

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

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37 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
- 40 explore patterns in turbulent heat fluxes, which vary across temporal and spatial scales, using
- 41 in situ high-frequency monitoring data from 45 globally distributed lakes. Our analysis
- 42 demonstrates that some of the lakes studied follow a marked seasonal cycle in their turbulent
- 43 surface fluxes, and that turbulent heat loss is highest in larger lakes and those situated at low
- 44 latitude. The Bowen ratio, which is the ratio of mean sensible to mean latent heat fluxes, is

- 45 smaller at low latitudes and, in turn, the relative contribution of evaporative to total turbulent
- 46 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
- 48 correlated significantly with latitude. The relative contributions to total turbulent heat loss
- 49 therefore differ among lakes and these contributions are influenced greatly by lake location.
- 50 Our findings have implications for understanding the role of lakes in the climate system,
- 51 effects on the lake water balance, and temperature-dependent processes in lakes.
- 52

53 Introduction

- 54 Wind stress and surface heating/cooling are two of the more important factors driving
- 55 physical processes within lakes (Wüest and Lorke 2003), wherein water movements forced
- 56 by the wind produce turbulent mixing that combines with surface heating/cooling to
- 57 determine the physical environment of the lake ecosystem. Lake thermal structure regulates
- 58 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
- 60 effects of climate change on the physics, chemistry, and biology of lakes (De Stasio et al.
- 61 1996) are associated with changes in thermal structure, heat budgets, and ultimately the
- 62 fluxes of heat and energy at the air-water interface (McCormick 1990; Livingstone 2003;
- 63 Fink et al. 2014; Schmid et al. 2014).
- 64 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 65 fluxes can alter key aspects of lake ecosystems, such as an increased occurrence of toxic 66 cyanobacterial blooms (Jöhnk et al. 2008), deep-water hypoxia (Jankowski et al. 2006; North 67 68 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 69 for water security and supply (Brookes et al. 2014) and, in turn, water management strategies 70 (Vörösmarty et al. 2000; Immerzeel et al. 2010; Vörösmarty et al. 2010). 71
- 72 Heat loss at the lake surface can modify the intensity of near-surface turbulence 73 (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. 74 2010; Vachon et al. 2010; Dugan et al. 2016). A detailed understanding of surface heat loss 75 processes is therefore essential given the growing realization of the importance of lakes in the 76 77 global carbon cycle (Cole et al. 2007; Raymond et al. 2013). Surface energy fluxes from 78 lakes can also influence the climate directly (Bonan 1995; Lofgren 1997; Samuelsson et al. 79 2010; Thiery et al. 2015). The surface fluxes of latent and sensible heat, representing the 80 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 81 the hydrological cycle (Rouse et al. 2005), which is sensitive to climate change (Wentz et al. 82 2007; Wu et al. 2013). 83
- 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,

89 NETLAKE; Global Lake Ecological Observatory Network, GLEON) dedicated to the collaborative analysis of high-frequency lake buoy data has provided opportunities for 90 global-scale analyses to be undertaken (Hamilton et al. 2015; Rose et al. 2016). We collated 91 data from 45 lakes across 5 continents (Fig. 1; Table S1) to examine patterns in turbulent 92 93 surface heat fluxes (i.e., latent and sensible heat fluxes) and determine how these patterns 94 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 95 variables that we hypothesize may have an effect, including altitude, lake surface area / wind 96 speed, and lake-air differences in temperature and humidity (Woolway et al. 2017a). We 97 predicted that absolute latitude, which is strongly related to annual mean air temperature and 98 net radiation, would have a strong influence on lake temperature (Straskraba 1980; Piccolroaz 99 et al. 2013) and thus heat fluxes at the air-water interface. Altitude can influence air-water 100 temperature relationships via differential lapse rates (Livingstone et al. 1999), and we thus 101 102 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 103 given that it regulates surface temperature at diel timescales (Woolway et al. 2016) and 104 thereby surface cooling in lakes and has also been shown as an important predictor of the 105 106 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 107 strongly with annual lake heat budgets (Gorham 1964), and so we predicted that depth could 108 109 also influence the surface energy fluxes.

