Lake-size dependency of wind shear and convection as controls on gas exchange

Jordan S. Read,[1] David P. Hamilton,[2] Ankur R. Desai,[3] Kevin C. Rose,[4,5] Sally MacIntyre,[6] John D. Lenters,[7] Robyn L. Smyth,[5] Paul C. Hanson,[8] Jonathan J. Cole,[9] Peter A. Staehr,[10] James A. Rusak,[11] Donald C. Pierson,[12] Justin D. Brookes,[13] Alo Laas,[14] and Chin H. Wu[1]

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[1] High-frequency physical observations from 40 temperate lakes were used to examine the relative contributions of wind shear (u_*) and convection (w_*) to turbulence in the surface mixed layer. Seasonal patterns of u_* and w_* were dissimilar; u_* was often highest in the spring, while w_* increased throughout the summer to a maximum in early fall. Convection was a larger mixed-layer turbulence source than wind shear ($u_*/w_* < 0.75$) for 18 of the 40 lakes, including all 11 lakes <10 ha. As a consequence, the relative contribution of convection to the gas transfer velocity (k, estimated by the surface renewal model) was greater for small lakes. The average k was 0.54 m day^{-1} for lakes <10 ha. Because u_* and w_* differ in temporal pattern and magnitude across lakes, both convection and wind shear should be considered in future formulations of lake-air gas exchange, especially for small lakes. **Citation:** Read, J. S., et al. (2012), Lake-size dependency of wind shear and convection as controls on gas exchange, *Geophys. Res. Lett.*, *39*, L09405, doi:10.1029/2012GL051886.

1. Introduction

[2] Lakes are important components of regional carbon budgets, where terrestrial and atmospheric sources of carbon can be sequestered via sedimentation, effluxed to the atmosphere in the form of greenhouse gases like CO_2 and CH_4, or lost to outflows [*Cole et al.*, 2007; *Bastviken et al.*, 2011]. The turbulent surface mixed layer (SML) plays an important role in regulating these processes, for example, vertically distributing resources and regulating the physical environment experienced by phytoplankton, as well as controlling diffusive fluxes of partially soluble gases across the air-water interface. Two of the most important properties of the SML are its depth (z_{mix}) and the intensity of turbulence within it (quantified by the turbulent kinetic energy dissipation rate, ε). These SML properties are dynamic through time and space within lakes and vary widely among lakes, being largely regulated by the balance between solar radiation (acting to enhance stratification) and wind and heat loss (acting to destabilize and deepen the layer). Efforts to quantify the generation of turbulence from these mixing sources have led to water-side velocity scales for convection (w_*) and wind shear (u_*), allowing SML turbulence to be parameterized according to the additive effects of w_* and u_* [*Imberger*, 1985].

[3] In addition to homogenizing the SML, the intensity of near-surface turbulence controls the exchange rate of gases across the air-water interface [*McGillis et al.*, 2004; *Zappa et al.*, 2007; *MacIntyre et al.*, 2010]. Therefore, an understanding of SML dynamics is integral to accurately estimating the efflux of gases like CO_2 and CH_4 from lakes. Gas flux can be calculated as the product of the gas transfer velocity (k) and the difference between the equilibrium and ambient gas concentration in the surface water [*Cole and Caraco*, 1998]. k has a strong dependence on ε [*Zappa et al.*, 2007], and thus can increase in response to wind, waves, convection, and rain events [*Zappa et al.*, 2004; *Soloviev et al.*, 2007]. Despite a basic understanding of the influence of these drivers on ε, the most commonly used models for k predict transfer velocity based only on wind speed measurements [e.g., *Cole and Caraco*, 1998], resulting in other drivers of k being implicitly integrated into the empirical model. Convection is also an important source of near-surface turbulence in lakes that has been shown to enhance gas exchange [*Eugster et al.*, 2003; *MacIntyre et al.*, 2010; *Rutgersson et al.*, 2011]. Despite this recognition, the relative roles of w_* and u_* in

