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Stronger winds over a large lake in response to weakening air-to-lake temperature gradient

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The impacts of climate change on the world's large lakes are a cause for concern[1–4]. For example, over the past decades, mean surface water temperatures in Lake Superior, North America, have warmed faster than air temperature during the thermally stratified summer season, because decreasing ice cover has led to increased heat input[2,5]. However, the effects of this change on large lakes have not been studied extensively[6]. Here we analyse observations from buoys and satellites as well as model reanalyses for Lake Superior, and find that increasing temperatures in both air and surface water, and a reduction in the temperature gradient between air and water are destabilizing the atmospheric surface layer above the lake. As a result, surface wind speeds above the lake are increasing by nearly 5% per decade, exceeding trends in wind speed over land. A numerical model of the lake circulation suggests that the increasing wind speeds lead to increases in current speeds, and long-term warming causes the surface mixed layer to shoal and the season of stratification to lengthen. We conclude that climate change will profoundly affect the biogeochemical cycles of large lakes, the mesoscale atmospheric circulation at lake–land boundaries and the transport of airborne pollutants in regions that are rich in lakes.

Since 1970, global average temperatures have increased at 0.2 °C decade^{-1}, largely, it is hypothesized, owing to anthropogenic emissions of greenhouse gases[1]. Temperate mid-continent regions such as the Midwest United States of America, not insulated by the buffering effects of ocean heat capacity or tropical moisture, have warmed even faster, and impacts on ecosystems and large lakes are starting to be felt[2]. Lakes, and especially large lakes, are known to be an important component of regional and possibly global biogeochemical cycles[3,4]. Yet, little is known about the impact of climatic warming on large lake physical and biological environments.

The Laurentian Great Lakes contain over 20% of the world's non-frozen fresh water, and Lake Superior, is the largest freshwater lake in the world by area[5]. The impact of warming temperatures on the dynamics of Lake Superior is poorly understood. One thing we do know is that regional warming has not been felt equally in lake and air. Since 1985, summer stratified season (July–September) buoy air temperatures over Lake Superior have increased by 1.05 ± 0.53 (1-σ least-squares slope) °C decade^{-1} and surface water temperatures by 1.21 ± 0.68 °C decade^{-1} (Fig. 1a).

Regression analysis of all decade or longer sub-periods within the record further corroborates that warming trends are robust and seen in >90% of all sub-periods. These decadal trends are similar in sign to those seen in the global temperature record, suggesting anthropogenic forcing is driving much of this change, although large climate variability, such as the 1998 El Niño are superimposed. These warming trends have raised summer surface water temperature in Lake Superior by 2.5 °C since 1980 (ref. 5) and 3.5 °C since 1906 (ref. 6). These rates are significantly in excess of rates of regional surface air temperature increase[5,6].