110

111 Materials and methods

We collected mostly continuous observations (measurement intervals range from 4 min to 1 112 h) of lake surface temperatures and meteorological conditions from 45 lakes (Fig. 1a), 113 ranging in surface area between 0.005 km² and 32,900 km², in altitude between 0 m above 114 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). 115 Instrumented buoys measured near-surface water temperature (T_o , °C) at an average depth of 116 approximately 0.5 m (range 0 to 1 m), always within the surface mixed layer. Meteorological 117 conditions including wind speed (U_z , m s⁻¹), air temperature (T_z , °C), and relative humidity 118 (*RH*, %) were measured on average z = 2.9 m (range 1.3 to 10 m) above the lake surface. 119 Fourteen lakes had observations available throughout at least one year. All lakes had 120 observations for the months of July to September (January to March in the Southern 121 Hemisphere) for at least one year. Note that lake variables were not measured annually in 122 some lakes as a result of the monitoring stations being removed prior to the formation of ice 123 cover in winter. Throughout the text we refer to July to September (January to March in the 124 Southern Hemisphere) as 'summer,' in-line with previous studies (Woolway et al. 2017a). 125 Each lake had measurements taken at a single location, except for Lake Tanganyika (two 126 127 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 128 statistical analyses (see below). Specifically, for lakes with more than one monitoring station, 129 we calculated the surface heat fluxes (see below) for each site individually and then 130

131 calculated a lake-wide average.

132	This paper focuses on sensible (Q_h) and latent (Q_e) heat fluxes at the lake surface,	
133	each of which is positive when the direction of heat transfer is from the lake to the	
134	atmosphere (i.e., during surface cooling). The turbulent fluxes, Q_h and Q_e , were ca	alculated as:
135	$Q_h = \rho_a C_{pa} C_h U_z (T_o - T_z),$	(1)
136	$Q_e = ho_a L_v C_e U_z (q_s - q_z)$,	(2)
137	where ρ_a is air density (kg m ⁻³), estimated as a function of air pressure, air temper	ature, and
138	humidity (Chow et al. 1988; Verburg and Antenucci 2010), $C_{pa} = 1005 \text{ J kg}^{-1} \text{ °C}^{-1}$	is the
139	specific heat of dry air at constant pressure, C_h and C_e are the transfer coefficients	for heat
140	and humidity, which were assumed to be equal and adjusted for atmospheric boun	dary layer
141	stability, measurement height, and wind speed (at z m above the lake surface) by following	
142	the computational method of Verburg and Antenucci (2010), and	
143	$L_{v} = 2.501 \times 10^{6} - 2370T_{o}$	(3)
144	is the latent heat of vaporization (J kg $^{-1}$).	
145	The humidity difference, q_s - q_z , which influences evaporative heat transfer	r at the air-
146	water interface, was calculated as the difference between the specific humidity of	saturated
147	air at the water surface temperature, q_s (kg kg ⁻¹):	
148	$q_s = 0.622 e_{sat}/p,$	(4)
149	and the specific humidity of unsaturated air at the measurement height, q_z (kg kg ⁻¹):
150	$q_z = 0.622 e_a/p,$	(5)
151	where e_{sat} is the saturated vapor pressure at T_o (mbar), calculated as:	
152	$e_{sat} = 6.11 \exp^{[17.27T_o/(237.3+T_o)]}$	(6)
153	and e_a is the vapor pressure (mbar), calculated as:	
154	$e_a = RHe_s/100,$	(7)
155	with e_s , the saturated vapor pressure at T_z (mbar), calculated as:	
156	$e_s = 6.11 \exp^{[17.27T_z/(237.3+T_z)]},$	(8)
157	and RH is relative humidity (%), and p is air pressure (mbar).	
158	In this study we also calculate the Bowen ratio (B) , which is commonly us	ed with the
159	energy budget method to estimate evaporation rates in lakes and reservoirs (Gibso	on et al.
160	1996; Lenters et al. 2005; Riveros-Iregui et al. 2017) and is defined as the ratio of	mean Q_h to
161	mean Q_e as:	
162	$B = Q_h / Q_e.$	(9)
163	We also calculate the relative contribution of evaporation to the total turbulent hea	at flux,
164	referred to hereafter as the evaporative fraction (EF), as:	
165	$EF = Q_e/(Q_h + Q_e) = 1/(1 + B).$	(10)
166	As air pressure was not measured on all instrumented buoys, and since loc	al
167	variability in air pressure has a negligible effect on the turbulent fluxes (Verburg a	and
168	Antenucci 2010), a constant air pressure was assumed for each lake in this study,	calculated
169	based on the altitude of the lake (Woolway et al. 2015a). With the exception of air pressure,	
170	all data used to estimate the turbulent surface fluxes were measured directly above the lake	
171	urfaces, as opposed to over land. The latter approach was formerly used to be more common	
172	n limnology (Derecki 1981; Croley 1989; Lofgren and Zhu 2000) but has often been shown	
173	cause large errors (Croley 1989), perhaps contributing to annual mean net surface fluxes	
174	that differ substantially from zero (Lofgren and Zhu 2000).	

