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Accepted Version

Woolway, R. I. ORCID: https://orcid.org/0000-0003-0498-7968, Verburg, P., Lenters, J. D., Merchant, C. J. ORCID: https://orcid.org/0000-0003-4687-9850, Hamilton, D. P., Brookes, J., de Eyto, E., Kelly, S., Healey, N. C., Hook, S., Laas, A., Pierson, D., Rusak, J. A., Kuha, J., Karjalainen, J., Kallio, K., Lepisto, A. and Jones, I. D. (2018) Geographic and temporal variations in turbulent heat loss from lakes: a global analysis across 45 lakes. Limnology and Oceanography, 63 (6). pp. 2436-2449. ISSN 0024-3590 doi: 10.1002/lno.10950 Available at https://centaur.reading.ac.uk/77266/

To link to this article DOI: http://dx.doi.org/10.1002/lno.10950

Publisher: Wiley

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Geographic and temporal variations in turbulent heat loss from lakes: A global analysis across 45 lakes

Author information

R. Iestyn Woolway[1*], Piet Verburg[2], John D. Lenters[3], Christopher J. Merchant[1, 4], David P. Hamilton[5], Justin Brookes[6], Elvira de Eyto[7], Sean Kelly[7, 8], Nathan C. Healey[9], Simon Hook[9], Alo Laas[10], Don Pierson[11], James A. Rusak[12], Jonna Kuha[13], Juha Karjalainen[13], Kari Kallio[14], Ahti Lepistö[14], Ian D. Jones[15]

Affiliation

1. *Department of Meteorology, University of Reading, Reading, UK*
2. *National Institute of Water and Atmospheric Research, Hamilton, New Zealand*
3. *Center for Limnology, University of Wisconsin-Madison, USA*
4. *National Centre for Earth Observation, University of Reading, Reading, UK*
5. *Australian Rivers Institute, Griffith University, Brisbane, Australia*
6. *The Environment Institute, School of Biological Sciences, University of Adelaide, Australia*
7. *Marine Institute, Furnace, Newport, Co Mayo, Ireland*
8. *Earth & Ocean Science, School of Natural Sciences, National University of Ireland Galway, Galway, Ireland*
9. *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA*
10. *Estonian University of Life Sciences, Institute of Agricultural and Environmental Sciences, Centre for Limnology, Tartu, Kreutzwaldi 5D, Estonia*
11. *Department of Ecology and Genetics/Limnology, Uppsala University, Uppsala, Sweden*
12. *Dorset Environmental Science Centre, Ontario Ministry of the Environment and Climate Change, Dorset, ON Canada*
13. *Department of Biological and Environmental Science, University of Jyväskylä, Jyväskylä, Finland*
14. *Finnish Environment Institute, Helsinki, Finland*
15. *Centre for Ecology & Hydrology, Lancaster Environment Centre, Lancaster, UK*

*Corresponding author; email: riwoolway@gmail.com

Abstract

Heat fluxes at the lake surface play an integral part in determining the energy budget and thermal structure in lakes, including regulating how lakes respond to climate change. We explore patterns in turbulent heat fluxes, which vary across temporal and spatial scales, using in situ high-frequency monitoring data from 45 globally distributed lakes. Our analysis demonstrates that some of the lakes studied follow a marked seasonal cycle in their turbulent surface fluxes, and that turbulent heat loss is highest in larger lakes and those situated at low latitude. The Bowen ratio, which is the ratio of mean sensible to mean latent heat fluxes, is

smaller at low latitudes and, in turn, the relative contribution of evaporative to total turbulent heat loss increases towards the tropics. Latent heat transfer ranged from ~60 to >90% of total turbulent heat loss in the examined lakes. The Bowen ratio ranged from 0.04 to 0.69 and correlated significantly with latitude. The relative contributions to total turbulent heat loss therefore differ among lakes and these contributions are influenced greatly by lake location. Our findings have implications for understanding the role of lakes in the climate system, effects on the lake water balance, and temperature-dependent processes in lakes.

Introduction

Wind stress and surface heating/cooling are two of the more important factors driving physical processes within lakes (Wüest and Lorke 2003), wherein water movements forced by the wind produce turbulent mixing that combines with surface heating/cooling to determine the physical environment of the lake ecosystem. Lake thermal structure regulates key aspects of lake ecosystems and is influenced by the interactions between the lake surface and the overlying atmosphere (Edinger et al. 1968). Some of the most important physical effects of climate change on the physics, chemistry, and biology of lakes (De Stasio et al. 1996) are associated with changes in thermal structure, heat budgets, and ultimately the fluxes of heat and energy at the air-water interface (McCormick 1990; Livingstone 2003; Fink et al. 2014; Schmid et al. 2014).

By modifying the key processes of mixing and stratification (Peeters et al. 2002; Perroud and Goyette 2010; Stainsby et al. 2011), climate-driven modulation of surface heat fluxes can alter key aspects of lake ecosystems, such as an increased occurrence of toxic cyanobacterial blooms (Jöhnk et al. 2008), deep-water hypoxia (Jankowski et al. 2006; North et al. 2014), and changes in lake productivity (Verburg et al. 2003; O'Beirne et al. 2017). Evaporative heat fluxes also alter lake levels (Gronewold and Stow 2014), with consequences for water security and supply (Brookes et al. 2014) and, in turn, water management strategies (Vörösmarty et al. 2000; Immerzeel et al. 2010; Vörösmarty et al. 2010).

Heat loss at the lake surface can modify the intensity of near-surface turbulence (Imberger 1985; Brubaker 1987; Schladow et al. 2002) and thereby influence the efflux of gases such as carbon dioxide and methane from lakes to the atmosphere (MacIntyre et al. 2010; Vachon et al. 2010; Dugan et al. 2016). A detailed understanding of surface heat loss processes is therefore essential given the growing realization of the importance of lakes in the global carbon cycle (Cole et al. 2007; Raymond et al. 2013). Surface energy fluxes from lakes can also influence the climate directly (Bonan 1995; Lofgren 1997; Samuelsson et al. 2010; Thiery et al. 2015). The surface fluxes of latent and sensible heat, representing the turbulent exchange of energy between a lake and the atmosphere, are critical components of the global surface energy cycle (Dutra et al. 2010; Le Moigne et al. 2016) and can influence the hydrological cycle (Rouse et al. 2005), which is sensitive to climate change (Wentz et al. 2007; Wu et al. 2013).

Until recently, in situ high-frequency measurements at the air-water interface that are required to accurately examine patterns in surface heat loss fluxes from lakes (e.g., wind speed, water temperature, air temperature, and relative humidity) were not widely available, thus preventing a consistent and comprehensive comparison across lakes. The recent establishment of scientific networks (e.g., Networking Lake Observatories in Europe, NETLAKE; Global Lake Ecological Observatory Network, GLEON) dedicated to the collaborative analysis of high-frequency lake buoy data has provided opportunities for global-scale analyses to be undertaken (Hamilton et al. 2015; Rose et al. 2016). We collated data from 45 lakes across 5 continents (Fig. 1; Table S1) to examine patterns in turbulent surface heat fluxes (i.e., latent and sensible heat fluxes) and determine how these patterns vary across time, space and different lake attributes, such as latitude and depth. To understand the controls on turbulent heat fluxes, we examine the influence of additional variables that we hypothesize may have an effect, including altitude, lake surface area / wind speed, and lake-air differences in temperature and humidity (Woolway et al. 2017a). We predicted that absolute latitude, which is strongly related to annual mean air temperature and net radiation, would have a strong influence on lake temperature (Straskraba 1980; Piccolroaz et al. 2013) and thus heat fluxes at the air-water interface. Altitude can influence air-water temperature relationships via differential lapse rates (Livingstone et al. 1999), and we thus predicted it would influence the cooling fluxes (Rueda et al. 2007; Verburg and Antenucci 2010). We predicted that lake area would be an important predictor of surface energy fluxes given that it regulates surface temperature at diel timescales (Woolway et al. 2016) and thereby surface cooling in lakes and has also been shown as an important predictor of the relative importance of convective vs wind-driven mixing (Read et al. 2012). Finally, lake depth can influence the interactions between a lake and the atmosphere and is often correlated strongly with annual lake heat budgets (Gorham 1964), and so we predicted that depth could also influence the surface energy fluxes.