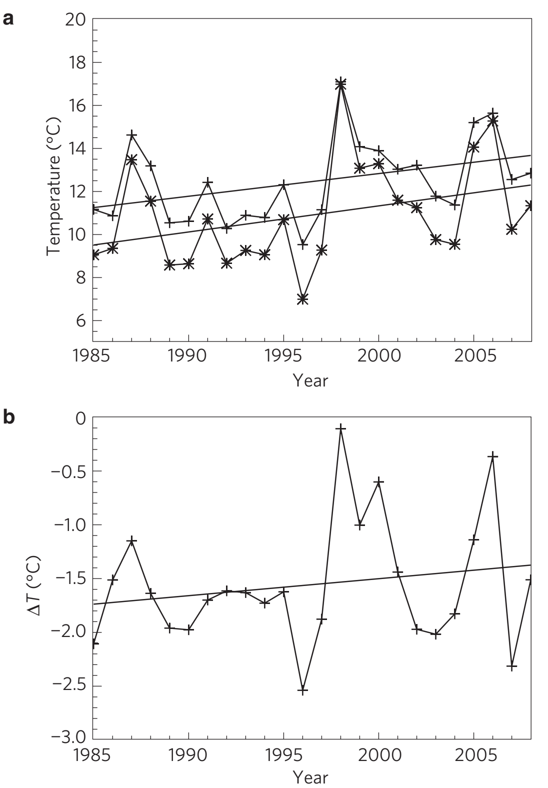

Figure 1 | Air and lake temperature from 1985 to 2008. a, Mean summer stratified (July–September) season temperatures for Lake Superior air (crosses) and surface water (stars), as observed by buoys. Surface water temperatures since 1985 are increasing at 1.21 ± 0.68 °C decade^{-1}, which is faster than near-surface air temperature (1.05 ± 0.53 °C decade^{-1}), owing to shortening of the winter ice season. **b**, The net result is a decline in the mean air–lake difference, leading to destabilization of the marine stable boundary layer by -0.16 ± 0.12 °C decade^{-1}.

Faster warming of water than air is contrary to what might be expected and what has been observed over the oceans[7]. Long-term trends in summer surface water temperature are stronger than those in the atmosphere primarily owing to a long-term decrease in ice cover[8]. Decreasing ice cover over the past century has been documented on rivers and lakes around the world, accelerating over the past few decades[2]. Decreased ice cover results in a significant change in albedo and a correspondingly greater input of heat in the

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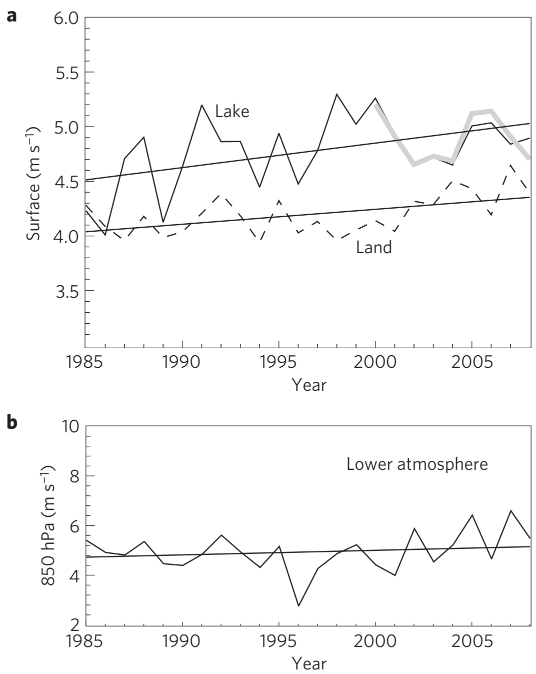

Figure 2 | Increasing regional wind speeds. a, Buoy (solid line) and satellite scatterometry (grey line) agree on the magnitude and trend of wind speed (0.22 ± 0.09 m s^{-1} decade^{-1}) since 1985. This increase is 64% faster than reanalysis wind speed trends (0.14 ± 0.05 m s^{-1} decade^{-1}) over land within a 3.75° latitude by 9° longitude area surrounding Lake Superior, suggesting that lake destabilization is causing the change in lake wind speeds. **b**, The wind speed trend (0.15 ± 0.17 m s^{-1} decade^{-1}) in the free troposphere at 850 hPa is similar to the land trend, strengthening arguments for surface-based forcing.

