to wind speed, water depth, water quality and the presence of submerged macrophytes. The annual mean Bowen ratio (0.12–0.13) of the lake was lower than those found in the literature for subtropical and northern lakes and also much lower than that observed at the adjacent land site (0.58). The experimental data were used to evaluate the performance of 19 lake evaporation models of varying complexities.

1. Introduction

This study is concerned with the radiation, energy and water vapor fluxes of Lake Taihu, a large (size 2400 km^2) and shallow (mean depth 1.9 m) freshwater lake in southern China. The surface radiation and energy exchange processes are important drivers of lake evaporation and the associated hydrological cycle (Stephens et al., 2012; Verburg and Antenucci, 2010). Our experimental data were obtained with an eddy covariance (EC) network consisting of three sites in the lake and one site on land. Since the 1990s, the EC technique has been widely used to measure heat, water vapor and momentum fluxes in numerous upland ecosystems (e.g., Aubinet et al., 2000; Baldocchi et al., 2001). Although logistically difficult, in recent years the technique has also been used in an increasing number of long-term field campaigns on lake-air interaction (Blanken et al., 2003, 2011; Liu et al., 2012a; Nordbo et al., 2011; Rouse et al., 2008). EC provides a more accurate alternative to the water balance method in the determination of lake evaporation because the water balance method can suffer from large uncertainties (especially for large lakes) due to the difficulty in measuring the inflows and outflows and in measuring precipitation over the lake. To date, most of the published EC observations were conducted in deep boreal lakes. Year-round EC observations in shallow lakes in more southern latitudes are still rare (Liu et al., 2012a).

Currently our knowledge is relatively poor on processes that drive shallow lake evaporation in subtropical climates. Subtropical shallow lakes differ from northern deep lakes in several respects. First, deep boreal or temperate lakes are usually dimictic: they experience turnover in the spring and the autumn, and are thermally stratified in the summer (Oswald and Rouse, 2004). In comparison, shallow lakes experience turnover occurrence at the diurnal scale, with the static stability oscillating between stable stratification in the daytime and convective unstable conditions during the nighttime (Deng et al., 2013). Second, the time lag between water and air temperature can be as long as 5 months

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* Corresponding author at: School of Forestry and Environmental Studies, Yale University, Kroon Hall, 195 Prospect Street, New Haven, CT 06511, USA. Tel.: +1 (203)432 6271; fax: +1 (203)432 5023.
E-mail address: xuhui.lee@yale.edu (X. Lee).

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for deep lakes (Blanken et al., 2011) but negligible for shallow lakes (Deng et al., 2013; Oswald and Rouse, 2004). Third, southern lakes are ice-free, whereas ice coverage occurs in northern lakes, effectively decoupling the lake-atmosphere interactions in the winter. It is shown that in northern latitudes, global circulation patterns such as ENSO can modulate ice duration and phenology, two important factors controlling the annual lake evaporation (Bai and Wang, 2012; Blanken et al., 2000, 2011). Such linkages are absent for ice-free lakes. In these regards, subtropical shallow lakes should evaporate more water vapor and respond more quickly to atmospheric forcings than northern deep lakes at the diurnal and seasonal scales.

Several considerations support the hypothesis that across immense lakes like Lake Taihu, lake evaporation should vary spatially due to spatial heterogeneity in biophysical properties of the lake. Variations in water pollution (Wang et al., 2011) are likely to generate variations in the turbulent fluxes due to the attenuation of solar radiation by the pollutants (Huang et al., 2009). Having lower heat capacity, shallow parts of the lake may undergo faster warming and cooling than the deep parts, resulting in spatial variability of water temperature. For instance, the near-shore surface temperature was 10 °C warmer than at the deepest region in the Great Slave Lake, in Canada after ice breakup (Schertzer et al., 2003). Wind speed, which is a meteorological variable regulating the turbulent fluxes, tends to be stronger, because of the open fetch, in the middle of the lake than in the near-shore environment (Schertzer et al., 2003). In addition, the heat, water vapor and momentum transfer coefficients are known to vary with wind speed and submerged vegetation (Xiao et al., 2013). Largely because of these spatial heterogeneities, errors in the daily lake evaporation estimate may be as large as 100% if the whole-lake evaporation is evaluated on observations made at a single location (Assouline and Mahrer, 1996). Furthermore, spatial variability of evaporation at Lake Superior can be as large as 7 mm d^{-1} in the winter (Spence et al., 2011). So far, the discussion on these spatial variability has been based on the bulk transfer relationships for the fluxes aided by meteorological variables from numerical weather predictions (Spence et al., 2011) or remote sensing and buoy observations (Laird and Kristovich, 2002; Lofgren and Zhu, 2000). Our work appears to represent the first attempt at testing the hypothesis on the evaporation spatial variability on the seasonal and annual time scales using direct flux observations.