Materials and methods

We collected mostly continuous observations (measurement intervals range from 4 min to 1 h) of lake surface temperatures and meteorological conditions from 45 lakes (Fig. 1a), ranging in surface area between 0.005 km^2 and 32,900 km^2, in altitude between 0 m above sea level (a.s.l.) and 1,897 m a.s.l., and in latitude between 38.8°S and 72.4°N (Table S1). Instrumented buoys measured near-surface water temperature (T_o, ºC) at an average depth of approximately 0.5 m (range 0 to 1 m), always within the surface mixed layer. Meteorological conditions including wind speed (U_z, m s^{-1}), air temperature (T_z, ºC), and relative humidity (RH, %) were measured on average z = 2.9 m (range 1.3 to 10 m) above the lake surface. Fourteen lakes had observations available throughout at least one year. All lakes had observations for the months of July to September (January to March in the Southern Hemisphere) for at least one year. Note that lake variables were not measured annually in some lakes as a result of the monitoring stations being removed prior to the formation of ice cover in winter. Throughout the text we refer to July to September (January to March in the Southern Hemisphere) as ‘summer,’ in-line with previous studies (Woolway et al. 2017a). Each lake had measurements taken at a single location, except for Lake Tanganyika (two locations) and Lake Tahoe (four locations). We analyzed the data independently from each monitoring station in Lakes Tanganyika and Tahoe before combining the results in our statistical analyses (see below). Specifically, for lakes with more than one monitoring station, we calculated the surface heat fluxes (see below) for each site individually and then calculated a lake-wide average.

This paper focuses on sensible (Q_h) and latent (Q_e) heat fluxes at the lake surface, each of which is positive when the direction of heat transfer is from the lake to the atmosphere (i.e., during surface cooling). The turbulent fluxes, Q_h and Q_e, were calculated as:

$$Q_h = \rho_a C_{pa} C_h U_z (T_o - T_z), \quad (1)$$

$$Q_e = \rho_a L_v C_e U_z (q_s - q_z), \quad (2)$$

where ρ_a is air density (kg m^{-3}), estimated as a function of air pressure, air temperature, and humidity (Chow et al. 1988; Verburg and Antenucci 2010), C_{pa} = 1005 J kg^{-1} ^{o}C^{-1} is the specific heat of dry air at constant pressure, C_h and C_e are the transfer coefficients for heat and humidity, which were assumed to be equal and adjusted for atmospheric boundary layer stability, measurement height, and wind speed (at z m above the lake surface) by following the computational method of Verburg and Antenucci (2010), and

$$L_v = 2.501 \times 10^6 - 2370 T_o \quad (3)$$

is the latent heat of vaporization (J kg^{-1}).

The humidity difference, q_s - q_z, which influences evaporative heat transfer at the air-water interface, was calculated as the difference between the specific humidity of saturated air at the water surface temperature, q_s (kg kg^{-1}):

$$q_s = 0.622 e_{sat}/p, \quad (4)$$

and the specific humidity of unsaturated air at the measurement height, q_z (kg kg^{-1}):

$$q_z = 0.622 e_a/p, \quad (5)$$

where e_{sat} is the saturated vapor pressure at T_o (mbar), calculated as:

$$e_{sat} = 6.11 \exp^{[17.27 T_o/(237.3 + T_o)]} \quad (6)$$

and e_a is the vapor pressure (mbar), calculated as:

$$e_a = RH e_s/100, \quad (7)$$

with e_s, the saturated vapor pressure at T_z (mbar), calculated as:

$$e_s = 6.11 \exp^{[17.27 T_z/(237.3 + T_z)]}, \quad (8)$$

and RH is relative humidity (%), and p is air pressure (mbar).

In this study we also calculate the Bowen ratio (B), which is commonly used with the energy budget method to estimate evaporation rates in lakes and reservoirs (Gibson et al. 1996; Lenters et al. 2005; Riveros-Iregui et al. 2017) and is defined as the ratio of mean Q_h to mean Q_e as:

$$B = Q_h/Q_e. \quad (9)$$

We also calculate the relative contribution of evaporation to the total turbulent heat flux, referred to hereafter as the evaporative fraction (EF), as:

$$EF = Q_e/(Q_h + Q_e) = 1/(1 + B). \quad (10)$$

As air pressure was not measured on all instrumented buoys, and since local variability in air pressure has a negligible effect on the turbulent fluxes (Verburg and Antenucci 2010), a constant air pressure was assumed for each lake in this study, calculated based on the altitude of the lake (Woolway et al. 2015a). With the exception of air pressure, all data used to estimate the turbulent surface fluxes were measured directly above the lake surfaces, as opposed to over land. The latter approach was formerly used to be more common in limnology (Derecki 1981; Croley 1989; Lofgren and Zhu 2000) but has often been shown to cause large errors (Croley 1989), perhaps contributing to annual mean net surface fluxes that differ substantially from zero (Lofgren and Zhu 2000).

To understand the drivers of variations in turbulent heat fluxes among lakes, we modeled the summer and (where available) annual mean fluxes, calculated from the raw, high-resolution data, against lake attributes using a multiple linear regression model. Latitude, altitude, lake surface area, and depth were used as predictors in each multiple linear regression model evaluated in this study. Altitude and latitude are proxies for climatic variables (e.g., annual mean temperature and/or net radiation). Thus, we are not attempting to comprehensively isolate the ultimate climatic drivers of surface heat fluxes in this study, but to identify patterns that would be of utility for simple geographic models.

All statistical analyses in this study were performed in R (R Development Core Team 2014). As the height of air temperature and relative humidity measurement varied among the lakes, we converted T_z and q_z to a surface elevation of 10 m (T_{10} and q_{10}) prior to performing comparisons among lakes (Woolway et al. 2015a). Similarly, in the across-lake comparisons, surface wind speed was adjusted to a height of 10 m (u_{10}) following the methods of Woolway et al. (2015a).

Results

Seasonal and diel cycles in turbulent surface fluxes - Many of the lakes investigated in this study followed a distinct seasonal cycle in their turbulent surface cooling terms (Fig. 2; Fig. 3), albeit less pronounced over, or even absent, in tropical lakes (Fig. 2), where the turbulent fluxes demonstrate near-constant monthly mean values (e.g., Corumba). The latent heat flux (Q_e), and also the sum of the turbulent fluxes (Q_e+Q_h), followed a clear seasonal cycle in many lakes, especially those situated in temperate regions, being highest in summer as a result of a greater air-water humidity difference (Fig. 3a, 3b). The sensible heat flux (Q_h) followed a less pronounced seasonal cycle among all lakes but was, on average, highest in autumn as a result of a greater air-water temperature difference (Fig. 3a, 3c). Specifically, the surface temperatures of lakes typically retain summertime heat well into autumn, resulting in a larger air-water temperature difference at this time of year. This is particularly the case for deep, mid-latitude lakes such as Tahoe (California/Nevada, USA; max. depth = 501m) and Taupo (New Zealand; max. depth = 186m), which experience highest turbulent heat fluxes well into autumn and winter as a result of their greater heat storage capacity. This also results in a higher Bowen ratio ($B = Q_h/Q_e$) in late autumn and winter (Fig. S1). The variation in surface wind speed, u_{10}, which was highest in winter, did not co-vary strongly with Q_e, Q_h, or Q_e+Q_h at seasonal timescales (Fig. 3d).