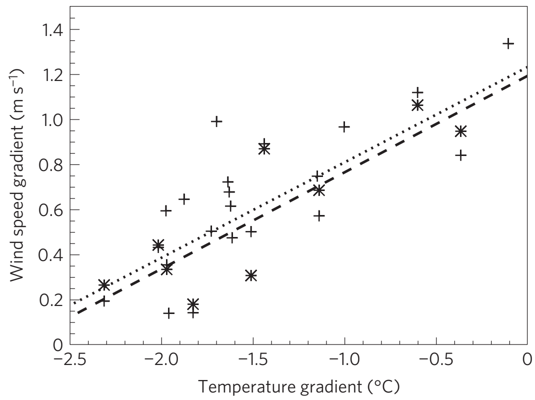

Figure 3 | Relationship of wind speed gradient to temperature gradient. A significant positive relationship exists between the lake-to-air temperature gradient and the mean stratified season lake-to-land wind speed gradient for buoy (crosses, $r^2 = 0.49, n = 29$, two-tail t-test $p = 0.0001$) and satellite (stars, $r^2 = 0.73, n = 9$, two-tail t-test $p = 0.003$) observations. The slopes of these fits for buoy (dotted line, 0.43 ± 0.10 m s^{-1} °C^{-1}) and satellite (dashed line, 0.42 ± 0.09 m s^{-1} °C^{-1}) data agree with theoretical predictions from a simple boundary layer model (0.41 ± 0.02 m s^{-1} °C^{-1}).

late winter and spring, which in turn leads to an earlier onset of summer stratification. Summer water temperatures are sensitive to the timing of the onset of stratification, and hence summer water temperatures are a strong function of winter ice conditions[5].

One result of faster warming of stratified season surface water than surface air is a weakening of the water–air temperature gradient, as confirmed by buoy observations in the lake (Fig. 1b), which show a gradient getting weaker by 0.16 ± 0.12 °C decade^{-1}. Consequently, the inversion of warmer air temperature over colder water that characterizes warm season marine boundary layers and summer season Great Lakes has become weaker. Reanalysis estimates of temperature trends over nearby land show a much weaker trend and little change in land–atmosphere temperature gradient (Supplementary Fig. S1).

The efficiency of transfer of momentum from the surface to the atmosphere in the stable layer is a strong function of the strength of this inversion[9]. Consequently, a less stable, more neutral boundary layer will lead to higher wind speeds near the surface, as demonstrated in simple, theoretical models (Supplementary Fig. S2). Although this coupling between water temperature and atmospheric boundary layer winds has been well observed over temperate[10] and especially over tropical[11–14] oceans, and also simulated in numerical models over the ocean[15,16], little is known about whether large lakes are able to influence the atmosphere in a similar way. Increasing wind speeds over Lake Superior have been noted and hypothesized to be due to destabilization of the atmospheric boundary layer[4], but it has not been tested or examined in detail.

Buoy averaged summer wind speeds over Lake Superior have increased 0.52 ± 0.20 m s^{-1} since 1985, an increase of nearly 12% (Fig. 2). Buoy wind observations before 1985 (1979–1984) could not be compared owing to a change in wind speed averaging routines and a small correction was needed for the use of the older routine on some buoys in later years (Supplementary Fig. S3). The wind observations are further corroborated by satellite scatterometry-based observations of basin average summer wind speeds (Fig. 2, grey line) and reanalysis estimated winds. Fitting the wind speed observation distribution to a Weibull distribution[17] shows that these wind speed increases are not due to changes in the shape of the wind speed distribution, but rather a shift in the magnitude parameter (Supplementary Figs S3 and S4), implying that the increase is not due to a higher incidence of very fast winds caused by a change in storminess, for example.

Moreover, the increase in wind speeds of Lake Superior is nearly twice the increase in regional reanalysis estimated surface winds (Fig. 2), and *in situ* wind speeds observed at most coastal stations and for terrestrial Minnesota[18] show little or no increase. Decreasing wind speeds have been observed over much of the contiguous United States[19]. Coastal sites around Lake Superior have trended towards higher wind speeds, but these trends are weaker than the observed open-water trends. Thus, although surface wind speeds are at most increasing weakly region-wide, another process must explain the faster increase over the lake. Contrary to findings from the lower Great Lakes[20], a shift in wind direction was not observed (Supplementary Fig. S4). Furthermore, trends in wind speeds detected in reanalysis observations of the lower atmosphere are weak (Fig. 2b), further bolstering the conclusion that over-lake wind speed changes are being driven primarily by changes in surface forcing and that these changes are restricted to the atmospheric surface layer.

