Wind Variability over a Small and Sheltered Lake: Trout Lake Field Study

by

Emily L. Resseger

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Minneapolis, Minnesota
The University of Minnesota is committed to the policy that all persons shall have equal access to its programs, facilities, and employment without regard to race, religion, color, sex, national origin, handicap, age or veteran status.
The research described in this project report was conducted by Emily Resseger while she was enrolled in the MS program in water resources Sciences. Financial support was provided by the USGS and the Mn DNR. Corey Markfort participated in the research while supported by a NASA Fellowship and enrolled in the PhD program in the Civil Engineering Program. Prof. Heinz Stefan was academic advisor to both Emily Resseger and Corey Markfort.

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Abstract

Wind is one of the most important, highly uncertain, and least investigated drivers of lake processes. In lake modeling, the wind over a lake is often estimated from point measurements at a remote weather station. Whether the surrogate wind data is representative of a lake's wind field depends on distance from the weather station as well as sheltering of the lake by trees and topography. To better understand the actual wind field over a small wind-sheltered lake we deployed five anemometers in different locations on Trout Lake, MN, for four months. We compared wind speeds and directions recorded on Trout Lake to Grand Marais Airport, 16 kilometers away. The effect of wind sheltering on the lake was quantified by a wind sheltering coefficient estimated using measured wind speeds and also an empirical model, adjusted for varying fetch and canopy cover depending on wind direction. Our long-term goal is to identify the data and analysis required to reduce uncertainty in lake water quality and fish habitat models.
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1. Introduction

Wind provides a key energy input to lakes, and moderates physical processes including stratification/destratification, surface gas transfer, and sediment resuspension, chemical processes including temperature/oxygen/salinity gradients and nutrient cycling, and biological aspects of lakes, including algal growth and fish habitat. Recently there has been added interest in understanding the functionality of inland lakes both as they contribute to the global carbon cycle (Tranvik et al., 2009), and as refuge lakes for cold water fish species (Jacobson et al., 2010).

To understand a lake’s biophysical processes, a plethora of data needs to be collected: water samples are taken at various depths to analyze chemical and biological constituents, field parameters like temperature and dissolved oxygen are collected in profiles, inflow and outflow discharge and constituents are measured, and climate data is collected. While instrumentation and computing power have improved exponentially in recent years, it is not possible to collect and measure all variables at every location within a lake continuously. Some generalization will always be needed, both spatially and temporally.

Of the field data collected to understand a lake’s processes, wind measurements are some of the most important but often least investigated. Wind is a key energy input to lakes, but for most lake studies, hourly/daily wind measurements are usually only available from a remote location (e.g. airport) or at best at one point on site. Using single point or remote wind measurements is undesirable because the wind field over a lake is quite variable and changes due to fetch, atmospheric boundary layer (ABL) conditions, and sheltering due to trees and topography.

In most lake models (e.g. ELCOM, MINLAKE, CE-QUAL-W2), wind speed and direction are accounted for by using available on lake point measurements or nearby airport data, and then the wind effects are adjusted using a calibration coefficient. Because there has been no independent method for estimating the wind field over a lake, Markfort et al. (2010) developed a model to estimate this wind sheltering coefficient, $W_{str}$, assuming a round lake with uniform surrounding canopy height.
The objective of the study described in this report which was also my Plan B paper for the M.S. degree in Water Resources Science, was to more thoroughly investigate the variability of the wind field over a lake and to examine how that wind is related to a remote weather station through a field study on Trout Lake, in northern Minnesota. We collected wind measurements at different locations on the lake and investigated differences in magnitude between them. We then compared the on-lake wind speed and direction to a remote weather station. We calculated the wind sheltering coefficient \( W_{str} \) introduced by Ford and Stefan (1980) from the observed wind measurements, using the round lake model from Markfort et al. (2010), and by modifying the round lake model to account for varying fetch and canopy cover depending on wind direction. We compared these calculated values to the \( W_{str} \) value of 0.1 that was obtained from previous calibration of the MINLAKE model for Trout Lake to observed temperature and dissolved oxygen profiles (Fang et al., 2010). Finally, we used LiDAR data to investigate improved methods to estimate land elevation and canopy height.
2. Background

2.1. Wind Theory

Near the earth’s surface, the wind profile over a flat and uniform surface follows the log-law (Stull, 1988):

\[ U = \frac{u_*}{\kappa} \ln \left( \frac{z}{z_0} \right) \] (1)

where \( U \) is the wind speed at a given height above the surface \( z \), \( u_* \) is the shear velocity, \( \kappa \) is the Von Kármán constant, and \( z_0 \) is the aerodynamic roughness.

Wind induces vertical mixing in a lake by applying shear stress on the lake surface which generates turbulent kinetic energy (TKE) in the surface waters. If the wind is fully available to act on the lake, for instance in a flat open field, the potential TKE available for lake mixing is (Ford and Stefan, 1980; Hondzo and Stefan, 1993):

\[ \text{Potential TKE} = \int_{A_s} u_{*,w} \tau dA \] (2)

where \( u_{*,w} \) is water side shear velocity and \( \tau \) is shear stress. The product represents energy per unit area and time, and is integrated over the entire surface area \( A_s \) of the lake.

However, wind sheltering reduces available wind energy at the air-water interface and subsequently reduces the amount of shear stress felt by a lake. Wind sheltering is effectively a reduction of the wind’s full strength with regard to momentum and mass transfer at the air-water interface. Sheltering is caused by wakes generated by obstacles surrounding a lake including hills, buildings, trees, and other obstructions.

When wind encounters a change in land cover type such as from a forest canopy to a lake surface, it goes through a transition, where the wind profile adjusts to the downstream surface (e.g. lake) from the upstream surface (e.g. canopy). This adjustment results in the development of the internal boundary layer (IBL) (Stull, 1988). The portion of the IBL that is fully adjusted to the water surface is called the equilibrium sublayer. For transitions from canopy to lake there is an added complication: the air flow separates from
the tree canopy and a downwind recirculation region forms before the airflow attaches to the water surface, as shown in Figure 1 (Markfort et al., 2012). Within the flow separation area and internal boundary layer the shear stress acting on the lake is reduced, and TKE delivered to the water surface is less than if there were no transition.

Therefore, when a lake is sheltered by canopy or topography, only a fraction of the potential TKE is actually available. A parameter, $W_{str}$, the wind sheltering coefficient (value between 0 and 1), represents the fraction of wind energy available for lake mixing (Ford and Stefan, 1980; Hondzo and Stefan, 1993). Then,

$$TKE = W_{str} \int_{As} u_{*,w} \tau dA$$

and

$$W_{str} = \frac{TKE_{sheltered}}{TKE_{unsheltered}}$$

(Markfort et al., 2012)
2.2. Empirical Wind Sheltering Model

Because we typically have very few on-lake sheltered wind measurements with which to estimate $W_{str}$ using Equation 4, Markfort et al. (2010) developed a model to estimate the wind sheltering coefficient. Markfort et al. (2010) reported on wind tunnel experiments which showed that the surface shear stress downwind of models representing bluffs and canopies of variable porosity recovered to an unsheltered value after approximately 50 canopy heights:

$$X_r = 50 h_c$$  \hspace{1cm} (5)

where $X_r$ is shear recovery length, $h_c$ is canopy height.

Markfort et al.'s (2010) model is illustrated in Figure 2A. The model simplifies TKE at the lake surface by assuming no TKE acts upon the lake in the sheltered part of the lake surface area, up to $50 h_c$, and the TKE acts with full effect in the unsheltered area.

Then,

$$W_{str} = \frac{A_{wind \, access}}{A_{lake}}$$  \hspace{1cm} (6)
where $A_{\text{wind access}}$ is the unsheltered area of the lake, as shown in Figure 2B.