The sensible and latent heat fluxes generally follow a clear diel cycle in summer, but the mean diel cycles are out-of-phase with each other, resulting in a minimal diel cycle in the sum of the turbulent fluxes (Fig. 4a) but considerable diel variability in B (Fig. S2). Q_e is highest during mid-afternoon and lowest during late evening and early morning hours as a result of the diel cycles in wind speed (Fig. 4d) and the humidity difference (Fig. 4b) at the air-water interface (see equation 2), both of which are highest during mid-afternoon. Sensible heat flux follows an opposite diel cycle, with highest Q_h during the late evening and early morning hours, as a result of a greater air-water temperature difference during that time of day (Fig. 4c). Air temperatures above the lake surface tend to be cooler during the evening while the surface water temperatures retain daytime heat longer, resulting in a larger temperature difference. Interestingly, the diel cycle in Q_h is opposite to that of u_{10}, to which

Q_h is related (see equation 1). This illustrates that the air-water temperature difference in the studied lakes is the main driver of the diel variability of Q_h, and that the magnitude of the air-water temperature difference outweighs the opposite influence of u_{10} at diel timescales.

Relationships between surface fluxes and lake attributes - A multiple linear regression model including latitude, altitude, lake surface area, and depth demonstrates a statistically significant ($p < 0.05$) effect of lake surface area and latitude on Q_e during summer and annually (Table S2). Q_e was higher in larger lakes (Fig. 5a; Table S2) and in lakes situated at low latitudes (Fig. 7a; Table S2). Lake surface area also had a statistically significant ($p < 0.05$) relationship with Q_h (Fig. 5b) within the multiple linear regression model, with Q_h typically being higher in larger lakes during summer but not annually (Table S2). The relationship between lake surface area and both Q_e and Q_h was not always statistically significant when computing the linear regression within specific climatic zones, but this was primarily a result of the limited number of lakes with available data in some climatic regions (e.g., $n = 8$ in the tropics; $n = 7$ in polar regions).

The relationship between lake size and both Q_e and Q_h is explained, in part, by the lake-size dependence in over-lake wind speed. Larger lakes with greater fetch typically experience higher wind speeds (Fig. 5c), via the acceleration of wind over water. In the lakes studied, there was a statistically significant positive linear relationship between lake size and u_{10} during summer ($r^2 = 0.23$, $p < 0.001$, $n = 45$) but not with latitude or altitude ($p > 0.1$), thus suggesting an effect of lake fetch. However, we must note that the linear lake-size dependence in u_{10} is not likely to extend indefinitely to the world's largest lakes, since once a lake reaches a certain (unknown) size threshold, the atmospheric boundary layer has essentially adjusted to the lake surface area, and so any further increases in lake size would not lead to further increases in over-lake wind speed.

The relationship of lake size and u_{10} results in greater Q_h and Q_e (equations 1 and 2) in the lakes studied. However, Q_h and Q_e are also influenced by the air-water temperature and humidity differences, respectively and, thus the lake-size dependence of these differences must also be considered. There is no statistically significant lake-size dependence in the air-water humidity difference ($r^2 = 0.04$, $p = 0.17$, $n = 45$), to which Q_e is related, in the studied lakes. However, we calculate a significant negative relationship between lake size and T_o - T_{10} ($r^2 = 0.16$; $p < 0.05$, $n = 45$), with a greater temperature difference in smaller lakes (Fig. 5d). Therefore, the influence of lake size on T_o - T_{10}, to which Q_h is related, is opposite to that of u_{10}, resulting in the relationship between lake size and Q_h being weaker than the observed relationship between lake size and Q_e (Table S2).

Relative contributions to total turbulent heat loss – In terms of the total turbulent heat fluxes ($Q_h + Q_e$), a multiple linear regression model (testing the influence of latitude, altitude, lake surface area, and lake depth) demonstrates that latitude and lake surface area are statistically significant predictors (Table S3). More total turbulent heat loss was found in lakes with greater surface area (Fig. 6) and for lakes situated at low latitude (Fig. 7c). In contrast to the diel cycle, which shows an out-of-phase covariance between Q_h and Q_e (Fig. 4a), lakes often show in-phase covariance on seasonal timescales (Fig. 3a). The magnitude of these turbulent fluxes, however, can differ considerably among lakes. The ratio of Q_h to Q_e (i.e., the Bowen ratio) demonstrates that Q_h is consistently lower than Q_e (Fig. 7d), with an average B (= Q_h/Q_e) across all lakes of 0.23 (±0.11 std. dev.) during summer ($n = 45$). Fitting a multiple linear regression model (testing the influence of latitude, altitude, lake surface area, and lake depth) demonstrates that latitude is the only statistically significant ($p < 0.05$) predictor of B (Table S4). Thus, during summer and across the year B is lower at lower latitude, as a result of Q_e, but not Q_h, increasing with decreasing latitude (Fig. 7; Table S2). As would be expected, the relevant contribution of Q_e to total turbulent heat loss, in turn, increases towards the tropics (Fig. 7d). Specifically, Q_e can contribute >90% of the total turbulent heat exchange in some lakes during summer (Fig. 7d). The contribution of Q_h to total turbulent heat exchange increases at higher latitude, where summer Q_h can contribute approximately 40% of the total turbulent heat exchange. Given the lack of year-round data for many of the lakes in this study, it is important to note that – particularly for deep lakes in mid-latitudes – significantly higher Q_h, and therefore B, can occur in late autumn and into winter (Fig. 3; Fig. S1).

The decrease in B with decreasing latitude is a result of the Clausius-Clapeyron relationship, with Q_e higher in warmer lakes situated in warmer climates. To explain the effect of latitude on Q_e (Fig. 7a), but not Q_h (Fig. 7b), we compared, across lakes, the humidity and temperature differences at the air-water interface, to which Q_e and Q_h are respectively proportional. With decreasing latitude, we calculated a rapid and statistically significant ($p < 0.05$) increase in q_s, q_{10}, T_o, and T_{10} (Fig. 8). We find no relationship of latitude to the air-water temperature difference in these lakes (T_o - T_{10}), while there was a statistically significant increase in the humidity difference (q_s - q_{10}) with decreasing latitude. The latter results from the non-linearity of the Clausius-Clapeyron relationship and the resulting dependence of vapor pressure difference on temperature (equations 6 - 8), which is strongly related to absolute latitude both annually ($r^2 = 0.89$, $p < 0.001$) and during summer ($r^2 = 0.79$, $p < 0.001$). Thus, at low latitudes, q_s - q_{10} will be greater, resulting in higher Q_e and lower B.

Discussion

We investigated the differences in turbulent surface heat fluxes from 45 lakes across five continents. These turbulent fluxes have been investigated in lakes around the world for many years (Dutton and Bryson 1962; Lofgren and Zhu 2000; MacIntyre et al. 2002; Momii and Ito 2008), but our study is the first, to our knowledge, to investigate and compare these fluxes across a range of climatic zones and lake attributes. In addition, many earlier studies that have calculated surface heat fluxes from lakes have used remotely sensed water temperature in combination with land-based meteorological measurements (Derecki 1981; Croley 1989; Lofgren and Zhu 2000) or reanalysis data (Moukomla and Blanken 2017), which can lead to erroneous estimates of air-water interactions. Studies that have calculated heat fluxes using in situ temperature and meteorology data have dealt primarily with single lakes (Laird and Kristovich 2002; MacIntyre et al. 2002; Lenters et al. 2005; Verburg and Antenucci 2010; Lorenzzetti et al. 2015; Dias and Vissotto 2017), or a number of lakes from a confined region (Woolway et al. 2015b). Prior to this investigation, no known previous studies have compared turbulent surface fluxes from continuously recorded buoy data at so many lakes across the globe, and at diel, seasonal, and annual timescales.