Indeed, when the summer average wind speeds over the lake are subtracted from the wind speeds over land and compared to the average lake-to-air temperature difference, there is a significant positive correlation between the wind speed excess over the lake and the air–lake temperature gradient (Fig. 3). The sensitivity and 1-σ uncertainty estimated by least-squares linear regression is 0.42 ± 0.10 m s^{-1} °C^{-1} for the buoy observations ($r^2 = 0.49, n = 29$, two-tail t-test $p = 0.0001$). This slope is very similar to that estimated by a theoretical stable layer marine wind profile model (Supplementary Fig. S2) of 0.41 ± 0.02 m s^{-1}. The strength of this relationship continues to be strong even in recent years when trends in mean temperature and temperature gradient have been

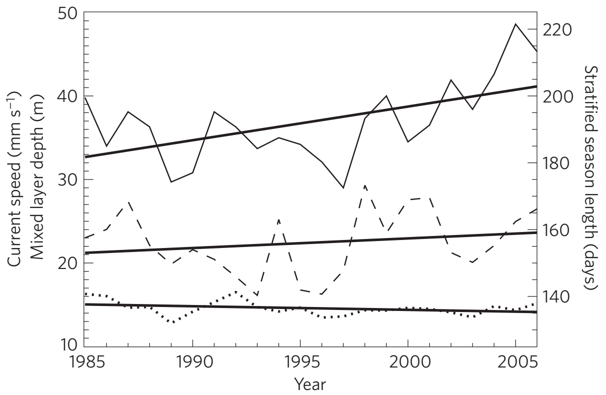

Figure 4 | Trends in Lake Superior physical circulation. Surface current speeds are primarily driven by surface wind forcing, and thus trends in wind speed are directly reflected in model surface currents (solid line, left axis) increasing by 4.0 ± 1.4 mm s^{-1} decade^{-1}. In contrast, warming temperatures drive shoaling of mixed layer depth (dotted line, left axis) by -0.43 ± 0.30 m decade^{-1} and increase in stratified season length (dashed line, right axis) by 2.9 ± 3.3 day decade^{-1}, although both trends are weak. These changes will probably affect ecosystem functioning in the lake.

changing relatively slowly, similar to global temperature trends, as demonstrated by the regression with satellite winds showing a slope of 0.43 ± 0.09 m s^{-1} °C^{-1} ($r^2=0.73, n=9$, two-tail t-test $p=0.003$). Consequently, we conclude that the destabilization of the lake boundary layer is causing an increase of near-surface wind speeds over the lake.

There are a number of implications to increasing wind speeds and decreasing temperature gradients on the physical environment of Lake Superior. Large-scale circulation patterns and vertical mixing strength in Lake Superior are primarily wind-driven (V.B., G.A.M., C. Wu, A.R.D., N. Urban & N. Kimura, manuscript in preparation). A sensitivity study (J.A.A. and J. Allen, manuscript in preparation) using a one-dimensional model and realistic surface forcing suggests that the vertical extent of the surface layer increases of the order of 1 m for every 1% increase in wind speed.

Simulations with a three-dimensional model of the lake indicate that increases in wind speed are driving an increase in surface current speeds ($r^2=0.59, n=28$, two-tail t-test $p=1.2\times10^{-6}$). The model reveals surface currents increasing by 4.0 ± 1.3 mm s^{-1} decade^{-1} (Fig. 4). Although decreased atmospheric inversion strength and stronger winds alone would increase summer mixed layer depths, we find shoaling of the summer mixed layer with time by -0.43 ± 0.30 m decade^{-1} in the model, indicating that increasing atmospheric temperatures are having a dominant effect. Increased atmospheric temperatures are also contributing to an increase in the length of the summer stratified period by 2.9 ± 3.3 days decade^{-1}. A longer stratified period and shallower mixed layers are probably contributing to the observed declining trends in lake-wide chlorophyll[21].