175 To understand the drivers of variations in turbulent heat fluxes among lakes, we

- 176 modeled the summer and (where available) annual mean fluxes, calculated from the raw,
- 177 high-resolution data, against lake attributes using a multiple linear regression model.
- 178 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 tocomprehensively 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.

183 All statistical analyses in this study were performed in R (R Development Core Team 184 2014). As the height of air temperature and relative humidity measurement varied among the 185 lakes, we converted T_z and q_z to a surface elevation of 10 m (T_{10} and q_{10}) prior to performing 186 comparisons among lakes (Woolway et al. 2015a). Similarly, in the across-lake comparisons, 187 surface wind speed was adjusted to a height of 10 m (u_{10}) following the methods of Woolway 188 et al. (2015a).

189

190 **Results**

191 Seasonal and diel cycles in turbulent surface fluxes - Many of the lakes investigated 192 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 193 turbulent fluxes demonstrate near-constant monthly mean values (e.g., Corumba). The latent 194 heat flux (Q_e) , and also the sum of the turbulent fluxes (Q_e+Q_h) , followed a clear seasonal 195 cycle in many lakes, especially those situated in temperate regions, being highest in summer 196 as a result of a greater air-water humidity difference (Fig. 3a, 3b). The sensible heat flux (Q_h) 197 followed a less pronounced seasonal cycle among all lakes but was, on average, highest in 198 autumn as a result of a greater air-water temperature difference (Fig. 3a, 3c). Specifically, the 199 surface temperatures of lakes typically retain summertime heat well into autumn, resulting in 200 201 a larger air-water temperature difference at this time of year. This is particularly the case for 202 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 203 well into autumn and winter as a result of their greater heat storage capacity. This also results 204 205 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 206 $Q_e + Q_h$ at seasonal timescales (Fig. 3d). 207

The sensible and latent heat fluxes generally follow a clear diel cycle in summer, but 208 the mean diel cycles are out-of-phase with each other, resulting in a minimal diel cycle in the 209 sum of the turbulent fluxes (Fig. 4a) but considerable diel variability in B (Fig. S2). Q_e is 210 highest during mid-afternoon and lowest during late evening and early morning hours as a 211 result of the diel cycles in wind speed (Fig. 4d) and the humidity difference (Fig. 4b) at the 212 air-water interface (see equation 2), both of which are highest during mid-afternoon. Sensible 213 heat flux follows an opposite diel cycle, with highest Q_h during the late evening and early 214 morning hours, as a result of a greater air-water temperature difference during that time of 215 day (Fig. 4c). Air temperatures above the lake surface tend to be cooler during the evening 216 while the surface water temperatures retain daytime heat longer, resulting in a larger 217 218 temperature difference. Interestingly, the diel cycle in Q_h is opposite to that of u_{10} , to which

219 Q_h is related (see equation 1). This illustrates that the air-water temperature difference in the 220 studied lakes is the main driver of the diel variability of Q_h , and that the magnitude of the air-221 water temperature difference outweighs the opposite influence of u_{10} at diel timescales.