[1]Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, Wisconsin, USA.
[2]Centre for Biodiversity and Ecology Research, University of Waikato, Hamilton, New Zealand.
[3]Department of Atmospheric and Oceanic Sciences, University of Wisconsin-Madison, Madison, Wisconsin, USA.
[4]Department of Zoology, Miami University, Oxford, Ohio, USA.
[5]Now at Smithsonian Environmental Research Center, Edgewater, Maryland, USA.
[6]Department of Ecology, Evolution and Marine Biology, University of California, Santa Barbara, California, USA.
[7]School of Natural Resources, University of Nebraska-Lincoln, Lincoln, Nebraska, USA.
[8]Center for Limnology, University of Wisconsin-Madison, Madison, Wisconsin, USA.
[9]Cary Institute of Ecosystem Studies, Millbrook, New York, USA.
[10]Institute of Bioscience, Aarhus University, Roskilde, Denmark.
[11]Dorset Environmental Science Centre, Ontario Ministry of the Environment, Dorset, Ontario, Canada.
[12]New York City Department of Environmental Protection, Kingston, New York, USA.
[13]School of Earth and Environmental Sciences, University of Adelaide, Adelaide, South Australia, Australia.
[14]Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences, Rannu, Estonia.

Corresponding author: J. S. Read, Department of Civil and Environmental Engineering, University of Wisconsin-Madison, 1261 Engineering Hall, Madison, WI 53706, USA. (jsread@wisc.edu)

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SML processes (such as gas exchange) have been quantified in only a small number of lakes [e.g., *MacIntyre and Melack*, 2009].

[4] Progress in quantifying the role of lakes in globally important processes such as the carbon cycle requires identifying common and predictable patterns in the controls of mixing within lakes [*Cole et al.*, 2007]. Differences in mixed layer depths and water temperatures are related to water color [*Persson and Jones*, 2008; *Tanentzap et al.*, 2008], wind sheltering [*Markfort et al.*, 2010], morphometry, and other properties of lakes [*Fee et al.*, 1996]. Analyses from a small number of tropical, temperate, and Arctic lakes indicate that both lake size and latitude are related to predictable variability in w_* and u_* [*MacIntyre and Melack*, 2009]. To develop robust generalizations that will allow scaling within regional and global models, we test the hypothesis that lake surface area and latitude influence the relative role of convection versus wind shear for mixing within the SML and inducing gas exchange in 40 temperate lakes. Additionally, we illustrate seasonal patterns of the magnitude and relative importance of u_* and w_* and quantify the contribution of wind shear and convection to k using a surface renewal model [*Lamont and Scott*, 1970].

2. Methods

[5] We collected high-frequency observations of water temperature and meteorological drivers from 40 temperate lakes (absolute latitude range: 24.6° to 60°) ranging in surface area from 0.06 ha to over 64,000 ha and totaling more than 24 million measurements (Table S1 in the auxiliary material).[1] Instrumented buoys measured water temperature at multiple depths, as well as wind speed above the surface of the water. Incoming shortwave and longwave radiation, relative humidity, and air temperature were either measured on the buoys (or a nearby location) or modeled as functions of other measured variables. Hypsographic curves for each lake were extracted from bathymetric maps or from concurrent GPS/depth-sounder data. For locations where neither of these datasets existed, the lakes were assumed to have a conical shape constrained by surface area and maximum depth.

[6] We used the velocity scales for wind shear and convection (u_* and w_*, respectively) as proxies for the magnitude of turbulence driven by wind and heat loss. The ratio of u_* to w_* is a dimensionless index which can be used to compare the relative importance of wind shear to convection as components in the SML turbulent kinetic energy budget [*Imberger*, 1985; *Rutgersson et al.*, 2011]. u_* and w_* have different efficiencies of integration into SML turbulence, and we used the ratio proposed by *Imberger* [1985], which considers $u_*/w_* = 0.75$ to be the threshold for equal input from the two components. Thus, ratios <0.75 would represent conditions where convection is a larger source of turbulent mechanical energy to the SML.

[1]Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2012gl051886. Other auxiliary material files are in the HTML. doi:10.1029/2012GL051886.