Using in situ observations from 45 lakes, we show that the turbulent surface fluxes of latent and sensible heat and their relative contributions to total turbulent heat loss at the air-water interface can vary considerably across temporal and spatial scales. Our analysis demonstrates that latent and sensible heat fluxes follow a pronounced diel cycle in summer and, for lakes with data available throughout the year, follow a predictable seasonal cycle in small to medium-sized temperate lakes, with high Q_e, Q_h, and $Q_e + Q_h$ in summer (later in the year for deeper lakes). In tropical lakes the turbulent surface fluxes follow a less pronounced seasonal cycle, but rather experience comparatively high turbulent heat loss throughout the year, which is expected given the increase in heat gain towards the equator (Verburg and Antenucci 2010; Woolway et al., 2017a). The reduced seasonality of the lake heat content (the difference between minimum and maximum heat content) towards the equator demonstrates that heating and cooling are more separated by season at higher latitudes, resulting in a greater amplitude of the heat budget. In deep and large temperate lakes, such as Tahoe and Taupo, the turbulent energy fluxes are greatest during autumn and winter, as a result of the large heat capacity that causes their surface waters to cool more slowly during winter than the ambient surface air, as has been reported in other studies focusing on large, deep North American lakes (Blanken et al. 2011; Moukomla and Blanken 2017). These results indicate that the season in which the turbulent surface energy fluxes from lakes interact most strongly with the overlying atmosphere (and also affect internal lake mixing processes) can vary considerably among lakes.

A comparison across lakes of the relative contributions of Q_h and Q_e to the total turbulent heat flux demonstrates interesting relationships. The Bowen ratio ($B = Q_h/Q_e$) is found to decrease toward the tropics, since Q_e increases with decreasing latitude (i.e., increasing lake surface temperature), while Q_h does not. B is lower in a warmer climate, both in summer and annually. Similar to lakes at low latitude, one might also expect that Q_e would vary with altitude, as a result of the decrease in air temperature with increasing altitude and the temperature dependence of the specific humidity differences (for a given relative humidity). Specifically, we would expect an altitudinal dependence of Q_e and also B in the studied lakes. However, our global-scale analysis demonstrated that altitude did not have a statistically significant effect when investigated alongside latitude, lake surface area, and depth. Latitude was the only statistically significant predictor of B. In turn, the relevant contribution of Q_e to total turbulent heat loss is greater in tropical lakes (upwards of 90%) and then decreases toward higher latitude (~60-70%). While this relationship is expected due to the temperature dependence of specific humidity differences, this study is the first to calculate B across a global sample of lakes using in situ high-resolution data collected at the lake surface. The lowest annual mean B calculated in this study was 0.06 for Lake Tanganyika, while the highest annual mean B was 0.31 for Rotorua. The lowest summer mean B calculated was 0.04 for Lake Tahoe, while the highest summer mean B calculated was 0.69 for Emaiksoun Lake, Alaska, USA. Even higher values of B have been reported on seasonal or shorter timescales in other lake studies. For example, Lenters et al. (2005) calculated a B of 0.85 during early November in Sparkling Lake (Wisconsin, USA), and other studies have demonstrated that B can approach and even exceed 1 for some lakes during winter (Lofgren and Zhu 2000; Blanken et al. 2011), indicating that Q_h can occasionally be larger than Q_e. This highlights the need for continued and expanded analysis of high-frequency heat flux measurements on lakes, particularly during the cold season when such measurements are difficult and infrequently undertaken.

Our results, in particular those that illustrate the non-linear functional form of B with latitude, are useful for measuring/predicting the energy balance of lakes globally, since a number of methods (and models) use estimates of B to solve the energy balance and/or to estimate Q_h or Q_e. A constant B is used commonly in, for example, paleoclimate studies and also in simplified lake models (Bultot 1993; Blodgett et al. 1997). Our results demonstrate that a common value of B should not be assumed, and our findings can provide ways of estimating B for lakes as a function of latitude, for example (e.g., in the absence of expensive instrumentation), which can help advance prediction of lake thermal processes. Moreover, our results challenge the validity of neglecting the effect of varying B, which has consequences for estimating lake thermal processes, which are fundamental to understanding lake biogeochemistry and ecology. The proportion of Q_h:Q_e is also important for understanding the influence of climate change on the water balance of lakes and in evaluating the role of lakes in the Earth's hydrologic cycle, which is expected to accelerate with climate change (Wentz et al. 2007; Wu et al. 2013; Wang et al. 2018).

While our analysis included observations from lakes across five continents, these were typically restricted to specific years and, as such, may not have captured "normal" meteorological conditions for a particular lake, nor a reasonable range of interannual variability. As such, any lake-to-lake comparisons could have been biased by the presence of 'abnormal' years (e.g., drought, flood, heat waves, etc.). For example, one lake may have experienced temperatures above the mean while another lake experienced temperatures below the mean, which could bias our global relationships. Nevertheless, we have found the relationships between the turbulent heat fluxes, in particular with latitude and lake size, to be statistically significant. This occurs despite potential errors in the data and that the 'noise' introduced into the global relationships by any one anomalous lake or anomalous weather during a given year. A caveat to our results regarding the relationship between latitude and the turbulent surface heat fluxes is that not all latitudes are equally represented by study lakes, with fewer or no lakes in areas of critical climate gradients, such as the descending branches of the Hadley cell, which can influence local climate. In addition, latitude serves as a proxy for climatic variables (e.g., air temperature and net radiation) but not completely as factors such as altitude also controls these same variables.

Although Q_h is a relatively minor component of total turbulent heat loss in some lakes, contributing ~10% during summer in the tropics, it can be much larger during certain times of the year (and at diel timescales), which could influence greatly convective mixing in a lake and gas transfer at the lake surface. In particular, estimates of carbon dioxide emissions from lakes can be considerably biased when Q_h is not considered (Podgrajsek et al. 2015). Climatic warming will likely increase Q_h in the future, as suggested by the observation that summer-mean water surface temperatures in many lakes have increased more than air temperatures in the past few decades (O'Reilly et al. 2015), thereby increasing the lake-air temperature difference, to which Q_h is proportional. Lake surface temperatures in high latitude lakes, in which Q_h is a relatively large contributor of total turbulent heat loss, have been suggested to experience an amplified response to air temperature variability (Woolway and Merchant 2017). Thus, as a result of the expected increase in Q_h with climate change, there will be a relatively greater increase in total turbulent heat loss at high latitude. Any enhanced lake-air temperature differences induced by climate warming are also likely to be accompanied by enhanced heat loss via Q_e and, in turn, affect gas fluxes into and out of lakes. However, we must note that changes in other meteorological variables associated with the turbulent fluxes, in particular surface wind speed (Woolway et al. 2017b), must also be considered.

This large-scale analysis of the spatial and temporal variations in turbulent surface heat flux processes among lakes has implications for carbon dioxide and methane emissions (Polsenaere et al. 2013; Podgrajsek et al. 2015). Previous studies have demonstrated that convective mixing dominates wind-induced mixing in small lakes (Read et al. 2012), and that a simple wind-based approach for estimating the gas transfer coefficient can underestimate lake metabolism and gas exchange with the atmosphere. While our results verify some aspects of this previous work, such as the significantly positive relationship between lake area and wind speeds, we also arrive at some important conclusions regarding the surface cooling processes that lead to convective mixing. For example, we show that turbulent surface cooling (esp. Q_e) is considerably lower in small lakes whereas large lakes have considerably larger Q_e and overall turbulent heat loss. These results indicate that the higher wind speeds that lead to greater wind-induced mixing on large lakes also lead to greater turbulent heat loss and potentially convective mixing, especially during times when such cooling processes are not offset by significant surface radiative heating (e.g., strong incoming solar and thermal radiation). Similarly high rates of Q_e and total turbulent surface heat loss are also found for lakes situated in warmer climates (e.g., tropical lakes). Therefore, our results suggest that convective mixing may be more important in large and tropical lakes than has been suggested previously and that convection may be a greater contributor to gas exchange in these systems as well.