The changes to the lake boundary layer atmosphere, currents and thermal stratification will probably have an impact on lake ecology, biogeochemical cycling and surface evaporation. Furthermore, changes to gradients in lake and land wind speeds will alter the vertical circulation above the lake, mesoscale weather phenomena and air pollutant transport. All of these impacts are understudied consequences of large lakes facing climate change, especially those with seasonal ice cover, and warrant further study.

Methods

Lake temperature, air temperature and surface wind observations were obtained from Lake Superior buoy data archived at the National Buoy Data Center. Processed satellite wind observations were obtained from the NASA (National Aeronautics and Space Administration) QuikSCAT SeaWinds ocean surface satellite observations at 0.25° resolution. Observations of land surface temperature, air temperature, surface winds and upper air winds at 32 km resolution over the Lake Superior region were retrieved from North American Regional Reanalysis[22] (NARR). All of these data were annually averaged over the mean stratified season (July–September). A power-law wind profile[23], and boundary layer similarity theory[9], with ocean surface parameters were used in construction of the theoretical model. The physical model is based on the Massachusetts Institute of Technology general circulation model configured to Lake Superior bathymetry, run at 2 km resolution. Details on each of these are provided below.

Lake meteorology. Three buoys, collecting hourly meteorology, have been operating on Lake Superior since 1979 at the earliest. All wind observations before 1985 relied on vector-averaged winds, where most data since used a scalar-average wind, and thus pre-1985 data were discarded and post-1985 vector winds were empirically corrected for a known low bias in vector-averaged winds (Supplementary Fig. S3). The results of the analysis do not qualitatively (and in most cases quantitatively) change if these data are included or the correction is not applied. Air temperature at 4 m, wind speed at 5 m and surface lake temperature at 0.5 m were retrieved, averaged for the summer season and averaged across the buoys. Temperature gradients were computed by subtracting mean air from mean surface water temperature.

Satellite winds. To verify that buoy average winds were reflective of basin average winds, satellite scatterometry data were used to compute whole lake mean winds. These data were derived from the Level 3 $0.25°\times0.25°$ NASA daily average SeaWinds product collected by the NASA QuikSCAT satellite. The daily averages are based on twice-daily (approximately 6 and 18 local time) passes of the satellite over the region. A similar averaging technique as for the buoy data was applied to these observations.

Land surface meteorology. The National Centers for Environmental Prediction NARR (ref. 22) provides 3-hourly 32-km-resolution gridded reanalysis meteorology. These data were extracted for the region defined as an area from 45.7500° N to 49.3125° N latitude and 92.5000° W to 83.6875° W longitude. Free troposphere wind velocities were computed from the U and V wind vectors at the 850 hPa pressure level. For surface 2 m air temperature and land surface temperature, NARR land cover data were used to mask out water grid cells before averaging.

Trend analysis. All trends were computed using standard least-squares regression, with linear slope and 1-σ slope uncertainty reported for all relevant meteorological variables. To further test the strength of these slopes, we carried out a boot-strapping trend analysis of all subsets of ten or more consecutive years of data, finding in all variables, that most trends match in sign and on average the magnitude of the trend for the entire data record studied.

Surface layer model. A power-law wind profile[23] was coupled to Monin–Obhukov flux-profile similarity functions[9,24] for stable layers. Charnock ocean surface stress functions[25] were applied to compute ocean momentum drag, roughness and friction velocity. A bulk parameterization of surface heat fluxes[9] was then used to compute the strength of the stability. An iterative solver is applied to these sets of equations, given typical surface layer mean winds, to solve for wind speed as a function of height for a range of air–water temperature gradients. Near-surface wind speed differences as a function of temperature gradient were then extracted and linearly fitted for wind speed sensitivity to inversion strength.