The energy and water fluxes of a lake differ from those in the surrounding vegetated terrain because of its low surface albedo, large heat capacity, unlimited water supply and low surface roughness (Henderson-Sellers, 1986; Subin et al., 2012; Venäläinen et al., 1999). Quantifying these contrasts is a critical step for accurate prediction of local thermal circulations (Crosman and Horel, 2010, 2012; Steyn, 2003) and the associated dispersion and transport of air pollutants (Flagg et al., 2008; Sills et al., 2011). There are five cities with population greater than 1 million around Lake Taihu, so it is important to understand how pollution dispersion is impacted by lake–land circulations and boundary layer dynamics. So far there have been few concurrent EC observations that compare lake energy and water fluxes with those on the adjacent land (Claussen, 1991; Eaton et al., 2001; Oncley et al., 1997; Venäläinen et al., 1999).

From the modeling perspective, there exist a large number of lake evaporation models of varying complexities (Brutsaert, 1982; Elsawwaf et al., 2010a; Rosenberry et al., 2007; Winter et al., 1995). So far, few studies have compared these models against a common EC dataset to evaluate their performance (Tanny et al., 2008, 2011). In this regard, the availability of the data on the lake surface radiation and energy balance is crucial because the most accurate lake evaporation models are believed to be those that have incorporated the radiation and energy balance constraints, such as the Bowen ratio energy budget model and the Priestley–Taylor model (Elsawwaf et al., 2010a, 2010b; Rosenberry et al., 2007; Winter et al., 1995).

In this paper, we aim to elucidate mechanisms underlying the observed temporal and spatial variations in radiation and energy fluxes across Lake Taihu. The goal is four-fold: (1) to quantify the evaporation and energy regimes through the diurnal and the seasonal cycle, (2) to test the hypothesis that there should exist discernible spatial variations in the energy and water fluxes across the lake, (3) to compare and contrast the fluxes between the lake and the surrounding land surface, and (4) to evaluate the accuracy of 19 classic evaporation models (Supplementary Table 1) against the EC observations.

2. Theoretical considerations

2.1. Surface energy balance

The energy balance of a lake surface is given by (Henderson-Sellers, 1986)

$$R_n - \Delta Q = H + \lambda E + \Delta Q_B + \Delta Q_F + \Delta Q_P \qquad (1)$$

where R_n is net radiation, ΔQ is lake heat storage determined with the time rate of change of the depth-weighted mean water temperature, ΔQ_B is the heat flux into the sediment, ΔQ_F is the net heat flux carried by the inflow and outflow of the lake, and ΔQ_P is the heat flux resulted from precipitation. The last three terms are negligible for the following reasons. We did not measure ΔQ_B. According to Wang and Bras (1999), it can be estimated with the time series of the observed sediment temperature. Using the thermal conductivity for saturated soils, their model yielded ΔQ_B values less than 0.5 W m^{-2} in magnitude. Similarly, ΔQ_F was no more than 0.5 W m^{-2} with the inflow of 9.3×10^9 m^3 yr^{-1} and assuming a temperature difference of 1 °C between the inflows and the lake water (Qin et al., 2007). At the annual precipitation rate of 1100 mm, ΔQ_P was estimated to be –0.5 W m^{-2} on the assumption that the rainwater had the wet bulb temperature (Gosnell et al., 1995; Shoemaker et al., 2005). Thus omitting the minor terms, the surface energy balance equation is reduced to:

$$R_n - \Delta Q = H + \lambda E \qquad (2)$$

Similarly, the energy balance equation of the land surface is given by

$$R_n - G = H + \lambda E \qquad (3)$$

where G is the heat flux at the soil surface.

For the lake sites, the energy balance closure can be assessed by the ratio (EBC, %) of the turbulent fluxes ($H + \lambda E$) to the available energy ($R_n - \Delta Q$):

$$\mathrm{EBC} = \frac{H + \lambda E}{R_n - \Delta Q} \times 100\% \qquad (4)$$

or in terms of an absolute residual (Res, W m^{-2}):

$$\mathrm{Res} = R_n - \Delta Q - \lambda E - H \qquad (5)$$

Eqs. (4) and (5) can be modified for the land site by simply replacing ΔQ with G.

2.2. Energy storage in the water column

The heat storage change (ΔQ) is determined by the variation in depth-weighted mean temperature ($d\overline{T_w}$) of the water column over the time interval (dt) (Blanken et al., 2000):

$$\Delta Q = \rho_w c_{pw} \int_0^z \frac{d\overline{T_w}}{dt} dz \qquad (6)$$