Conclusions

We have analyzed high-resolution monitoring data from 45 lakes across 5 continents to study the global variation in mean (summer and annually) turbulent surface heat fluxes at the air-water interface. Our results indicate the relative importance of lake location and lake specific characteristics (e.g., surface area and depth) to the turbulent exchange of heat and energy at the lake surface and also how these fluxes vary at diel, seasonal and annual timescales. We demonstrate that the turbulent fluxes follow predictable diel and seasonal cycles in many lakes, and that, on average, the sum of the turbulent fluxes are greater in larger lakes and in those situated at low latitude. The ratio of mean sensible to mean latent heat fluxes, often referred to as the Bowen ratio and used commonly to estimate evaporation rates in lakes, was shown to vary predictably with latitude, being lower in the tropics. In turn, our study demonstrates that the relative contribution of latent to total turbulent heat loss in lakes varies predictably with latitude. Our results, therefore, demonstrate that the latent and sensible contributions to total turbulent heat loss differ among lakes and these contributions are influenced greatly by lake location. This will be useful for predicting the energy balance of lakes globally, in particular in the absence of expensive instrumentation required to solve the lake energy budget.

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Acknowledgements

RIW was funded by EUSTACE (EU Surface Temperature for All Corners of Earth), which received funding from the European Union's Horizon 2020 Programme for Research and Innovation, under Grant Agreement no 640171. We thank individuals that contributed to the collection of data included in this analysis: Jon Cole (Peter Lake); Ken Hinkel and Brittany Potter (Emaiksoun Lake); Peter Staehr (Hampen Soe and Grib Soe); Hilary Swain (Lake Annie). This work benefited from participation in the Global Lake Ecological Observatory Network (GLEON) and the Networking Lake Observatories in Europe (NETLAKE). JAR acknowledges funding from the Ontario Ministry of the Environment and Climate Change and the Inter-American Institute for Global Change Research (Grant CRN3038). JDL was supported by a grant from the National Science Foundation (NSF) Arctic Observing Network (AON; grant number 1107792). Data collection for Lake Võrtsjärv was supported by the Estonian Ministry of Education and Research, grant IUT21-2. The Centre for Ecology and Hydrology, UK, funded data collection from the Cumbrian lakes. We thank Kevin Rose who provided a helpful review of an early version of this work. Researchers from various institutions provided data used this study. Please contact R. Iestyn Woolway (riwoolway@gmail.com) for more information regarding requests for data from the relevant individuals. We would like to thank two anonymous reviewers who provided a constructive review of this manuscript.

Figures

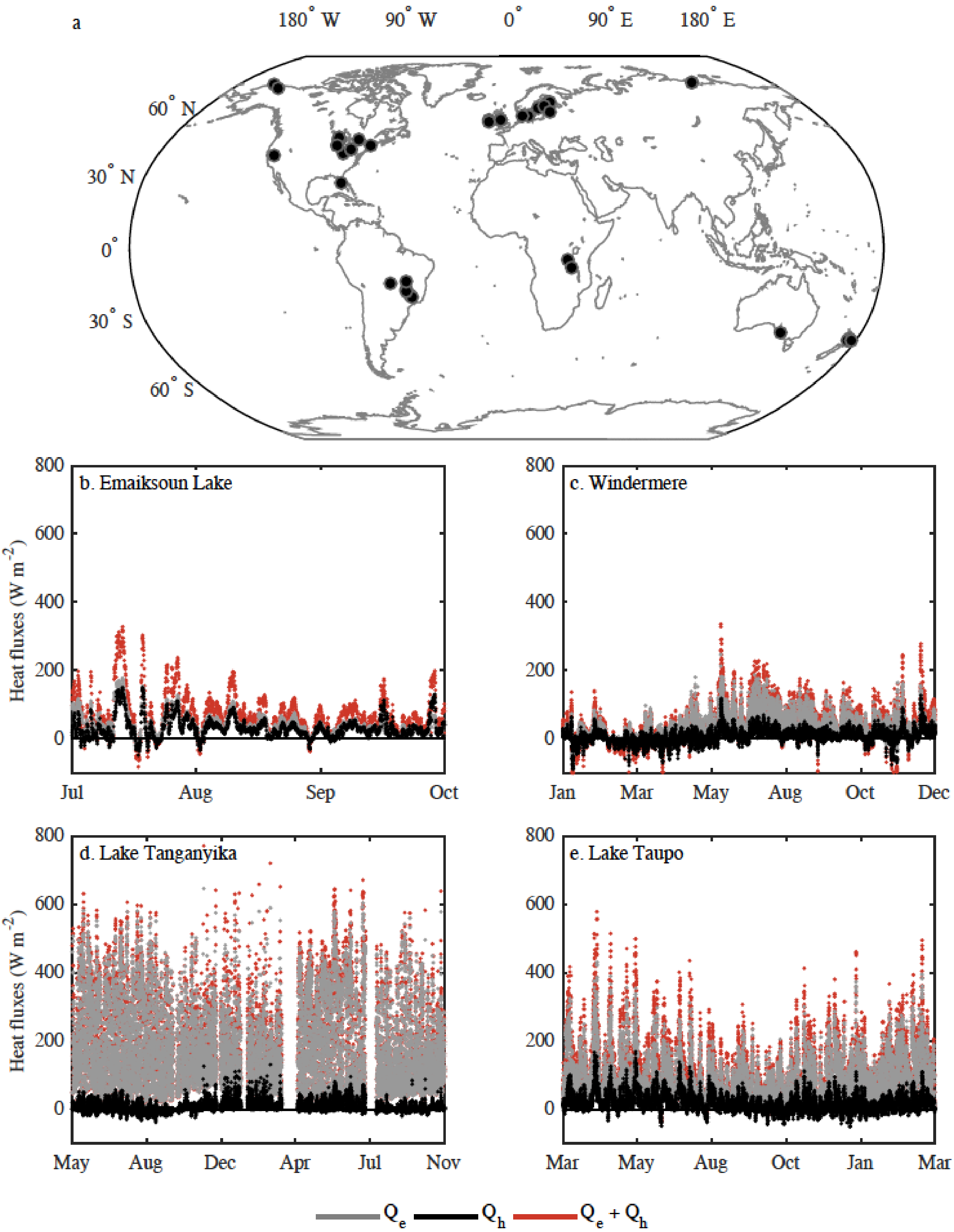

Figure 1. (a) Locations of the 45 lakes in this study for which turbulent surface heat fluxes were estimated, and examples of calculated hourly latent (Q_e, gray), sensible (Q_h, black) and the sum of turbulent heat fluxes ($Q_e + Q_h$, red) at (b) Emaiksoun Lake (Alaska, USA; 71.24°N, -156.78°E), (c) Windermere (United Kingdom; 54.35°N, -2.98°E), (d) Lake Tanganyika (south basin; East Africa; -8.47°N, 30.91°E), and (e) Lake Taupo (New Zealand; -38.80°N, 175.90°E). Positive values indicate cooling of the lake surface.