Lake Superior numerical model. The Massachusetts Institute of Technology general circulation model[26,27] was configured to Lake Superior bathymetry[28] at 2 km horizontal resolution. The model has 28 vertical layers of varying thickness, with a finest resolution of 5 m in the top 50 m, increasing with depth. The model was forced with 32-km-resolution 3-hourly air temperature, humidity, winds and surface down-welling radiation from NARR (ref. 22) between 1979 and 2006. A model bulk formula uses atmospheric stability to determine wind stress, latent and sensible heat fluxes at the air–lake interface. Daily fractional ice coverage from National Oceanic and Atmospheric Administration[8] was applied to each model grid cell and used to decrease momentum and heat exchange between the lake and atmosphere by the percentage the grid is ice covered. The K-profile parameterization vertical mixing scheme[29] and Smagorinsky horizontal diffusivity scheme[30] were used to parameterize sub-gridscale processes. The model is spun up for five years using 1979 forcing before the final run through 2006.

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Author contributions

A.R.D. developed the analysis framework, built the surface layer model, carried out the correlation analyses and wrote most of the manuscript. J.A.A. suggested the initial idea and analysed the buoy data. V.B. parameterized, ran and analysed the physical model of Lake Superior. G.A.M. designed the physical model framework and discussed lake biogeochemical implications. All authors discussed and revised the manuscript and figures.

Additional information

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SUPPLEMENTARY INFORMATION
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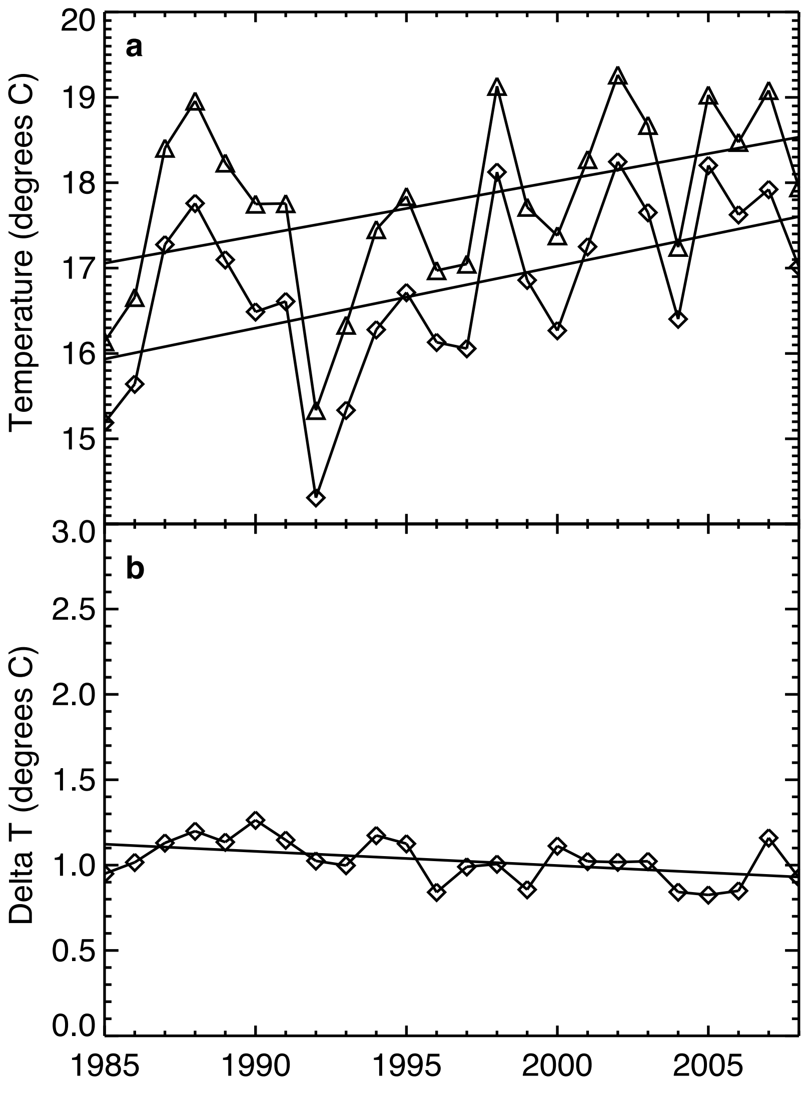
Supp Figure 1 l **Trends in air temperature over land**. a, Reanalysis regional 2 m (diamonds) and surface (triangles) land temperatures during the summer season show warming trends with smaller magnitude (0.72 +/- 0.27 C decade-1 at 2 m, 0.64 C decade-1 at surface) than air temperature over the lake (1.05 +/- 0.53 C decade-1) and b, a weak, declining (stabilizing) trend (-0.08 +/- 0.03 C decade-1) in land-air temperature gradient.