![Figure 2: Wind Sheltering Empirical Model](image)

This model was tested against MINLAKE calibrated $W_{str}$ values for eight lakes covering a wide range of lake sizes and shapes (Markfort et al., 2010) and gave good results. Canopy height was estimated using topographic maps, satellite photos and field observations. Each lake was modeled as a round lake, so that $A_{\text{wind access}}$ was the same irrespective of wind direction. In reality, if a lake is significantly longer in one direction, or the tree canopy varies based on side of the lake, $A_{\text{wind access}}$ can differ substantially depending on wind direction.
3. Site Description

In 2008, the Minnesota Department of Natural Resources (Pereira, 2008) began a project entitled “Sustaining Lakes in a Changing Environment” (Sentinel Lake project) to study the effects of climate and land use change on lakes (MnDNR, 2008). 24 sentinel lakes were chosen for detailed monitoring and assessment from across a gradient of ecoregions, depths, and nutrient levels. From these 24 lakes, three lakes were chosen as “super-sentinel lakes” for further investigation by the United States Geological Survey (USGS), including detailed bio-physical modeling. The three super-sentinel lakes harbor cold water fisheries but have diverse watershed conditions. The three super-sentinel lakes are Lake Carlos in Douglas County near Alexandria, MN; Elk Lake in Itasca State Park in Clearwater County; and Trout Lake in Cook County near Grand Marais, MN. Funding for the Sentinel Lakes project is from the Minnesota Legislative-Citizen Commission on Minnesota Resources (LCCMR) project entitled “Assessing the consequences of ecological drivers of change on water quality and habitat dynamics of deep-water lakes with coldwater fish populations” (MnDNR, 2008).

We were part of the project team studying the three super-sentinel lakes. To aid in the lake modeling, meteorological data was collected at each lake. We chose Trout Lake as the focus of this more in-depth meteorological investigation because it has a small surface watershed with minimal inflows. The lake remains thermally stratified for much of the year, and the thermocline depth is controlled by the heat budget at the water surface and wind generated mixing of the surface waters as illustrated in Figure 3.

Trout Lake is a 1.04 square kilometer deep, cold water fishery approximately 18 kilometers northeast of Grand Marais, MN, and 16 kilometers from the Grand Marais airport, as shown in Figure 4. Trout Lake is approximately 2.25 times as long as it is wide, with as maximum east-west fetch of 850 meters, and a maximum north-south fetch of 1900 meters. The lake has two deep holes with a shallower bench in between stretching from east to west (Figure 5). The maximum depth of the north hole is 77 feet (23.5 meters) and the south hole is 75 feet (22.9 meters), with the bench between at 29 feet (8.8 meters). Trout Lake is located in a topological bowl with the land around the lake rising quickly,
especially along the north side as shown in Figure 6. The lake normal water level is 506 meters amsl (above mean sea level), and the ridge on the north side peaks at 573 meters amsl. Trout Lake’s watershed area is 4.65 square kilometers, which gives a watershed to lake ratio of 4.5, which is fairly small. The majority of the watershed is located in the Superior National Forest. The only development is a small resort on the south side. The forest surrounding Trout Lake is a mixture of deciduous and coniferous trees with a mean tree height of 10.7 meters and a maximum tree height of 28.6 meters within a 1 km buffer of the lake.
Figure 4: Trout Lake Location

Figure 5: Trout Lake Bathymetry
Figure 6: Ground Elevation (amsl) around Trout Lake
4. Field Instrumentation

As part of the Sentinel Lakes project, a floating data collection platform was deployed on Trout Lake from July 12, 2011 to November 10, 2011. The platform was constructed from a 4'x4' encapsulated foam filled dock float, with a 2'x4' wood structure bolted on top to hold the equipment. A steel tripod was bolted to the wood structure to hold the equipment, with a steel mast and steel and aluminum cross-bars. The float was anchored from the center of each side of the platform by 28 lb. anchors, which were extended as far out from the platform as possible for platform stability. In addition, 30 lb. anchors were installed at each of the four corners of the platform to lower the platform in the water. A Campbell Scientific CR1000 data logger was housed inside a shelter, powered by a 12 volt rechargeable battery and solar panel. The equipment installed on the platform is shown in Figure 7 and listed in Table 1.
Figure 7: Platform Instrumentation

Table 1: Instrumentation

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Name</th>
<th>Brand</th>
<th>Height above water level (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anemometer</td>
<td>Anemometer 1</td>
<td>R.M. Young 3001</td>
<td>2.18</td>
</tr>
<tr>
<td></td>
<td>Anemometer 2</td>
<td>Met One 014A</td>
<td>1.68</td>
</tr>
<tr>
<td></td>
<td>Anemometer 3</td>
<td>Met One 014A</td>
<td>1.34</td>
</tr>
<tr>
<td>Wind Vane</td>
<td>Wind Vane</td>
<td>R.M. Young 3001</td>
<td>2.18</td>
</tr>
<tr>
<td>Temperature/Relative Humidity</td>
<td>Temp/RH1</td>
<td>Vaisala HMP35C</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td>Temp/RH2</td>
<td>Vaisala HMP45C</td>
<td>2.0</td>
</tr>
<tr>
<td>Pyranometer</td>
<td>Pyranometer</td>
<td>LI-COR LI200</td>
<td>1.8</td>
</tr>
<tr>
<td>Net radiometer</td>
<td>Net radiometer</td>
<td>REBS Q-7.1</td>
<td>0.9</td>
</tr>
</tbody>
</table>
In addition to the platform, four Met One 014A anemometers were installed in the north, east, south, and west parts of the lake, as shown in Figure 8 and Figure 9. The anemometers were attached to steel conduit strapped to steel T-posts hammered into the lake bottom. The lake has very steep slopes, so anemometers were generally installed 10 to 15 meters from shore. Because bedrock dominates the surficial geology in the area, it was not always possible to install the anemometers in the exact location desired, as we had to find cracks in the bedrock in which to hammer the T-posts.

Each anemometer was nominally installed 2 meters above the water level, but the anemometers were fixed to the ground so that height above the water surface varied with water elevation. However, throughout the study period the water level in Trout Lake was very stable.
5. Data Collected

Wind speed was measured every three seconds at the main platform and the four standalone anemometers, and every ten minutes the average, maximum and standard deviation for that ten minute period were recorded on the data loggers using programs written in Campbell Scientific’s CR Basic and Edlog programs (copies of the programs are included in Appendix A). On the platform, 10-minute average and standard deviation of wind direction were also recorded.

A 10-minute wind averaging interval was chosen to capture as much dynamic variability in the wind as possible without capturing turbulence dynamics, which the cup anemometers are not designed for. Van der Hoven (1957) showed that turbulence time scales can be as large as 1 minute; therefore 10-minute intervals seemed large enough to avoid turbulence dynamics. A sampling rate of 3 seconds was selected to ensure an adequate sample size for 10-minute averages.

Data was collected from July 12, 2011 at 11:50 to November 10, 2011 at 8:40. Two interim trips to Trout Lake on August 8 and September 7-9, 2011 were used to download data. Because of battery and storage issues, the four standalone anemometers had some data gaps. The record of data available for all anemometers is shown in Table 2.