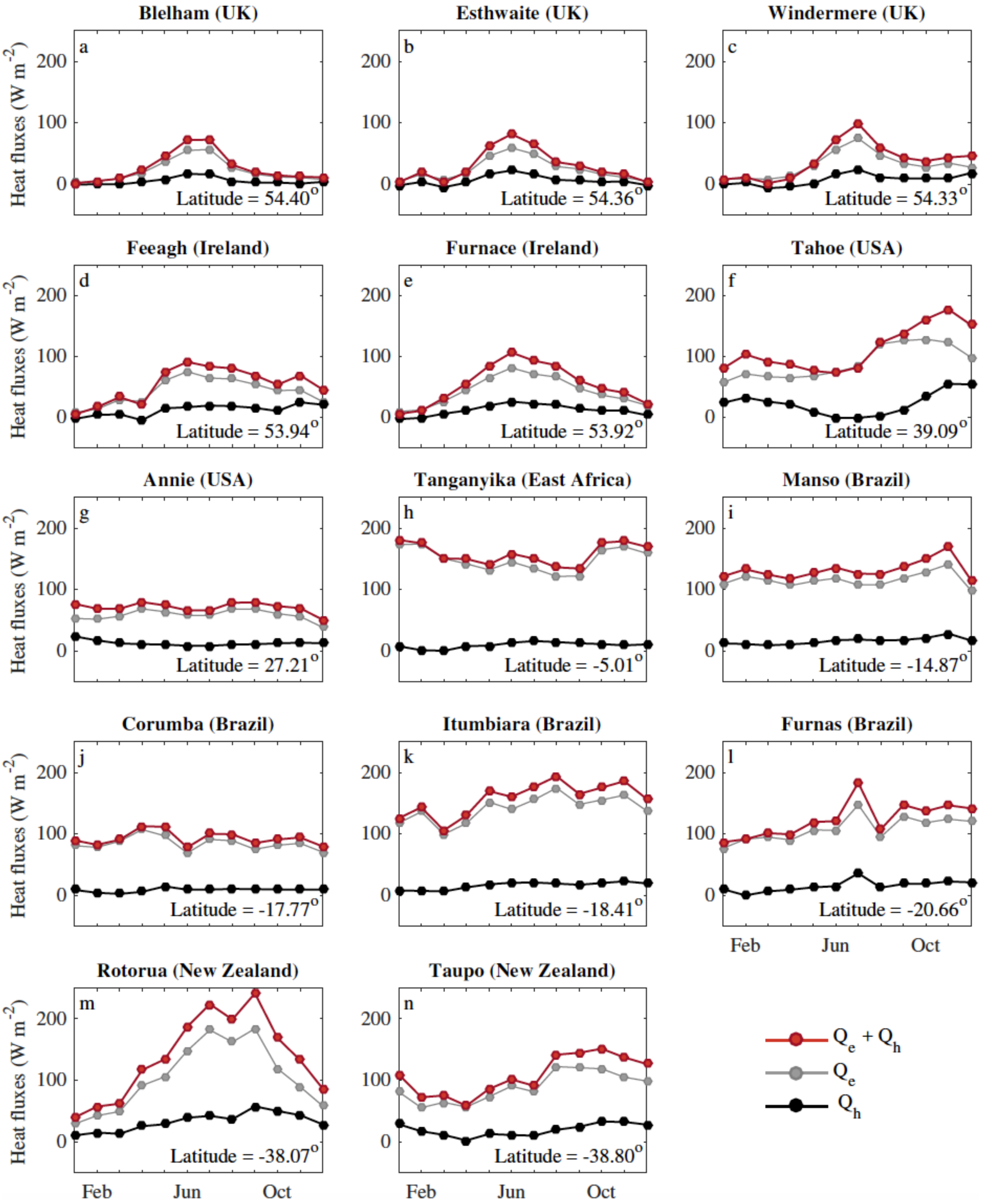

Figure 2. Monthly averaged latent (Q_e, gray), sensible (Q_h, black) and the sum of turbulent heat fluxes ($Q_e + Q_h$, red) for 14 lakes with data available throughout the year. Lakes are arranged by latitude from north to south. Southern hemisphere lakes were shifted by 182 days.

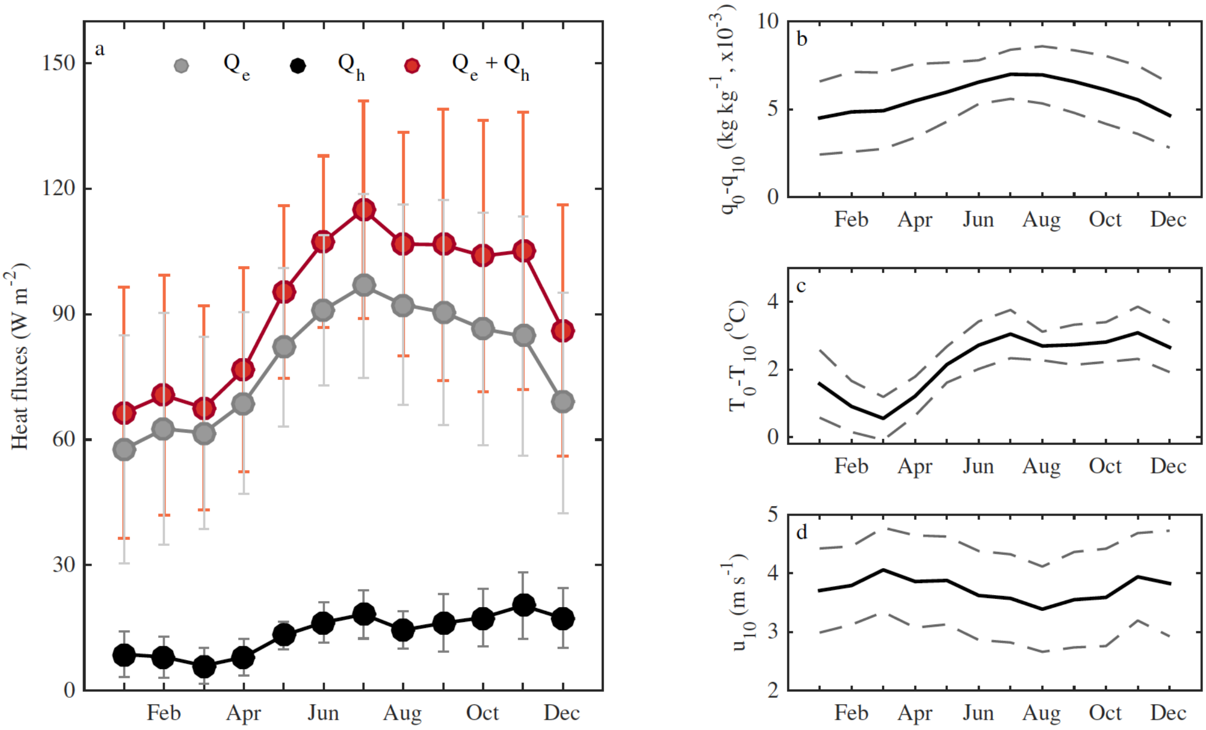

Figure 3. Across-lake monthly averaged (a) latent (Q_e, gray), sensible (Q_h, black) and the sum of turbulent heat fluxes ($Q_e + Q_h$, red) at the water-air interface, (b) the water-air humidity difference, (c) the water-air temperature difference, and (d) the wind speed adjusted to a height of 10 m (u_{10}). Averages are shown for 14 lakes with data available throughout the year (as shown in Fig. 2). The 95% confidence intervals are also shown.