Relationships between surface fluxes and lake attributes - A multiple linear regression 222 223 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 224 annually (Table S2). Qe was higher in larger lakes (Fig. 5a; Table S2) and in lakes situated at 225 226 low latitudes (Fig. 7a; Table S2). Lake surface area also had a statistically significant (p < p0.05) relationship with Q_h (Fig. 5b) within the multiple linear regression model, with Q_h 227 typically being higher in larger lakes during summer but not annually (Table S2). The 228 relationship between lake surface area and both Q_e and Q_h was not always statistically 229 significant when computing the linear regression within specific climatic zones, but this was 230 primarily a result of the limited number of lakes with available data in some climatic regions 231 232 (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 233 lake-size dependence in over-lake wind speed. Larger lakes with greater fetch typically 234 235 experience higher wind speeds (Fig. 5c), via the acceleration of wind over water. In the lakes 236 studied, there was a statistically significant positive linear relationship between lake size and u_{10} during summer (r² = 0.23, p < 0.001, n = 45) but not with latitude or altitude (p > 0.1), 237 thus suggesting an effect of lake fetch. However, we must note that the linear lake-size 238 dependence in u_{10} is not likely to extend indefinitely to the world's largest lakes, since once a 239 lake reaches a certain (unknown) size threshold, the atmospheric boundary layer has 240 essentially adjusted to the lake surface area, and so any further increases in lake size would 241 not lead to further increases in over-lake wind speed. 242

The relationship of lake size and u_{10} results in greater Q_h and Q_e (equations 1 and 2) in 243 the lakes studied. However, Q_h and Q_e are also influenced by the air-water temperature and 244 humidity differences, respectively and, thus the lake-size dependence of these differences 245 must also be considered. There is no statistically significant lake-size dependence in the air-246 water humidity difference ($r^2 = 0.04$, p = 0.17, n = 45), to which Q_e is related, in the studied 247 lakes. However, we calculate a significant negative relationship between lake size and T_o -248 T_{10} (r² = 0.16; p < 0.05, n = 45), with a greater temperature difference in smaller lakes (Fig. 249 5d). Therefore, the influence of lake size on T_o - T_{10} , to which Q_h is related, is opposite to that 250 of u_{10} , resulting in the relationship between lake size and Q_h being weaker than the observed 251 relationship between lake size and Q_e (Table S2). 252

253 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, 254 lake surface area, and lake depth) demonstrates that latitude and lake surface area are 255 statistically significant predictors (Table S3). More total turbulent heat loss was found in 256 257 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. 258 4a), lakes often show in-phase covariance on seasonal timescales (Fig. 3a). The magnitude of 259 these turbulent fluxes, however, can differ considerably among lakes. The ratio of Q_h to Q_e 260 (i.e., the Bowen ratio) demonstrates that Q_h is consistently lower than Q_e (Fig. 7d), with an 261 262 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)
- 265 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 275 relationship, with Q_e higher in warmer lakes situated in warmer climates. To explain the 276 effect of latitude on Q_e (Fig. 7a), but not Q_h (Fig. 7b), we compared, across lakes, the 277 humidity and temperature differences at the air-water interface, to which Q_e and Q_h are 278 279 respectively proportional. With decreasing latitude, we calculated a rapid and statistically 280 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 281 statistically significant increase in the humidity difference $(q_s - q_{10})$ with decreasing latitude. 282 The latter results from the non-linearity of the Clausius-Clapeyron relationship and the 283 resulting dependence of vapor pressure difference on temperature (equations 6 - 8), which is 284 strongly related to absolute latitude both annually ($r^2 = 0.89$, p < 0.001) and during summer 285 $(r^2 = 0.79, p < 0.001)$. Thus, at low latitudes, $q_s - q_{10}$ will be greater, resulting in higher Q_e and 286 lower *B*. 287
- 288

289 **Discussion**

- 290 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 291 years (Dutton and Bryson 1962; Lofgren and Zhu 2000; MacIntyre et al. 2002; Momii and Ito 292 293 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 294 have calculated surface heat fluxes from lakes have used remotely sensed water temperature 295 in combination with land-based meteorological measurements (Derecki 1981; Croley 1989; 296 Lofgren and Zhu 2000) or reanalysis data (Moukomla and Blanken 2017), which can lead to 297 erroneous estimates of air-water interactions. Studies that have calculated heat fluxes using in 298 situ temperature and meteorology data have dealt primarily with single lakes (Laird and 299 Kristovich 2002; MacIntyre et al. 2002; Lenters et al. 2005; Verburg and Antenucci 2010; 300 301 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 302 compared turbulent surface fluxes from continuously recorded buoy data at so many lakes 303
- 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
- 306 latent and sensible heat and their relative contributions to total turbulent heat loss at the air-