[7] w_* was calculated from $w_* = (-\beta z_{mix})^{1/3}$, where z_{mix} is the SML depth, and buoyancy flux (β) was estimated using the mean of two separate approaches for calculating surface heat fluxes to reduce uncertainty, including measured changes in internal energy and the sum of surface fluxes [*Jonas et al.*, 2003; *Verburg and Antenucci*, 2010] (see auxiliary material). We set $w_* = 0$ when buoyancy flux was positive (i.e., gaining stratification). u_* was calculated as $u_* = (\tau_0/\rho_w)^{1/2}$ where $\tau_0 = C_D U_{10}^2 \rho_a$ is the wind-shear, ρ_w and ρ_a are the densities of water and air, respectively, C_D is the drag coefficient (as a function of wind speed and atmospheric stability) [*Verburg and Antenucci*, 2010], and U_{10} is the measured wind speed transformed to a 10 m height [*Amorocho and Devries*, 1980]. A sheltering coefficient was applied to τ_0 for lakes where the wind measurement location was likely influenced by terrestrial sheltering [*Markfort et al.*, 2010] (applied to the 14 smallest lakes; see auxiliary material). u_*, w_*, β, and z_{mix} were calculated on an hourly timestep using filtering routines from *Read et al.* [2011] and the atmospheric stability functions from *Verburg and Antenucci* [2010]. Indices hereafter reported as *temporally-averaged* were averages of hourly variables over the entire time series for each lake.

[8] To compare patterns in the seasonality of u_* and w_*, we aggregated normalized 3-week averages for both parameters across all 40 lakes (i.e., subtracting the long-term mean and dividing by the standard deviation of the 3-week averages). 3-week averages were the mean of all values of u_* or w_* that fell within each interval. This process was used to remove lake-specific variations in the seasonal amplitude of w_* and u_* that might arise from differences in geographic location, while still preserving seasonal patterns. For each interval, we calculated the mean and inter-quartile ranges of u_* and w_* across all lakes.

[9] We estimated an hourly time series of near-surface ε for each lake following the approach of *Soloviev et al.* [2007], with ε being the sum of inputs from wind shear (ε_u) and convection (ε_w) (Figure S1). Our approach differed slightly from *Soloviev et al.* [2007] in that we ignored the breaking-wave component of ε. Turbulence from wind shear was calculated as $\varepsilon_u = (\tau_t/\rho_w)^{3/2}/(\kappa\delta_v)$, where τ_t is the tangential shear stress, κ is the Von Karman constant, and δ_v is the stirring-dependent thickness of the viscous sublayer [see *Soloviev et al.*, 2007]. For ε_w, we used $\varepsilon_w = -\beta$, but we caution that this scaling relationship deviates from unity at depths below the near-surface layer [*Jonas et al.*, 2003]. The surface renewal model was used to predict k from ε as $k = \eta(\varepsilon\nu)^{1/4} Sc^{-n}$, where η is the constant of proportionality, ν is the kinematic viscosity of water, Sc is the Schmidt number of the gas, and n is a coefficient representing surface conditions. k was calculated using this equation and with $\eta = 0.29$, $n = 0.5$, and $Sc = 600$. We also calculated k as a function of ε_w alone, namely $k(w_*) = \eta(\varepsilon_w\nu)^{1/4} Sc^{-n}$, and this relationship was used to parameterize the percentage of total k driven by convection as $k(w_*)\% = (k(w_*)/k)100\%$.

3. Results

[10] The relative importance of wind and convection for SML turbulence varied greatly among the 40 lakes, but several basic patterns emerged that were related to lake size,