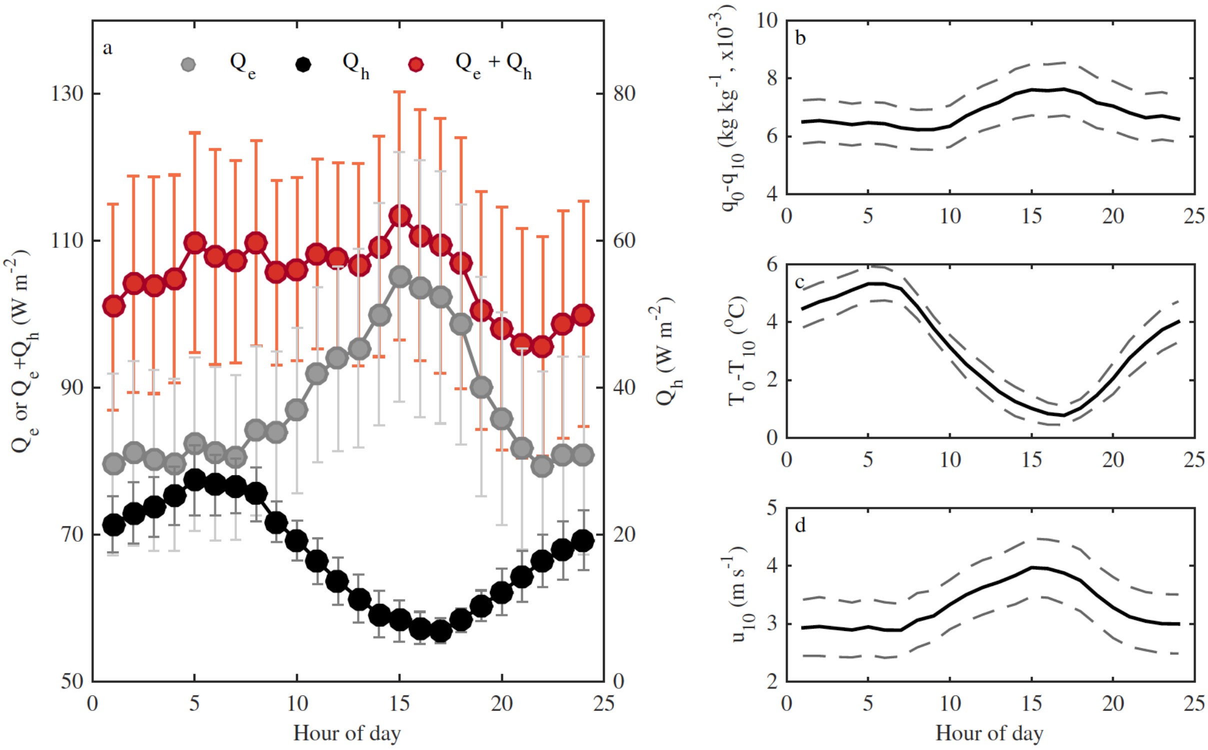

Figure 4. Across-lake summer (July-September in northern hemisphere and January-March in southern hemisphere) average diel cycles of (a) latent (Q_e, gray), sensible (Q_h, black) and the sum of turbulent heat fluxes ($Q_e + Q_h$, red) at the water-air interface, (b) the water-air humidity difference, (c) the water-air temperature difference, and (d) the wind speed adjusted to a height of 10 m (u_{10}). Averages are shown for 45 lakes. The 95% confidence intervals are also shown.

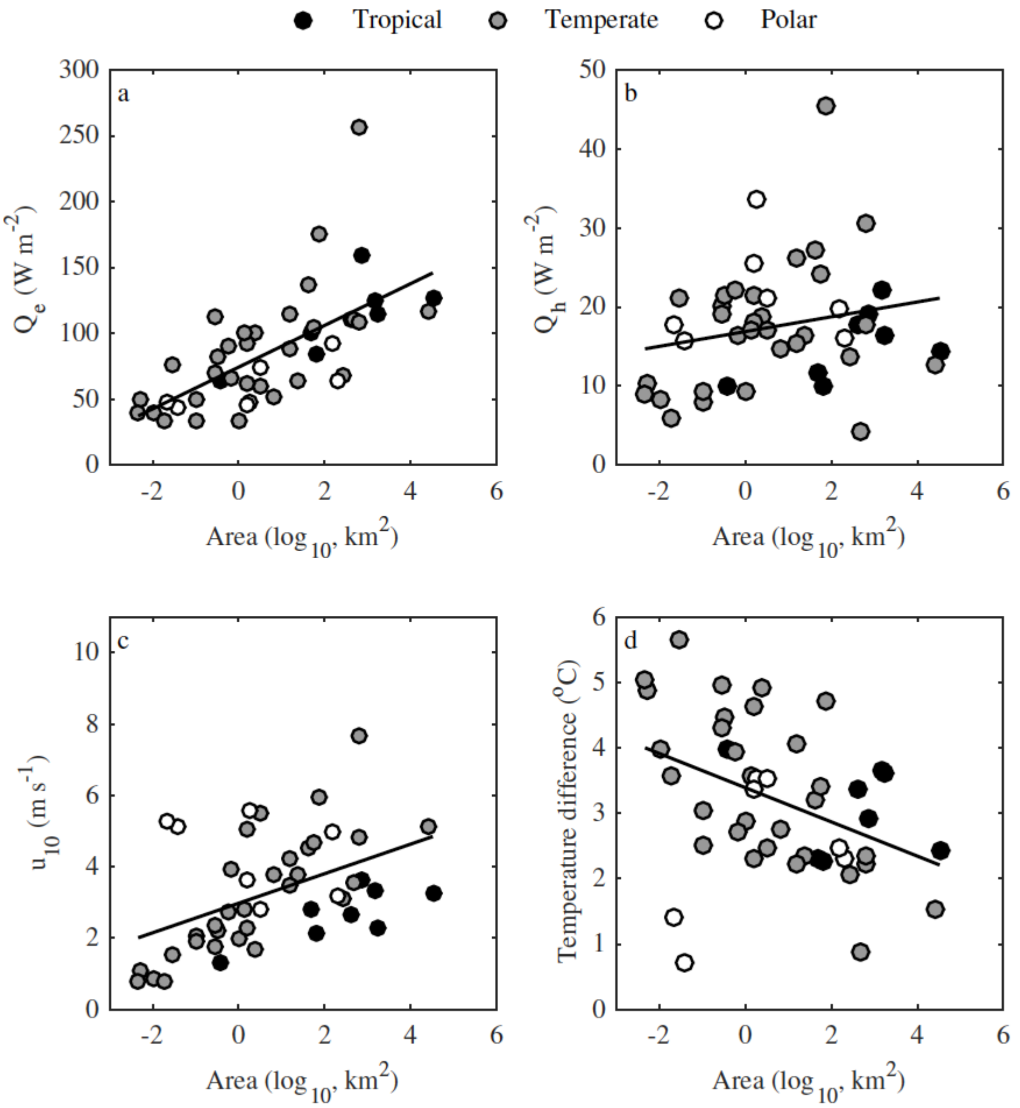

Figure 5. Relationship between lake surface area ($\log_{10}$) and summer-mean (July-September in northern hemisphere and January-March in southern hemisphere) (a) latent (Q_e) and (b) sensible (Q_h) heat fluxes, (c) surface wind speeds adjusted to a height of 10 m (u_{10}), and (d) the water-air temperature difference across 45 lakes. Points are colored according to climatic zones, which are defined by the absolute latitude of each lake: tropical (<30°, black), temperate (30-60°, gray), and polar (>60°, white). Statistically significant ($p < 0.05$) linear fits to the data are shown.

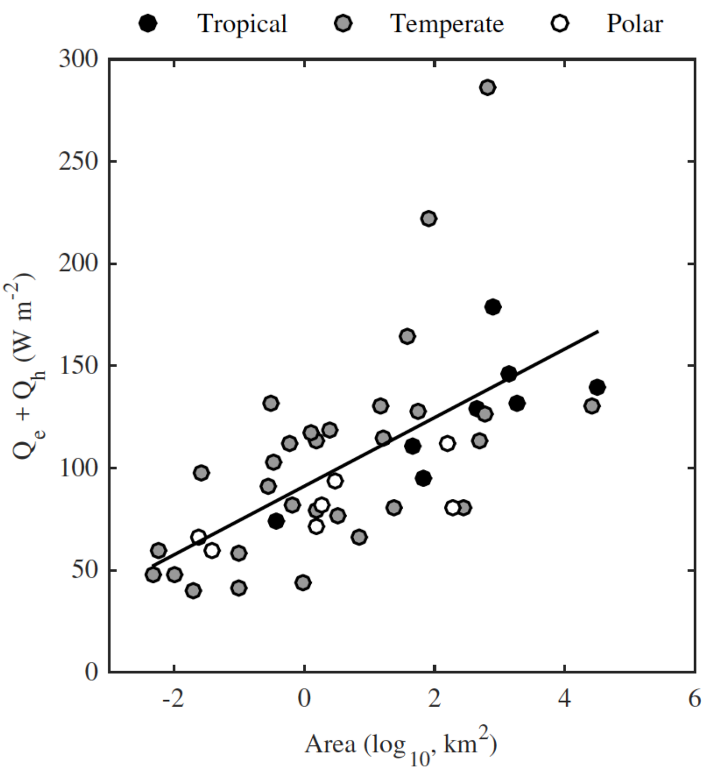

Figure 6. Relationship between lake surface area (log_{10}) and summer-mean (July-September in northern hemisphere and January-March in southern hemisphere) sum of turbulent heat fluxes ($Q_e + Q_h$) at the water-air interface across 45 lakes. Points are colored according to climatic zones, which are defined by the absolute latitude of each lake: tropical (<30°, black), temperate (30-60°, gray), and polar (>60°, white). A statistically significant ($p < 0.05$) linear fit to the data is shown.