<table>
<thead>
<tr>
<th>Table 2: Data Collection Periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
</tr>
<tr>
<td>Platform (all 3 anemometers)</td>
</tr>
<tr>
<td>East anemometer</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>North anemometer</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>West anemometer</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>South anemometer</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
Additional weather data was collected at the site but not used in this study. 10-minute air temperature, relative humidity, solar radiation flux and flux density, and net solar radiation were collected at the platform. In the lake, 15-minute temperature profiles were recorded from 2010 to 2012 using a thermistor chain attached to a buoy (Onset Hobo U22-001 loggers) near the deepest part of the northern half of the lake; thermistor spacing was close to 1 meter in the epilimnion and thermocline, and 2 meters in the hypolimnion. The USGS and Minnesota Pollution Control Agency (MPCA) alternated visits to Trout Lake biweekly through the growing season from 2009 to 2012 to collect profiles of temperature, pH, conductivity and dissolved oxygen, and to take epilimnetic and hypolimnetic water samples for chemical analysis.
6. Data Analysis

6.1. Lake Platform

10-minute wind speed and direction were recorded at three heights on the platform. The highest anemometer (2.18 meters) and wind vane were used in comparisons with the stand-alone anemometers and to the Grand Marais airport as part of this project.

Over the entire study period, the primary wind directions at the lake were from the north (20.2%) and northwest (18.9%) as shown in Figure 10. Those wind directions were also associated with the highest average wind speeds of 4.32 m/s and 4.12 m/s, respectively, as shown in Table 3.

![Figure 10: Trout Lake Wind Direction, July 12-Nov 10, 2011](image)

Calculated from 10-minute wind direction measurements at Trout Lake platform

<table>
<thead>
<tr>
<th>Direction</th>
<th>Angles</th>
<th>Average wind speed at 2 meters (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>337.5°-22.5°</td>
<td><strong>4.32</strong></td>
</tr>
<tr>
<td>NE</td>
<td>22.5°-67.5°</td>
<td>2.32</td>
</tr>
<tr>
<td>E</td>
<td>67.5°-112.5°</td>
<td>1.82</td>
</tr>
<tr>
<td>SE</td>
<td>112.5°-157.5°</td>
<td>2.48</td>
</tr>
<tr>
<td>S</td>
<td>157.5°-202.5°</td>
<td>2.66</td>
</tr>
<tr>
<td>SW</td>
<td>202.5°-247.5°</td>
<td>3.18</td>
</tr>
<tr>
<td>W</td>
<td>247.5°-292.5°</td>
<td>3.36</td>
</tr>
<tr>
<td>NW</td>
<td>292.5°-337.5°</td>
<td>4.12</td>
</tr>
<tr>
<td>All data</td>
<td></td>
<td>3.28</td>
</tr>
</tbody>
</table>

(Highest wind speed is indicated in bold)

When wind speed and direction are investigated by month, one can see wind direction shifting from northwest to north through the summer into the fall as shown in Figure 11. Average wind speeds follow a similar pattern with the highest average wind speeds from the northwest for July and August, and north for September and October as shown in Table 4. In November the highest wind speeds are from the west, and there is an increase in frequency in wind from the west as well. The magnitude of average wind speeds increases from July-September to October-November.
Figure 11: Trout Lake Wind Direction by Month

Table 4: Platform Average Wind Speed (m/s) by Wind Direction and Month

<table>
<thead>
<tr>
<th>Wind From Direction</th>
<th>July (last 20 days)</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November (first 10 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>3.25</td>
<td>3.73</td>
<td><strong>4.41</strong></td>
<td><strong>5.04</strong></td>
<td>3.68</td>
</tr>
<tr>
<td>NE</td>
<td>2.66</td>
<td>1.95</td>
<td>2.53</td>
<td>2.40</td>
<td>1.26</td>
</tr>
<tr>
<td>E</td>
<td>2.60</td>
<td>1.67</td>
<td>1.59</td>
<td>1.98</td>
<td>1.01</td>
</tr>
<tr>
<td>SE</td>
<td>2.56</td>
<td>2.37</td>
<td>2.49</td>
<td>2.54</td>
<td>2.11</td>
</tr>
<tr>
<td>S</td>
<td>2.58</td>
<td>2.65</td>
<td>2.52</td>
<td>2.59</td>
<td>3.31</td>
</tr>
<tr>
<td>SW</td>
<td>2.94</td>
<td>3.24</td>
<td>2.86</td>
<td>3.25</td>
<td>4.00</td>
</tr>
<tr>
<td>W</td>
<td>3.30</td>
<td>3.28</td>
<td>2.69</td>
<td>2.76</td>
<td><strong>5.52</strong></td>
</tr>
<tr>
<td>NW</td>
<td><strong>4.00</strong></td>
<td><strong>3.99</strong></td>
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<td>4.49</td>
<td>3.83</td>
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<tr>
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<td>3.10</td>
<td>3.11</td>
<td>3.19</td>
<td>3.58</td>
<td>3.57</td>
</tr>
</tbody>
</table>

(Highest wind speed for each month is indicated in bold)
6.2. Comparison of Trout Lake 2-meter High Weather Stations

The average wind speeds over the lake varied greatly between stations. Figure 12 shows variability in wind speed and direction over a typical three day period from 7/25/11 to 7/28/11. When the wind direction was between west (270°) and northwest (315°), the platform had the highest wind speed. However when the wind direction was between northwest (315°) and north (360°), the platform and south anemometer wind speeds were highest and approximately equal, while the north and east anemometer wind speeds were lowest. When the wind direction was from southeast (135°) and south (180°), the platform and north anemometer wind speeds were highest and approximately equal, followed closely by the west anemometer, while the south anemometer was lowest.

Figure 12: 10-minute Wind Speed Dynamics at Five Anemometers and Associated Wind Directions, 7/25/11-7/28/11
The patterns observed over the three-day time period continue throughout the entire study period as shown in Error! Reference source not found.. When the wind is coming from the west and northwest, the platform has the highest average wind speed. When the wind is coming from the north, the wind speed at the platform and the south anemometer are approximately equal, and the north and east anemometer have the lowest wind speed. When the wind is coming from the south and southeast, the platform, north and west anemometers have the highest speeds, while the south and east anemometers have the lowest wind speeds.

<table>
<thead>
<tr>
<th>Location</th>
<th>Wind Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
</tr>
<tr>
<td>Platform</td>
<td>3.55</td>
</tr>
<tr>
<td>East</td>
<td>1.39</td>
</tr>
<tr>
<td>North</td>
<td>1.32</td>
</tr>
<tr>
<td>South</td>
<td>3.61</td>
</tr>
<tr>
<td>West</td>
<td>2.01</td>
</tr>
</tbody>
</table>

(Highest wind speed for each wind direction is indicated in bold)

We also compared the most upwind to downwind wind speeds on the lake for different wind directions to try and understand the degree of wind sheltering. Four correlation plots are shown in Error! Reference source not found.. In Error! Reference source not found.A, the wind is coming from the north (337.5°-22.5°) and the north anemometer (upwind) wind speed is correlated with the south (downwind) anemometer wind speed. In Error! Reference source not found.B, the wind is coming from the south (157.5° -202.5°) and the south anemometer wind speed is correlated with the north anemometer wind speed. In Error! Reference source not found.C, the wind is from the east (67.5° -112.5°) and the east anemometer wind speed is correlated with the west anemometer wind speed. In Error! Reference source not found.D, the wind is from the west (247.5° -292.5°), and the west anemometer wind speed is correlated with the east anemometer wind speed.
**Figure 13: Anemometer Correlations between Upstream and Downstream Anemometers for Each Major Wind Direction**

A: Correlation between the north and south anemometer wind speeds when wind is from the north.
B: Correlation between the south and north anemometer wind speeds when wind is from the south.
C: Correlation between the east and west anemometer wind speeds when wind is from the east.
D: Correlation between the west and east anemometer wind speeds when wind is from the west.