307 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 308 and, for lakes with data available throughout the year, follow a predictable seasonal cycle in 309 small to medium-sized temperate lakes, with high Q_e , Q_h , and $Q_e + Q_h$ in summer (later in the 310 year for deeper lakes). In tropical lakes the turbulent surface fluxes follow a less pronounced 311 seasonal cycle, but rather experience comparatively high turbulent heat loss throughout the 312 year, which is expected given the increase in heat gain towards the equator (Verburg and 313 Antenucci 2010; Woolway et al., 2017a). The reduced seasonality of the lake heat content 314 (the difference between minimum and maximum heat content) towards the equator 315 demonstrates that heating and cooling are more separated by season at higher latitudes, 316 resulting in a greater amplitude of the heat budget. In deep and large temperate lakes, such as 317 Tahoe and Taupo, the turbulent energy fluxes are greatest during autumn and winter, as a 318 result of the large heat capacity that causes their surface waters to cool more slowly during 319 winter than the ambient surface air, as has been reported in other studies focusing on large, 320 deep North American lakes (Blanken et al. 2011; Moukomla and Blanken 2017). These 321 results indicate that the season in which the turbulent surface energy fluxes from lakes 322 323 interact most strongly with the overlying atmosphere (and also affect internal lake mixing 324 processes) can vary considerably among lakes.

A comparison across lakes of the relative contributions of Q_h and Q_e to the total 325 turbulent heat flux demonstrates interesting relationships. The Bowen ratio $(B = Q_h/Q_e)$ is 326 found to decrease toward the tropics, since Q_e increases with decreasing latitude (i.e., 327 increasing lake surface temperature), while Q_h does not. B is lower in a warmer climate, both 328 in summer and annually. Similar to lakes at low latitude, one might also expect that Q_e would 329 vary with altitude, as a result of the decrease in air temperature with increasing altitude and 330 the temperature dependence of the specific humidity differences (for a given relative 331 humidity). Specifically, we would expect an altitudinal dependence of Q_e and also B in the 332 studied lakes. However, our global-scale analysis demonstrated that altitude did not have a 333 334 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 335 contribution of Q_e to total turbulent heat loss is greater in tropical lakes (upwards of 90%) 336 and then decreases toward higher latitude (~60-70%). While this relationship is expected due 337 to the temperature dependence of specific humidity differences, this study is the first to 338 calculate B across a global sample of lakes using in situ high-resolution data collected at the 339 lake surface. The lowest annual mean B calculated in this study was 0.06 for Lake 340 Tanganyika, while the highest annual mean *B* was 0.31 for Rotorua. The lowest summer 341 mean B calculated was 0.04 for Lake Tahoe, while the highest summer mean B calculated 342 was 0.69 for Emaiksoun Lake, Alaska, USA. Even higher values of B have been reported on 343 seasonal or shorter timescales in other lake studies. For example, Lenters et al. (2005) 344 345 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 346 winter (Lofgren and Zhu 2000; Blanken et al. 2011), indicating that Q_h can occasionally be 347 larger than Q_e. This highlights the need for continued and expanded analysis of high-348 frequency heat flux measurements on lakes, particularly during the cold season when such 349 350 measurements are difficult and infrequently undertaken.

351 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 352 number of methods (and models) use estimates of B to solve the energy balance and/or to 353 estimate Q_h or Q_e . A constant B is used commonly in, for example, paleoclimate studies and 354 also in simplified lake models (Bultot 1993; Blodgett et al. 1997). Our results demonstrate 355 that a common value of B should not be assumed, and our findings can provide ways of 356 estimating B for lakes as a function of latitude, for example (e.g., in the absence of expensive 357 instrumentation), which can help advance prediction of lake thermal processes. Moreover, 358 our results challenge the validity of neglecting the effect of varying B, which has 359 consequences for estimating lake thermal processes, which are fundamental to understanding 360 lake biogeochemistry and ecology. The proportion of $Q_h:Q_e$ is also important for 361 understanding the influence of climate change on the water balance of lakes and in evaluating 362 the role of lakes in the Earth's hydrologic cycle, which is expected to accelerate with climate 363 364 change (Wentz et al. 2007; Wu et al. 2013; Wang et al. 2018).