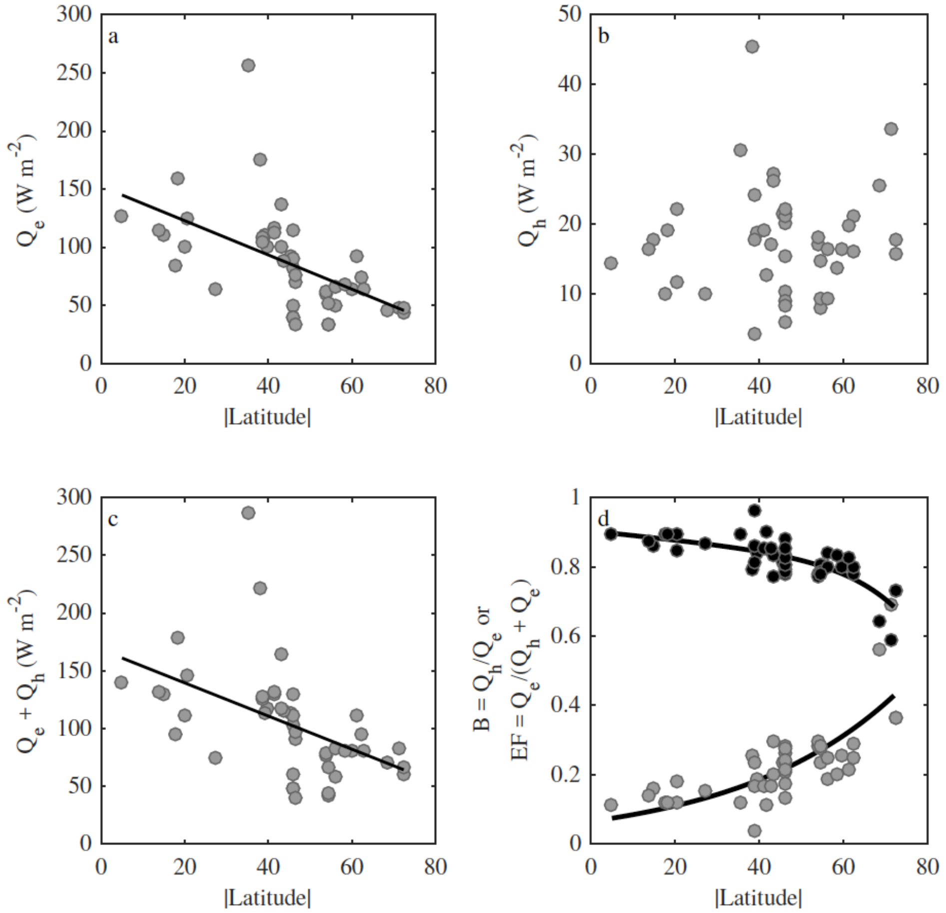

Figure 7. Relationship between latitude (shown as absolute latitude) and (a) latent (Q_e), (b) sensible (Q_h) and (c) the sum of turbulent heat fluxes ($Q_e + Q_h$) at the water-air interface, and (d) the ratio of the summer-mean Q_h to summer-mean Q_e ($B = Q_h/Q_e$; gray), and the relative contribution of summer-mean Q_e to the summer-mean total turbulent heat flux ($EF = Q_e/(Q_h + Q_e)$; black). Statistically significant ($p < 0.05$) linear fits to the data are shown, except for Fig. 7d where an exponential relationship is shown.

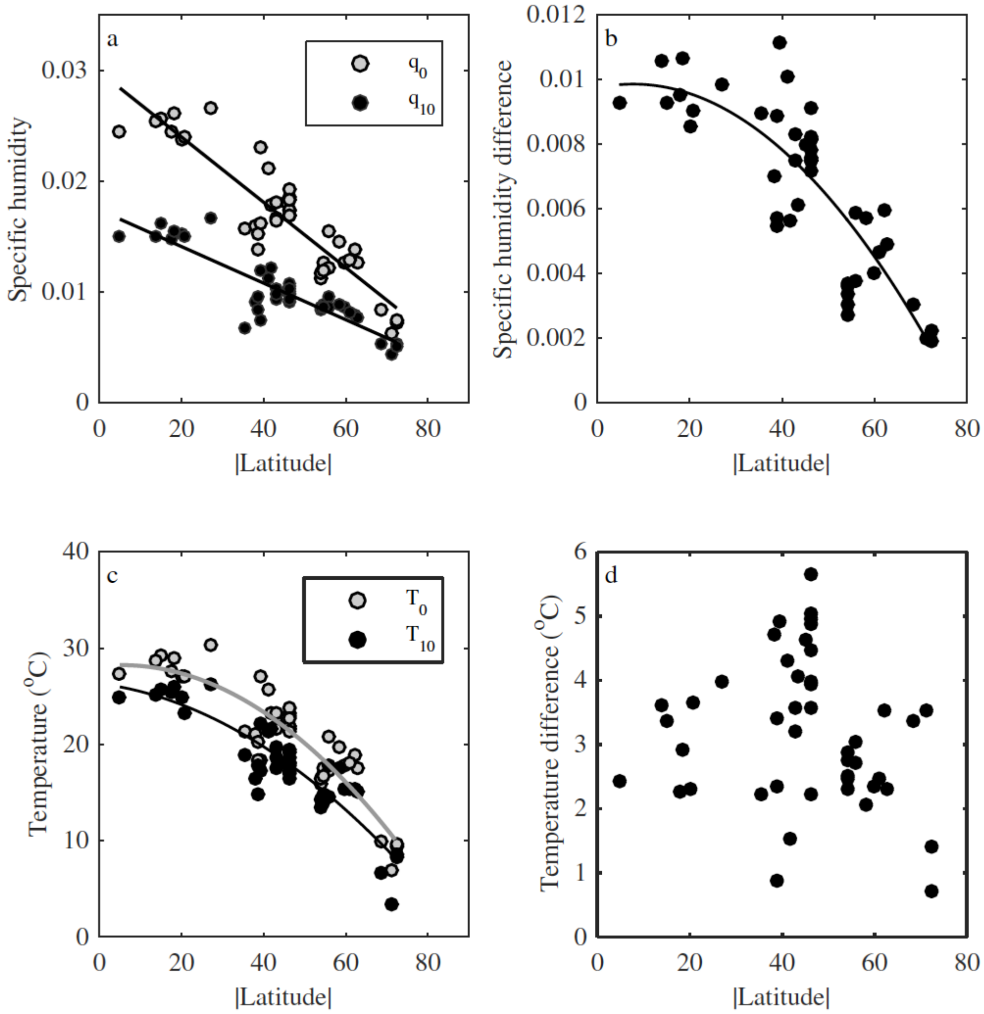

Figure 8. Relationship between latitude (shown as absolute latitude), and (a) the specific humidity above the lake surface (q_{10}; black) and at saturation (q_s; gray); (b) the specific humidity difference (q_s - q_{10}); (c) mean surface air temperature (T_{10}; black) and lake surface temperature (T_o; gray); (d) the temperature difference at the water-air interface (T_o - T_{10}). Relationships are shown for summer (July-September in northern hemisphere and January-March in southern hemisphere) means across 45 lakes. Statistically significant ($p < 0.05$) linear fits to the data are shown, except for Figs 8b and 8c where an exponential relationship is shown.