When the wind is from the north or the south the fetch over the lake is about the same, however, the ratios of upwind to downwind measured wind speeds are different. When the wind is from the north, the ratio is 0.3, when the wind is from the south it is 0.7.
Likewise, when the wind is from the east or the west the lake fetch is about the same, but the ratios of upwind to downwind measured wind speeds are different. When the wind is from the east the upwind to downwind ratio is 0.2, while from the west it is 0.6. While some of the differences may be attributed to the nuances of the Trout Lake shape (the west anemometer especially may not be fully sheltered even over the 247.5° to 292.5° wind directions because of the lobes on the west side of the lake), the canopy and topographic sheltering also vary on different sides of the lake.

6.3. Comparison between Trout Lake Platform and Grand Marais Airport

The Grand Marais airport is the nearest National Weather Service weather station to Trout Lake at a comparable elevation and distance from Lake Superior. The Grand Marais airport is approximately 16 kilometers from Trout Lake, and Trout Lake is at an elevation of 506 meters amsl, while the airport is 548 meters amsl. The Grand Marais airport is an Automated Weather Observing System (AWOS) IIIP/T automated weather station, and reports wind speed and direction point measurements at 20-minute intervals. A 10-meter height for anemometer and wind vane is standard for an AWOS station.

To compare the Trout Lake platform and Grand Marais airport wind speed and direction directly, the 2-meter Trout Lake platform wind speeds were adjusted to a height of 10 meters using the log-law. First Equation 1 is rearranged into a linear form to solve for \( z_0 \):

\[
U = \frac{u_*}{\kappa} \ln(z) - \frac{u_*}{\kappa} \ln(z_0)
\]

(7)

Using the three wind speeds recorded every 10 minutes on the platform at elevations of 1.34, 1.68, and 2.18 meters, a linear regression was performed for each 10-minute interval between the wind speeds and \( \ln(z) \) using Equation 7. Because of unsteady wind speeds and directions, the anemometers at 1.34 or 1.68 meters sometimes had the highest wind speed, while the log-law would indicate under steady wind conditions that the highest anemometer should have the highest wind speed. This demonstrates the
complicated nature of wind over the lake, including changes in wind speed and direction and turbulent eddies. In order to obtain a representative $z_0$ for the entire study period, only time periods where $U_{2.18}>U_{1.69}>U_{1.34}$ were included in the calculation. Of all 17,406 10-minute wind measurements made over a four month period, only 4,275 measurements, or almost exactly 25% of the measurements, were taken where $U_{2.18}>U_{1.69}>U_{1.34}$.

Aerodynamic roughness or $z_0$ estimates varied widely, from $2.7 \times 10^{-9}$ m to 1.5 m. Because neither the $\ln(z_0)$ values nor the $z_0$ values appear to follow a normal distribution and the range was so great, the median value of $z_0$ was calculated for the lake. This value was 0.011 m. When the 10-minute wind speeds were averaged to the hour and the same analysis was completed, a median $z_0$ of 0.009 m was determined. A $z_0$ value of 0.01 m for Trout Lake was used going forward. This value is within the well understood $z_0$ value range of $10 \times 10^{-5}$ to 0.1 m for open water (Markfort et al., 2010). The wind measurements are somewhat sensitive to changes in $z_0$: an order of magnitude increase in $z_0$ from 0.01 to 0.1 increases $U_{10}$ by approximately 16.5%. An order of magnitude decrease in $z_0$ from 0.01 to 0.001 decreases $U_{10}$ by approximately 7%.

After the Trout Lake platform wind speeds were adjusted from 2.18 meters to 10 meters using the calculated value of $z_0$ and the log-law, the two weather stations were adjusted to a consistent time scale. For this analysis the 10-minute Trout Lake average measurements and the Grand Marais 20-minute point measurements were both averaged to the hour.

As shown in Figure 14, the wind speeds between Trout Lake and Grand Marais airport are well correlated, regardless of wind direction, and the wind speed at Grand Marais airport is about twice the Trout Lake wind speed averaged over an hourly period.
The Trout Lake platform wind direction and Grand Marais wind direction are also compared on an hourly basis in

**Figure 14:**

**Figure 15:** A is a wind rose comparing Trout Lake and Grand Marais airport over the four month study period. The majority of Grand Marais airport wind is coming from the west and northwest, followed by the south. The majority of Trout Lake platform wind is coming from the north and northwest. It appears as though the platform wind rose is rotated from the airport wind rose. Indeed, as shown in

**Figure 15:** B, the platform and airport wind directions are well correlated \((R^2=0.84)\) and an offset value of \(15.4^\circ\) relates the wind directions. It is not clear what causes the apparent rotation between the wind directions. Perhaps the northwestern lobe of the lake combined with a lower hill in the northwest funnels the wind differently to the lake, or the difference in wind vane heights (2.18 meters vs. 10 meters) contributes to the offset.
Figure 15: Trout Lake Platform and Grand Marais Airport Hourly Average Wind Direction
7. $W_{str}$ Estimates from Measured Wind Speeds

The intent of this paper, besides investigating wind variability over a highly sheltered lake, was to estimate values for the wind sheltering coefficient $W_{str}$. We first estimated $W_{str}$ for Trout Lake from the wind speeds measured in this project. We used Equations 2-4 and Grand Marais airport wind speed to compute potential TKE. We first calculated $W_{str}$ using the point wind measurement recorded at the Trout Lake platform, and applied them over the entire lake surface area. This station and the entire lake area are shown in Figure 16. We then estimated $W_{str}$ using all five Trout Lake anemometers. The Thiessen polygon method was selected to assign representative areas to all anemometer locations on the lake. The Thiessen polygon method assigns each location within an area a value equal to the nearest sample location (anemometer) as seen in Figure 17. Several other methods were considered and tried to estimate a "representative" wind speed over the entire lake, including contouring using spline, nearest neighbor, and kriging methods. Because of the relative lack of data points and complexity of the lake and surrounding canopy and topography, we selected the Thiessen method because it requires the least

![Figure 16: Single Measurement Point $W_{str}$ Estimate](image-url)
number of assumptions. The Thiessen method is only appropriate for investigation of the bulk $W_{str}$ for the lake, and is not an appropriate method to estimate the actual wind speed at any individual location.

The details of the $W_{str}$ calculation are shown in the Appendix B. $W_{str}$ was estimated from hourly wind speeds at Trout Lake and Grand Marais. For each hour, TKE on Trout Lake and TKE at the Grand Marais airport were calculated, and then $W_{str}$ was determined from Equation 4. The distribution of calculated $W_{str}$ values was skewed, with a few values greater than 1.0 when the wind speed on Trout Lake was higher than at the Grand Marais airport (probably due to distance between the stations). Therefore we calculated a representative $W_{str}$ as the median $W_{str}$ value for both the point and Thiessen methods for each wind direction, as well as for all data (irrespective of wind direction), as shown in Table 6 and Table 7. Because we were missing data from individual anemometers at various points in the study period, $W_{str}$ was only calculated for the point measurement and Thiessen methods on days when wind data was available for all five anemometers and the airport.
Table 6: Single Measurement Point $W_{str}$ Estimates

<table>
<thead>
<tr>
<th>Wind Direction</th>
<th>$W_{str}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>0.27</td>
</tr>
<tr>
<td>NE</td>
<td>0.23</td>
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<tr>
<td>E</td>
<td>0.28</td>
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<tr>
<td>SE</td>
<td>0.52</td>
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<tr>
<td>S</td>
<td>0.33</td>
</tr>
<tr>
<td>SW</td>
<td>0.39</td>
</tr>
<tr>
<td>W</td>
<td>0.69</td>
</tr>
<tr>
<td>NW</td>
<td>0.51</td>
</tr>
<tr>
<td>All data</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Table 7: Thiessen Method $W_{str}$ Estimates