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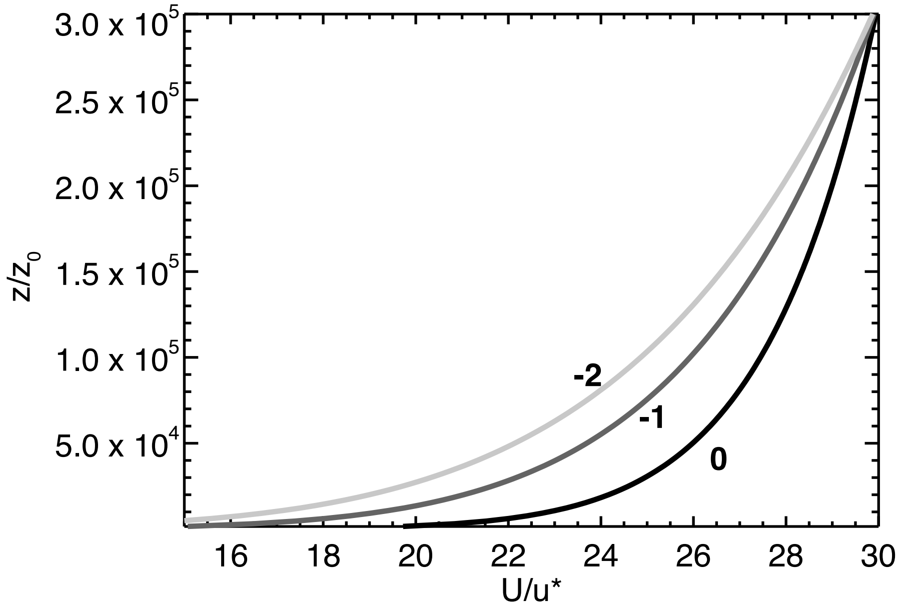
Supp Figure 2 | **Model predictions of stable layer wind profiles.** Parameterized non-dimensional power-law wind profiles from the simple boundary layer model for 0 C (black), -1 C (dark gray) and -2 C (light gray) lake-air temperature gradients. Increasingly stable (more negative) wind profiles inhibit the downward transfer of momentum to the surface for a given wind speed. The effect is non-linear since surface drag coefficients and heat fluxes are functions of both wind speed and temperature gradients.