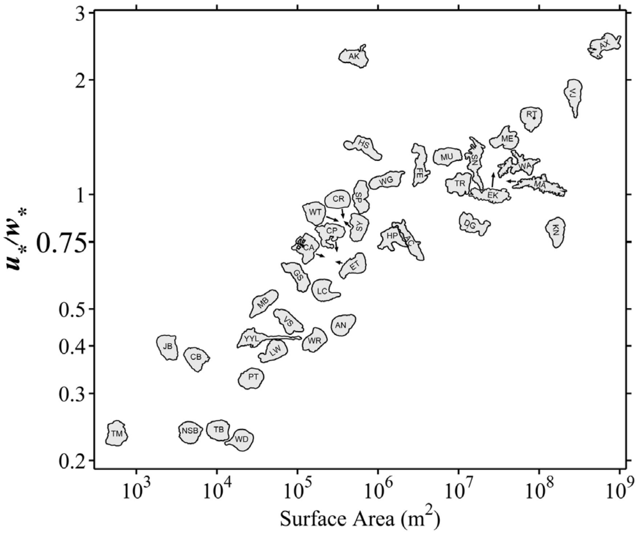

Figure 1. Ratio between the temporally-averaged velocity scales for wind shear (u^*) and convection (w^*), where averages were applied over the entire time series of observations for each lake. Lake shapes were used for plot symbols, and were shifted when overlapping (see tip of arrows).

latitude, and SML depth. We used a non-parametric test (Spearman rank correlation) to evaluate the statistical dependence between paired variables. The ratio of u_* to w_* had a significant relationship with lake size ($p < 0.01$; Figure 1), with wind shear dominating large lakes and convection dominating small lakes, although both u_* to w_* were positively related to lake surface area ($p < 0.01$; Table 1). w_*, but not u_*, had a significant negative relationship with latitude ($p < 0.05$; Table 1). The average of $u_*^3 + w_*^3$, which is often used to parameterize turbulent flux into the mixed layer [*Imberger*, 1985], was significantly related to SML depth ($p < 0.01$).

[11] Seasonal patterns in u_* and w_* were dissimilar when aggregated across all 40 lakes (Figure 2). w_* was typically lowest during the early spring, and increased to a maximum during late summer and early fall before declining again near the end of fall. In contrast, u_* was more often at a maximum during late spring, with a common minimum during the middle of summer (Figure 2; see auxiliary material for hourly results data).

[12] As expected, k was of greater magnitude on larger lakes ($p < 0.01$; Table 1). The percentage of this transfer velocity that was driven by convection alone ($k(w_*)$%) was significantly related to lake size and season ($p < 0.01$; Table 1 and Figure 3). Similar to the seasonal patterns in u_* and w_* (Figure 2), the average convective influence on gas transfer was significantly higher (Mann-Whitney U-test;

Table 1. Spearman Rank Correlation Coefficients (Across Lakes) Between Temporally-Averaged Turbulence Parameters and Lake Properties[a]

	w_*	u_*	$u_*^3 + w_*^3$	u_*/w_*	$k(w_*)$%	$k(w_*, u_*)$
Surface Area	0.626[a]	0.914[a]	0.873[a]	0.877[a]	−0.917[a]	0.918[a]
Latitude	−0.382[b]	−0.228	−0.307	0.071	0.047	−0.238

[a]$p < 0.01$.
[b]$p < 0.05$.

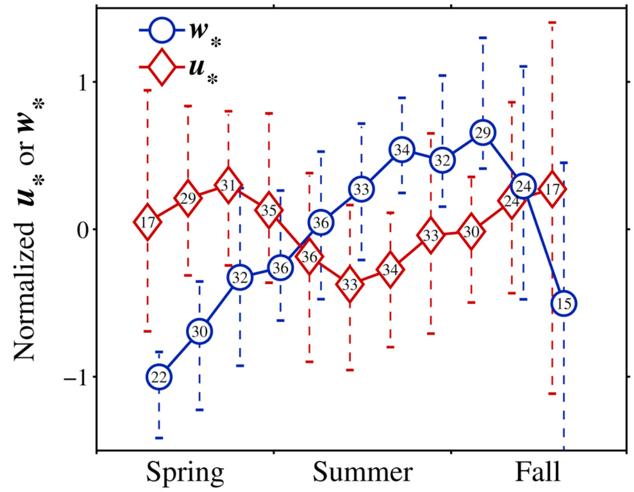

Figure 2. Average, normalized values of u^* and w^* across 40 lakes, plotted on 3-week intervals. u^* and w^* were offset by 4 days to improve figure clarity. Seasonal periods were based on day-of-year 81–173, 173–265, and 265–356 for Northern Hemisphere lakes, while Southern Hemisphere lakes were shifted by 182 days. Error bars represent the interquartile range (across lakes) of individually normalized values in each interval. The number of lakes used for each interval is displayed inside each marker.