<table>
<thead>
<tr>
<th>Wind Direction</th>
<th>$W_{str}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>0.18</td>
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<tr>
<td>NE</td>
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</tr>
<tr>
<td>E</td>
<td>0.19</td>
</tr>
<tr>
<td>SE</td>
<td>0.45</td>
</tr>
<tr>
<td>S</td>
<td>0.27</td>
</tr>
<tr>
<td>SW</td>
<td>0.29</td>
</tr>
<tr>
<td>W</td>
<td>0.41</td>
</tr>
<tr>
<td>NW</td>
<td>0.25</td>
</tr>
<tr>
<td>All data</td>
<td>0.26</td>
</tr>
</tbody>
</table>

The $W_{str}$ estimates using just the platform anemometer are always higher than the estimates using all five anemometers. There is also noticeable variability in $W_{str}$ between wind directions. For the Thiessen method, the lowest $W_{str}$ (highest degree of sheltering) is from the northeast, closely followed by the north and east. This is reasonable because the lake’s fetch is shortest north-south, and also because there is denser canopy and higher topography to the north and east to provide more sheltering. The highest $W_{str}$ (lowest degree of sheltering), is when winds are from the southeast. The lake fetch is longest from the east/southeast, and the topography is lower in the southeast.
8. $h_c$ Estimates

To use the empirical wind sheltering model, canopy height around Trout Lake needs to be measured in a consistent and dependable way. We first tried using a rangefinder and clinometer before using aerial LiDAR data to estimate canopy height.

8.1. $h_c$ Estimates Using a Rangefinder and Clinometer

We tried to calculate tree height above the water surface using a traditional forester technique of a rangefinder and clinometer (Frank, 2010). However, to have a clear view of the trees we were trying to measure, we needed to take readings from a boat. To determine tree height, a distance to the tree and an angle reading are required. We found that we drifted too much within single measurements to feel confident in our measured values. We also had difficulty surveying a large number of trees in order to get a good average value in a reasonable amount of time. When our measurements were later plotted on a cross-section of the lake, we found problems, e.g. some trees were in the lake. This method was abandoned because we were unable to measure a good sample of trees from shore.

8.2. $h_c$ Estimates Using LiDAR

In the spring of 2012, Minnesota aerial LiDAR data for the portion of Minnesota containing Trout Lake became available from the MnDNR. Aerial Light Detection and Ranging (LiDAR), is a remote sensing method that shoots laser pulses at the earth’s surface from a plane to determine the elevation of objects on Earth. For the portion of Minnesota including Trout Lake, the LiDAR data has one meter mean point spacing and a vertical accuracy of 12.4 centimeters. LiDAR was flown in the spring of 2011, just prior to the field work for this project.

Individual LiDAR points are coded by type, so we were able to isolate the points coded as vegetation and generate a 3-meter resolution raster surface showing canopy height elevation (Sumerling, 2011) as shown in Figure 18. Using this surface and the elevation of Trout Lake, we were able to generate a surface showing canopy elevation above Trout Lake (Figure 19). Finally, using the canopy height elevation surface and the 3-meter DEM
(digital elevation model) supplied by the state, we were able to calculate tree height (Figure 20).

Figure 18: Tree Canopy Elevation (meters amsl)
Figure 19: Canopy Elevation above Trout Lake (meters)

Figure 20: Tree Height (meters)
9. Trout Lake Topography and Control of Wind Sheltering

Figure 6 shows that Trout Lake is in a topological bowl, with the ground coming up from the lake on almost all sides. The ridge is highest around the west-northwest-north and northeast-east. The lowest point adjacent to Trout Lake is in the south by the lake outlet. Figure 20 shows that the majority of trees immediately surrounding the lake are in the range of 6-21 meters, though there are a number of trees between 21-27 meters along the north shore of the lake.

The LiDAR plots of Trout Lake indicate a potential complication in using an empirical wind sheltering model to estimate $W_{sr}$ for Trout Lake. Markfort et al. (2010) studied shear stress recovery in the wind tunnel assuming a uniform canopy on flat terrain surrounding a lake. The canopy surrounding Trout Lake is fairly uniform, but the topography surrounding Trout Lake is not. Figure 19 shows that the highest tree canopy above Trout is often 600 to 1000 meters away from shore.

Figure 21 shows cross-sections of Trout Lake and its surrounding topography from north to south and from east to west. The north-south profile especially shows that the trees on the ridge to the north are significantly higher above the water level of Trout than the trees right at the shore, even if some of the shore trees are actually taller.

We considered which trees would govern sheltering: those right at the shore, or those set back from shore but higher in elevation on the hills above Trout Lake. Which trees control sheltering will depend on whether the wind field separates when going over the hills above Trout Lake. If the flow does separate, there will be a similar transition as from shore to lake, and there will be an extended period of recovery. There may still be an additional flow separation at the boundary from shore trees to lake. If there is no separation of the flow coming over the hill, then the primary flow transition from canopy to lake should still occur at the shore as in the flat topography example, and the shore trees will govern.
Figure 21: Trout Lake Cross-sections

x-axis is distance from Trout Lake centroid in meters; y-axis is meters amsl. Tree height is shown in green above ground height in black. The vertical scale is exaggerated.

According to Belcher et al. (2012) the separation of flow going over a hill depends on steepness of slope and canopy density. Determining whether flow separation occurs over the hills around Trout Lake is beyond the scope of this project. Therefore we calculated two $W_{str}$ values, one assuming that the shore trees control sheltering, and another assuming that the highest trees on top of the hill above the lake (correcting for distance
from the lake) control the flow field. The reality may be that the highest trees topographically and the trees adjacent to shore combine to control wind sheltering in a way we do not yet understand.
10. $W_{str}$ Calculated from an Empirical Model

Markfort et al.’s (2010) empirical wind sheltering model was applied to the lake, first by estimating the lake as round and assuming a constant tree height with no topographic change around the lake, and then by modifying the model to account for wind direction, variable fetch and varying canopy height and topography.

10.1 $W_{str}$ Estimates Assuming a Round Lake and Uniform Canopy

$W_{str}$ was estimated using Markfort et al.’s (2010) wind sheltering model assuming a uniform canopy and a round lake. This model is defined by the following equation, derived from geometry (Markfort et al., 2010):

$$W_{str} = \frac{2}{\pi} \cos^{-1}\left(\frac{X_t}{D}\right) - \left(\frac{2X_t}{\pi D^2}\right) \sqrt{D^2 - X_t^2}$$

where $X_t$ is shear recovery length and $D$ is lake diameter.

The selected canopy height for the round lake model was the 90th percentile of all tree heights within a 50 meter band of land along the shoreline. The 50 meter band was selected because it is the approximate width of flatter ground around the lake before the topography begins to climb away from Trout Lake. Several statistics of tree height were considered for $h_c$. We considered the mean tree height, but determined that from an aerodynamic perspective the taller trees are likely to control wind sheltering. We considered the maximum tree height, and experimented with smoothing the canopy height raster at different scales to remove outlier trees or errors in the data. However we still found that small patches of trees were controlling $h_c$ and did not seem to reflect a representative tree canopy. We decided to use the 90th percentile tree height because it favors the very tall trees, but eliminates a few outliers. Li (2009) found 90th percentile tree height to be comparable to field measured plot tree height (average height of trees with diameter of 5 inches or greater). More research on the trees that control canopy height for sheltering is needed.
The value for $h_c$ calculated from LiDAR for the entire lake shore was 17.1 meters. Using this value of $h_c$ in Equation 5 and then Equation 8 with lake diameter of 1150 meters (calculated assuming a round lake with Trout Lake’s area), the round lake model result was $W_{str} = 0.15$.