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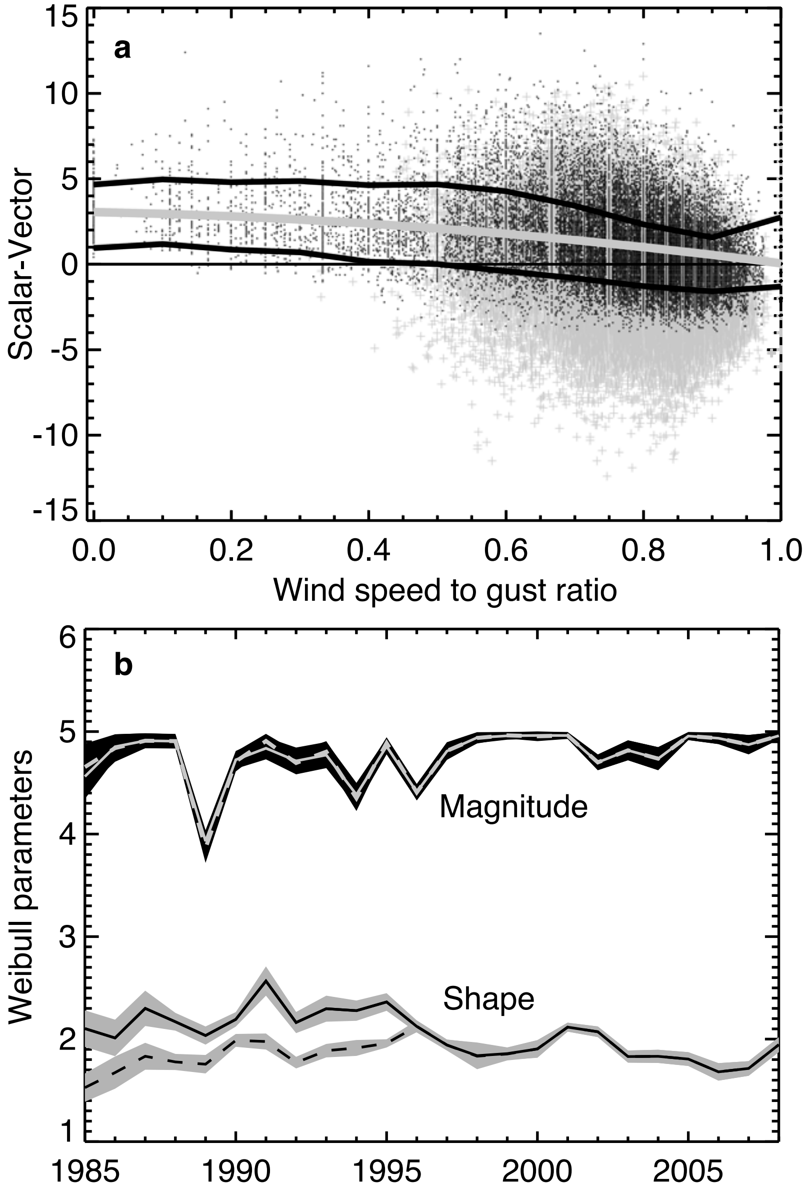
Supp Figure 3 l **Correction to vector averaged winds**. Wind observations over Lake Superior in the early part of the record rely on a vector averaging instrument package, which is shown to be low-biased against more recently used scalar averaging systems, especially during light and variable winds. a, An empirical correction was applied to light vector-averaged winds < 4 m s-1 (black stars and gray lines showing bin-averaged one standard deviation) as a function of wind variability, which was estimated using a proxy of wind speed to gust ratio. The fit (white line) was applied to records when vector wind sensors were used. b, Histograms of the uncorrected and corrected hourly wind speeds for each summer were fit to a Weibull distribution. Compared to uncorrected winds (dotted lines), corrected wind speeds (solid lines) only slightly alter the Weibull magnitude parameter (gray lines on black), while leading to a more consistent and expected shape parameter (black lines on gray) across the years.



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Supp Figure 4 l **Wind and temperatures distributions**. Histogram of hourly stratified season observations of a, wind speed, b, wind gust, c, wind direction, and d, air-lake temperature difference for the first ten years (1985-1994, dotted lines) compared to the last ten years (1999-2008, solid lines). Distributions show that the increasing in wind speeds and temperature differences were due to a shift in the central tendency of the distribution, and less likely due to a change in gustiness, an increase very high winds, or a shift in wind directions.