While our analysis included observations from lakes across five continents, these 365 were typically restricted to specific years and, as such, may not have captured "normal" 366 meteorological conditions for a particular lake, nor a reasonable range of interannual 367 variability. As such, any lake-to-lake comparisons could have been biased by the presence of 368 'abnormal' years (e.g., drought, flood, heat waves, etc.). For example, one lake may have 369 experienced temperatures above the mean while another lake experienced temperatures below 370 the mean, which could bias our global relationships. Nevertheless, we have found the 371 relationships between the turbulent heat fluxes, in particular with latitude and lake size, to be 372 statistically significant. This occurs despite potential errors in the data and that the 'noise' 373 introduced into the global relationships by any one anomalous lake or anomalous weather 374 during a given year. A caveat to our results regarding the relationship between latitude and 375 the turbulent surface heat fluxes is that not all latitudes are equally represented by study 376 lakes, with fewer or no lakes in areas of critical climate gradients, such as the descending 377 378 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 379 factors such as altitude also controls these same variables. 380

381 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 382 times of the year (and at diel timescales), which could influence greatly convective mixing in 383 a lake and gas transfer at the lake surface. In particular, estimates of carbon dioxide emissions 384 from lakes can be considerably biased when Q_h is not considered (Podgrajsek et al. 2015). 385 Climatic warming will likely increase Q_h in the future, as suggested by the observation that 386 summer-mean water surface temperatures in many lakes have increased more than air 387 temperatures in the past few decades (O'Reilly et al. 2015), thereby increasing the lake-air 388 temperature difference, to which Q_h is proportional. Lake surface temperatures in high 389 latitude lakes, in which Q_h is a relatively large contributor of total turbulent heat loss, have 390 been suggested to experience an amplified response to air temperature variability (Woolway 391 and Merchant 2017). Thus, as a result of the expected increase in Q_h with climate change, 392 there will be a relatively greater increase in total turbulent heat loss at high latitude. Any 393 394 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.

399 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 400 (Polsenaere et al. 2013; Podgrajsek et al. 2015). Previous studies have demonstrated that 401 402 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 403 lake metabolism and gas exchange with the atmosphere. While our results verify some 404 aspects of this previous work, such as the significantly positive relationship between lake area 405 and wind speeds, we also arrive at some important conclusions regarding the surface cooling 406 processes that lead to convective mixing. For example, we show that turbulent surface 407 408 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 409 that lead to greater wind-induced mixing on large lakes also lead to greater turbulent heat loss 410 and potentially convective mixing, especially during times when such cooling processes are 411 not offset by significant surface radiative heating (e.g., strong incoming solar and thermal 412 radiation). Similarly high rates of Q_e and total turbulent surface heat loss are also found for 413 lakes situated in warmer climates (e.g., tropical lakes). Therefore, our results suggest that 414 convective mixing may be more important in large and tropical lakes than has been suggested 415 previously and that convection may be a greater contributor to gas exchange in these systems 416 as well. 417

418

419 Conclusions

We have analyzed high-resolution monitoring data from 45 lakes across 5 continents to study 420 421 the global variation in mean (summer and annually) turbulent surface heat fluxes at the air-422 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 423 the lake surface and also how these fluxes vary at diel, seasonal and annual timescales. We 424 425 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 426 those situated at low latitude. The ratio of mean sensible to mean latent heat fluxes, often 427 referred to as the Bowen ratio and used commonly to estimate evaporation rates in lakes, was 428 shown to vary predictably with latitude, being lower in the tropics. In turn, our study 429 demonstrates that the relative contribution of latent to total turbulent heat loss in lakes varies 430 predictably with latitude. Our results, therefore, demonstrate that the latent and sensible 431 contributions to total turbulent heat loss differ among lakes and these contributions are 432 433 influenced greatly by lake location. This will be useful for predicting the energy balance of 434 lakes globally, in particular in the absence of expensive instrumentation required to solve the lake energy budget. 435

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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



-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.



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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} , km⁻) (a) latent (Q_e) and (b) 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.



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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

700 contribution of summer-mean Q_e to the summer-mean total turbulent heat flux

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701 $(EF=Q_e/(Q_h+Q_e); \text{ black})$. Statistically significant (p < 0.05) linear fits to the data are shown, 702 except for Fig. 7d where an exponential relationship is shown.



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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