10.2. $W_{str}$ Estimates Assuming Shore Trees Control Sheltering

We then considered wind direction and varying tree height and topography in the empirical $W_{str}$ model. We first considered the case where the shore trees would control sheltering. Separate $W_{str}$ values were calculated for the eight primary wind directions. Similar to the round lake model, the 90th percentile tree height within a 50 meter band of shore was calculated for each wind direction for that portion of shore where the trees would shelter the lake. The length of shore covered differs depending on the wind direction because Trout Lake is not round (circular).

After $h_c$ was calculated for each wind direction, $X_r$ was calculated using Equation 5, and the lake shape was spatially offset by $X_r$ along the wind direction axis, similar to the drawing shown in Figure 2B. The intersection of the two shapes (lake shape and offset lake shape) is $A_{wind\ access}$. Two examples of the calculation are shown Figure 22. Figure 22A shows the offset lake shape and $A_{wind\ access}$ when wind is from the east; Figure 22B shows the offset lake shape and $A_{wind\ access}$ when wind is from the southwest.

This process was repeated for all eight wind directions, and $W_{str}$ was calculated for each wind direction using Equation 5. $W_{str}$ was estimated for the entire study period by a weighted average of the eight wind direction $W_{str}$ values (weighting by wind direction frequency over the study period). The $W_{str}$ values are shown in Table 8, along with the calculated values of $h_c$ and $X_r$ and an average fetch for each wind direction. The $W_{str}$ values vary with fetch: the highest $W_{str}$ values are where the wind is from the east and west and fetch is longest. From the north and south, where fetch is shortest, the lake is calculated to be completely sheltered ($W_{str} = 0.00$)
Figure 22: Determination of $A_{\text{wind\ access}}$ when Shore Trees Control Sheltering and Wind is from A) the East, and B) the Southwest
Table 8: $W_{str}$ Estimates for Wind Sheltering by Shore Trees

<table>
<thead>
<tr>
<th>Wind Direction</th>
<th>$h_c$ ($m$)</th>
<th>$X_r$ ($m$)</th>
<th>Lake fetch ($m$)</th>
<th>$W_{str}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>17.9</td>
<td>897</td>
<td>777</td>
<td>0.00</td>
</tr>
<tr>
<td>NE</td>
<td>18.0</td>
<td>902</td>
<td>943</td>
<td>0.02</td>
</tr>
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<td>E</td>
<td>17.4</td>
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<td>1779</td>
<td>0.34</td>
</tr>
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<td>16.7</td>
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<td>1107</td>
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</tr>
<tr>
<td>S</td>
<td>16.6</td>
<td>832</td>
<td>777</td>
<td>0.00</td>
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<tr>
<td>SW</td>
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<td>943</td>
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</tr>
<tr>
<td>W</td>
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<td>1779</td>
<td>0.36</td>
</tr>
<tr>
<td>NW</td>
<td>17.1</td>
<td>856</td>
<td>1107</td>
<td>0.12</td>
</tr>
<tr>
<td>Weighted Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.11</td>
</tr>
</tbody>
</table>

10.3. $W_{str}$ Estimates Assuming Hill Trees Control Sheltering

We then estimated $W_{str}$ assuming that the hills plus the trees on top control wind sheltering. For this method, we used the canopy elevation above Trout Lake as shown in Figure 19. For the hills plus trees we had to account for distance from Trout Lake because if hills plus trees are far enough away, any flow separation that occurs will reattach well before reaching the lake. The controlling canopy needed to be both elevated above Trout Lake and also reasonably close. We defined a modified shear recovery length to account for the distance of the hills plus trees from shore:

$$X_{r,\text{effective}} = 50h_c - D_s$$ (9)

Where $X_{r,\text{effective}}$ is the adjusted shear recovery length, $h_c$ is the canopy elevation above the Trout Lake water surface, and $D_s$ is the perpendicular distance from the apex of the hill to shore for a given wind direction.

Within a 5 kilometer radius of Trout Lake, $X_{r,\text{effective}}$ was calculated for every 3-meter grid cell. Eight different grids were calculated for the eight wind directions, because the perpendicular distance from shore for any given tree varies depending on the wind direction. All grid cells with a non-negative value for $X_{r,\text{effective}}$ were considered, and the
90\textsuperscript{th} percentile $X_{r,\text{effective}}$ for each wind direction was assumed to control sheltering, to maintain consistency with the shore control sheltering.

As with the $W_{str}$ calculation for the shore trees, the Trout Lake shape was offset by the controlling $X_{r,\text{effective}}$ for the eight wind directions. However, in this case the calculated shear recovery lengths are so great that the offset polygons do not intersect Trout Lake at all, for any wind direction. This results in uniformly zero $W_{str}$ values as shown in Table 9. For a given wind direction, it is possible that $X_{r,\text{effective}}$ is equal between more than one spatial location; therefore average $h_c$ and $D_s$ values were calculated from all locations with the 90\textsuperscript{th} percentile $X_{r,\text{effective}}$ value, to give a general idea of how far from Trout Lake the controlling canopy would be, and how high the canopy is above Trout Lake.

### Table 9: $W_{str}$ Estimates for Wind Sheltering by Hill Trees

<table>
<thead>
<tr>
<th>Wind Direction</th>
<th>Average $h_c$ (m)</th>
<th>Average $D_s$ (m)</th>
<th>$X_{r,\text{effective}}$ (m)</th>
<th>$W_{str}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>65.4</td>
<td>609</td>
<td>2,661</td>
<td>0</td>
</tr>
<tr>
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<td>63.1</td>
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<td>SE</td>
<td>54.7</td>
<td>408</td>
<td>2,326</td>
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<tr>
<td>S</td>
<td>36.2</td>
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<tr>
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<td>29.0</td>
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<td>856</td>
<td>2,399</td>
<td>0</td>
</tr>
</tbody>
</table>

| Weighted Average | -     | 0       |

According to the results in Table 9, the distant hills plus trees control wind sheltering of Trout Lake, because the lowest $W_{str}$ values are obtained. The assumption is that Markfort et al.'s (2010) empirical wind sheltering model is representative of the real flow over the hill, down the hill and on to the lake. We believe that the model is incorrect because the calibrated $W_{str}$ value is 0.10, not 0.00. Flow over hills plus canopies needs further investigation.
11. Conclusions

Wind is probably as important in controlling the physical, chemical and biological processes of lakes as are transfer of heat and light at the lake surface, and inputs of dissolved and suspended substances by inflows. However, estimating the magnitude and variability of wind over a lake and its effects has not received the attention that it deserves, probably because only remote weather station data are usually available, and wind is complicated. To investigate the effect of wind sheltering on wind speeds on a lake surface, we collected 10-minute average wind speed at five locations on Trout Lake for a four month period, and compared wind speed measurements at different locations on the lake. Wind varied significantly over the lake, with downwind speeds often 2 to 3 times greater than upwind speeds. Not surprisingly, the anemometer with highest wind speed changed depending on wind direction.

We also compared wind speed and direction at the Trout Lake platform with wind measurements collected at Grand Marais Airport, 16 kilometers away. There was good correlation in wind speed and direction between these two weather stations. The wind speed at the platform near the middle of Trout Lake was generally about half the wind speed at the Grand Marais airport, which was anecdotal evidence of the degree of wind sheltering on the lake. Interestingly, the Trout Lake wind direction showed an approximate 15 degree shift from the Grand Marais airport wind direction. This could have an impact on $W_{str}$ estimations accounting for wind direction if Grand Marais airport wind direction is used as a surrogate for Trout Lake.