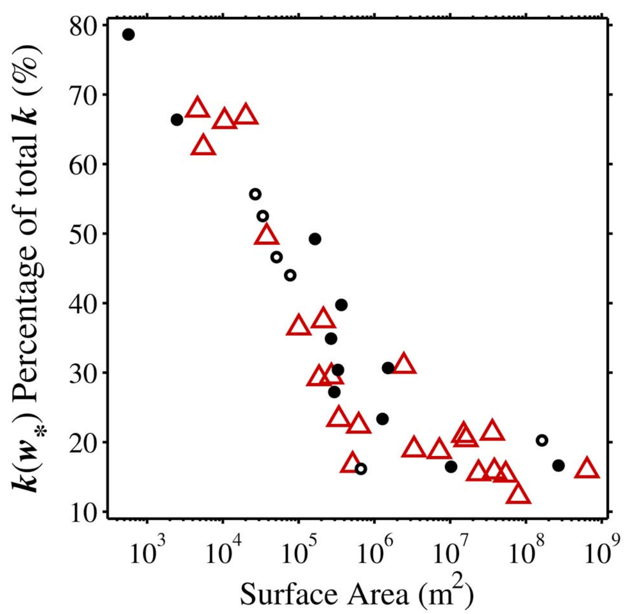

Figure 3. Temporally-averaged convective fraction (%) of total gas transfer velocity calculated using the surface renewal model for 40 lakes. Seasonal differences in $k(w^*)$% were tested for lakes with at least 21 days of observations for spring and summer periods (day-of-year 81–173; 173–265, respectively) using a Mann-Whitney U-test. Lakes without sufficient data are shown as black dots, lakes with no significant seasonal difference ($p > 0.01$) are shown as open black circles, and lakes where summer $k(w^*)$% was significantly higher than spring $k(w^*)$% are shown as red, upward-pointing triangles.

$p < 0.01$) during summer than spring for 23 of the 29 lakes with representative data for both periods (at least 21 days).

4. Discussion

[13] Our analysis leveraged physical measurements from 40 temperate lakes to examine the relative roles of wind shear and convection in driving turbulence-dependent SML processes (such as gas exchange). Convection was of increasing importance for the smaller lakes in our analysis. This result is important for scaling biogeochemical measurements, as small lakes are numerically dominant across the global landscape [*Downing et al.*, 2006] and often represent disproportionately large areal fluxes of greenhouse gases, even when k is estimated conservatively [*Cole et al.*, 2007]. Many investigators have shown evidence of gas transfer enhancement during convective conditions [*Eugster et al.*, 2003; *Jeffery et al.*, 2007; *MacIntyre et al.*, 2010; *Rutgersson et al.*, 2011], but our analysis is the first to highlight – across a broad range of lakes – the importance of convectively derived turbulence in small lakes. In particular, we found a strong size dependence for u_*/w_* (Figure 1), as well as a pattern of increased convective contribution to gas transfer velocities in smaller lakes (Figure 3). w_* was of greater magnitude on larger lakes (likely due to greater mixed layer depths and more rapid wind-driven heat losses), and generally increased at lower latitudes for the lakes in our analysis (Table 1). Both of these patterns were consistent with *MacIntyre and Melack* [2009]. While our results revealed a likely dependence of w_* on surface area and latitude, convection was the dominant temporally-averaged source of SML turbulence in small lakes (<10 ha), regardless of latitude.

[14] Wind shear followed the expected temporal pattern for most of the lakes included in this analysis, with maximum values occurring during the spring and fall (Figure 2), periods that often represents the windiest time of the year in temperate regions. Conversely, w_* lagged u_* by several months, generally reaching a maximum during late summer and early fall. This lag is a result of the thermal inertia of these lakes, which causes maximum cooling to lag maximum summer water temperatures (as a function of lake depth and vertical mixing). Because of the contrasting seasonal patterns in u_* and w_*, as well as their differing contributions according to lake size, we would expect processes driven by SML turbulence (such as k) to exhibit patterns that are closely related to the relative contribution of these two drivers to ε.