To quantify wind sheltering, a wind sheltering coefficient was estimated for Trout Lake using the measured wind speeds on the lake and at Grand Marais airport. Two $W_{str}$ estimates were made: one using a single point measurement (lake platform only) and another using all five anemometers. The Thiessen polygon method that used all five anemometers resulted in a lower overall $W_{str}$ of 0.26 versus 0.40 for the single point estimate. $W_{str}$ also varied substantially when calculated for individual wind directions, which reflects differences in canopy height and fetch around the lake. The Thiessen method estimate is believed to be more accurate because it includes more stations.
distributed around the lake. However, both $W_{str}$ estimates were substantially higher than the MINLAKE calibrated $W_{str}$ value of 0.10. This overestimation demonstrates the difficulty of estimating wind effects correctly even when a weather station on a lake is available. In order to accurately estimate $W_{str}$ using measured wind speeds on the lake, we needed substantially more anemometers on the lake to fully characterize the level of sheltering. That is a big handicap suggesting that single point on-lake measurements are not sufficient to assess wind sheltering impact.

A wind sheltering coefficient $W_{str}$ was then estimated using Markfort et al.'s (2010) empirical model, first for a round lake with uniform canopy height, and then expanding the model for varying fetch and canopy height depending on wind direction. New aerial LiDAR data were very useful to estimate canopy heights around Trout Lake by a fairly simple method. The existing round lake wind sheltering model gave $W_{str} = 0.15$. The empirical wind sheltering model adjusted for wind direction and heterogeneous canopy height and topography was then used, first assuming that the canopy adjacent to the lake shoreline controls sheltering, and then that the hills plus trees set back from the shoreline control the wind sheltering of Trout Lake. Assuming that shoreline trees control wind sheltering and weighting by frequency of wind direction gave $W_{str} = 0.11$. Assuming that hills plus trees control gave $W_{str} = 0$ for all wind directions. We do not have a firm understanding of how wind flows over hills with trees, so it is not possible to say exactly how the presence of hills set back from the lake contributes to sheltering. We believe, however, that the $W_{str} = 0$ estimate is not realistic. Trout Lake would be 100% sheltered all of the time, and our field data and the calibrated sheltering coefficients prove that this is not the case. More experimental studies and simulations are needed to understanding the effects of topography on wind sheltering.

The round lake model $W_{str}$ estimate of 0.15 and the $W_{str}$ estimate considering wind direction and based on shoreline tree heights of 0.11 are similar, but the model adjusted for wind direction and varying canopy height is in better agreement with the MINLAKE calibrated $W_{str}$ value of 0.10. Adapting the round lake model to account for wind direction and varying canopy height was not an undue burden, so we recommend using the adjusted model in the future. However both versions of this model are very sensitive to canopy
height: a change of 1 meter in $h_c$, in the round lake model changes $W_{str}$ by about 25% on the heavily sheltered Trout Lake. We chose to use the 90th percentile tree height within 50 meters of shore for $h_c$, but the aerodynamics of flow over canopies needs to be investigated further to determine the appropriate height in a heterogeneous canopy that controls flow separation.

This study supports what fishermen, scientists, and lake modelers already know: the wind field over a lake is complicated to describe, and cannot be easily approximated with a single weather station on a lake or at a remote location. Without building a complicated and challenging to calibrate physical or numerical wind model, a simple empirical model such as the one proposed by Markfort et al. (2010), but adjusted for varying canopy height and wind direction, seems to be a reasonable approach to account for wind variability over a lake in models and other analyses.
References


Appendix A: Campbell Scientific Programs

Platform program

'Program is written in CR Basic, created by Short Cut (2.5) for CR1000

'Declare Variables and Units
Dim CorrFa_14
Public Batt_Volt
Public AirTC
Public RH
Public RH_Frac
Public e_Sat
Public e_kPa
Public AirTC_2
Public RH_2
Public RH_Frac_2
Public e_Sat_2
Public e_kPa_2
Public WS_ms
Public WindDir
Public WS_ms_2
Public WS_ms_3
Public StrkW
Public StrMJ
Public NR_Wm2
Public CNR_Wm2

'Batt_Volt= 12 Volt battery voltage
'AirTC= 1.31 meter air temperature
'RH= 1.31 meter relative humidity as percent
'RH_Frac= 1.31 meter relative humidity as fraction
'e_Sat=1.31 meter saturated vapor pressure
'e_kPa=1.31 meter vapor pressure
'AirTC_2= 2.0 meter air temperature
'RH_2= 2.0 meter relative humidity as percent
'RH_Frac_2= 2.0 meter relative humidity as fraction
'e_Sat_2= 2.0 meter saturated vapor pressure
'e_kPa_2= 2.0 meter vapor pressure
'WS_ms= 2.18 meter wind speed
'WindDir= 2.18 meter wind direction
'WS_ms_2= 1.68 meter wind speed
'WS_ms_3= 1.34 meter wind speed
'StrkW=Solar radiation flux
'StrMJ= Solar radiation flux density
'NR_Wm2= Net radiation
'CNR_Wm2= Corrected net radiation
'CorrFa_14=Correction factor for net radiation

Units Batt_Volt=Volts
Units AirTC=Deg C
Units RH=%
Units e_Sat=kilopascals
Units e_kPa=kilopascals
Units AirTC_2=Deg C
Units RH_2=%
Units e_Sat_2=kilopascals
Units e_kPa_2=kilopascals
Units WS_ms=meters/second
Units WindDir=Degrees
Units WS_ms_2=meters/second
Units WS_ms_3=meters/second
Units SIR_Wk=kW/m²
Units SIR_MJ=MJ/m²
Units NR_Wm2=Watts/meter²
Units CNR_Wm2=Watts/meter²

'Define Data Tables
DataTable(Trou1,True,-1)
  DataTableInterval(0,10,Min,10)
  Minimum(1,Batt_Volt,FP2,False,False)
  Average(1,AirTC,FP2,False)
  Average(1,RH,FP2,False)
  Average(1,e_Sat,FP2,False)
  Average(1,e_kPa,FP2,False)
  Average(1,AirTC_2,FP2,False)
  Average(1,RH_2,FP2,False)
  Average(1,e_Sat_2,FP2,False)
  Average(1,e_kPa_2,FP2,False)
  WindVector(1,WS_ms,WindDir,FP2,False,0,0,0)
  FieldNames("WS_ms_S_WVT,WindDir_D1_WVT,WindDir_SD1_WVT")
  Maximum(1,WS_ms,FP2,False,False)
  StdDev(1,WS_ms,FP2,False)
  Average(1,WS_ms_2,FP2,False)
  Maximum(1,WS_ms_2,FP2,False,False)
  StdDev(1,WS_ms_2,FP2,False)
  Average(1,WS_ms_3,FP2,False)
  Maximum(1,WS_ms_3,FP2,False,False)
  StdDev(1,WS_ms_3,FP2,False)
  Average(1,SIR_Wk,FP2,False)
  Average(1,NR_Wm2,FP2,False)
  Average(1,CNR_Wm2,FP2,False)
EndTable