[15] Convection made a large contribution to k for smaller lakes, where temporally-averaged $k(w_*)$% was greater than 60% for the six smallest lakes, and as much as 79% of total k for the smallest lake (Figure 3). Larger lakes (>10 km^2) had a range in $k(w_*)$% between 12–21%, indicating that while convection was a much smaller driver of k than wind shear, it was still important. The convective component of k was often greater in summer compared to spring. For example, of the 29 lakes that had sufficient data for the spring and summer periods, 23 of these lakes had significantly higher $k(w_*)$% during the summer ($p < 0.01$; Figure 3). Most models for gas transfer are parameterized by wind speed and, therefore, have temporal patterns that are closely aligned with the dynamics of u_* [*Wanninkhof*, 1992; *Cole and Caraco*, 1998]. Wind-based models may be appropriate for larger lakes with higher u_*/w_*, but for smaller lakes where convection is increasingly important, they likely fail to adequately reproduce the temporal dynamics of k.

[16] While our results highlight a potential lack of coherence between wind-modeled k and k that is modeled from both ε_u and ε_w (particularly for small lakes; Figures 2 and 3), our methods are based purely on physical principles. Therefore, further improvements to gas exchange estimates should couple the analysis used here with continuous turbulent flux observations [e.g., *MacIntyre et al.*, 2010; *Huotari et al.*, 2011] across a wide distribution of lakes. However, the mechanistic physical model employed here is likely more transferable across a variety of diverse water bodies compared to site-specific empirical models for gas exchange.

[17] The lakes included in this analysis span large gradients in size, latitude, shape, and color (Table S1), and these factors drive unique SML dynamics in each lake. The temporal coverage of the measurement campaigns also varied among lakes. We applied consistent and sometimes redundant methods for most lakes for the calculation of ε, u_*, and w_*, with an understanding that our methods may not represent ideal approaches for individual lakes (see auxiliary material). Despite these limitations, we have highlighted several important and robust physical patterns for a diverse set of lakes.

[18] At present, the constant of proportionality relating $\varepsilon^{1/4}$ to k is poorly constrained, with recent investigators disagreeing by almost 3-fold on the magnitude of η [e.g., *Zappa et al.*, 2007; *MacIntyre et al.*, 2010; *Vachon et al.*, 2010]. We used a modified version of the estimate of η from *Zappa et al.* [2007], a study where ε and k were measured during various forcings. Because the depths of our near-surface estimates of ε were shallower than field measurements in *Zappa et al.* [2007], we used their lower boundary of $\eta = 0.29$. We assumed that disagreement in η is related to the corresponding depth of ε (as surface-generated turbulence decreases with depth) and parameterized our model of k accordingly, but this topic warrants further examination.

[19] Using a conservative value for η, our average k for the 11 smallest lakes (<10 ha) was 0.54 m day^{-1} (standard deviation of 0.12 m day^{-1}; Table S3). This range is in good agreement with transfer velocity estimates for small temperate lakes from a variety of different methods [*Cole et al.*, 2010] and slightly higher than *Cole et al.*'s [1994] 0.5 m day^{-1}, which was used as an estimate of the global average k. Our results suggest that $k = 0.54$ m day^{-1} is a conservative mean value for extremely common small (<10 ha) temperate lakes, and that larger lakes likely have stronger winds and higher k (Table S4; see auxiliary material for hourly k).

[20] Our results build on earlier work that highlights the role of convection in enhancing the gas transfer velocity for lakes [*Eugster et al.*, 2003; *MacIntyre et al.*, 2010]. Given that convection is a significant component of k, then the seasonal, diurnal, and latitudinal dependence of w_* has likely been missing from most efflux estimates to date. These potential errors include the sub-daily parameterization of k in free-water metabolism models [*Staehr et al.*, 2010], as well as gas exchange in cases where seasonal variation in both k and gas concentration would combine to significantly influence total flux magnitudes. Because the majority of lakes are small and often wind-sheltered, the convective component of near-surface turbulence must be considered in future formulations of k and in calculations of lake gas exchange.

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