'Main Program
BeginProg
  Scan(3,Sec,1,0)
    'Default Datalogger Battery Voltage measurement Batt_Volt:
    Battery(Batt_Volt)
    'HMP35C Temperature & Relative Humidity Sensor measurements AirTC and RH:
    Therm107(AirTC,1,1,1,0,0,60Hz,1,0,0,0)
    PortSel(1,1)
    Delay(0,150,mSec)
    VoltSel(RH,1,mV2500,2,0,0,60Hz,0,1,0)
    PortSel(1,0)
    If RH>100 AND RH<108 Then RH=100
'Calculate vapor pressure
'Convert RH percent to RH fraction
RH_Frac=RH*0.01
'Calculate saturated vapor pressure
SatVP(e_Sat,AirTC)
'Compute vapor pressure
e_kPa=e_Sat*RH_Frac
'HMP45C (7-wire) Temperature & Relative Humidity Sensor measurements
AirTC_2 and RH_2:
PortSet(2,1)
Delay(0,150,mSec)
VoltSe(AirTC_2,1,mV2500,3,0,0,.60Hz,0.1,-40.0)
VoltSe(RH_2,1,mV2500,4,0,0,.60Hz,0.1,0)
PortSet(2,0)
If RH_2>100 AND RH_2<108 Then RH_2=100
'Calculate vapor pressure
'Convert RH percent to RH fraction
RH_Frac_2=RH_2*0.01
'Calculate saturated vapor pressure
SatVP(e_Sat_2,AirTC_2)
'Compute vapor pressure
e_kPa_2=e_Sat_2*RH_Frac_2
'03001 Wind Speed & Direction Sensor measurements WS_ms and WindDir
(changed calibration factors according to wind tunnel results
PulseCount(WS_ms_1,1,1,1,1,0.7135,0.5664)
If WS_ms<0.21 Then WS_ms=0
BrHalf(WindDir,1,mV2500,5,1,1,2500,True,0,.60Hz,355,0)
If WindDir>=360 Then WindDir=0
'014A Wind Speed Sensor measurement WS_ms_2:
PulseCount(WS_ms_2,1,2,2,1,0.8,0.447)
If WS_ms_2<0.457 Then WS_ms_2=0
'014A Wind Speed Sensor measurement WS_ms_3:
PulseCount(WS_ms_3,1,3,2,1,0.8,0.447)
If WS_ms_3<0.457 Then WS_ms_3=0
'LI200X Pyranometer measurements SlrMJ and SlrkW:
VoltDiff(SlrkW,1,mV7,5,4,True,0,.60Hz,1,0)
If SlrkW<0 Then SlrkW=0
SlrMJ=SlrkW*0.0006
SlrkW=SlrkW*0.2
'Q-7.1 Net Radiometer (dynamic wind speed correction) measurements NR_Wm2
and CNR_Wm2:
VoltDiff(NR_Wm2,1,mV250,5,True,0,.60Hz,1,0)
If NR_Wm2>=0 Then
CorrFa_14=1+(0.066*0.2*WS_ms_3)/(0.066+(0.2*WS_ms_3))
NR_Wm2=NR_Wm2*8.57
Else
CorrFa_14=(0.00174*WS_ms_3)+0.99755
NR_Wm2=NR_Wm2*10.62
EndIf
CNR_Wm2=NR_Wm2*CorrFa_14
'Call Data Tables and Store Data
CallTable(Trout1)
Individual Anemometer Program

;Program is written in Edlog, created by Short Cut (2.5) for CR500

*Table 1 Program
01: 3.0000  Execution Interval (seconds)

1: Batt Voltage (P10)
   1: 1  Loc [ Batt_Volt ]

2: Pulse (P3)
   1: 1  Reps
   2: 1  Pulse Channel 1
   3: 22 Switch Closure, Output Hz
   4: 3  Loc [ WS_ms ]
   5: 0.8 Multiplier
   6: 0.447 Offset

3: If (X<=F) (P89)
   1: 3  X Loc [ WS_ms ]
   2: 4  <
   3: 0.457  F
   4: 30 Then Do

4: Z=F x 10^n (P30)
   1: 0  F
   2: 0  n, Exponent of 10
   3: 3  Z Loc [ WS_ms ]

5: End (P95)

6: If time is (P92)
   1: 0  Minutes (Seconds -->) into a
   2: 10 Interval (same units as above)
   3: 10 Set Output Flag High (Flag 0)

7: Set Active Storage Area (P80)^8717
   1: 1  Final Storage Area
   2: 0  Array ID @@0

8: Real Time (P77)^2488
   1: 0220  Day,Hour/Minute (midnight = 2400)

9: Average (P71)^10802
   1: 1  Reps
   2: 3  Loc [ WS_ms ]

10: Maximum (P73)^32177
    1: 1  Reps
    2: 0  Value Only
    3: 3  Loc [ WS_ms ]

11: Standard Deviation (P82)^20901
1: 1 Reps
2: 3 Sample Loc [ WS_ms ]

*Table 2 Program
01: 0.0000 Execution Interval (seconds)

*Table 3 Subroutines

End Program

-Input Locations-
1 Batt_Volt 1 0 1
2 Prog_Sig 1 0 0
3 WS_ms 1 4 2
4 _______ 0 0 0
5 _______ 0 0 0
6 _______ 0 0 0
7 _______ 0 0 0
8 _______ 0 0 0
9 _______ 0 0 0
10 _______ 0 0 0
11 _______ 0 0 0
12 _______ 0 0 0
13 _______ 0 0 0
14 _______ 0 0 0
15 _______ 0 0 0
16 _______ 0 0 0
17 _______ 0 0 0
18 _______ 0 0 0
19 _______ 0 0 0
20 _______ 0 0 0
21 _______ 0 0 0
22 _______ 0 0 0
23 _______ 0 0 0
24 _______ 0 0 0
25 _______ 0 0 0
26 _______ 0 0 0
27 _______ 0 0 0
28 _______ 0 0 0

-Program Security-
0000
0000
0000
-Mode 4-
0
-CR10X ID-
0
-DLD File Labels-
0
-Final Storage Labels-
0,Day_RTM,2488
0, Hour_Minute_RTM
1, WS_ms_AVG = 3,10802
2, WS_ms_MAX = 3,32177
3, WS_ms_STD = 3,20901
4, 8717
Appendix B: $W_{str}$ calculation

$W_{str}$ calculated from measured wind speeds

$$TKE = W_{str} \int_{A_s} u_{*,w} \tau dA = W_{str} \sum_{A_s} u_{*,w} \tau \Delta A$$

$$\tau_a = \tau_w$$

$$\tau_a = C_{D,z} \rho_a U_z^2$$

$$\tau_w = \rho_w u_{*,w}^2$$

$$C_{D,z} \rho_a U_z^2 = \rho_w u_{*,w}^2$$

$$u_{*,w} = \left(\frac{C_{D,z}}{\rho_w} \frac{\rho_a}{\rho_w} \right)^{1/2} U_z$$

$$TKE = W_{str} \int_{A_s} \left( \frac{C_{D,z}}{\rho_w} \frac{\rho_a}{\rho_w} \right)^{1/2} U_z \left( C_{D,z} \rho_a U_z^2 \right) dA = W_{str} \sum_{A_s} \left( \frac{C_{D,z}}{\rho_w} \frac{\rho_a}{\rho_w} \right)^{1/2} U_z \left( C_{D,z} \rho_a U_z^2 \right) \Delta A$$

$$TKE = W_{str} \int_{A_s} \rho_a^{3/2} \rho_w^{-1/2} C_{D,z}^{3/2} U_z^3 dA = W_{str} \sum_{A_s} \rho_a^{3/2} \rho_w^{-1/2} C_{D,z}^{3/2} U_z^3 \Delta A$$

$C_{D,10} = 0.0044 U_{10}^{-1.15}$ for $U_{10} < 4$ m/s

$C_{D,10} \approx -8.34022 \times 10^{-7} U_{10}^2 + 7.60691 \times 10^{-5} U_{10} + 6.53167 \times 10^{-4}$ for $U_{10} \geq 4$ m/s

(polynomial fit to Charnock's law for $4 \leq U_{10} \leq 18.5$ m/s)

(Wüest and Lorke, 2003)

At 10 meters where $U_{10} < 4$ m/s

$$TKE = W_{str} \sum_{A_s} \rho_a^{3/2} \rho_w^{-1/2} C_{D,z}^{3/2} U_z^3 \Delta A$$
\[ TKE = W_{str} \sum_{As} \left( 0.0044 U_{10}^{-1.15} \right)^{\frac{3}{2}} \rho_a^{\frac{3}{2}} \rho_w^{\frac{-1}{2}} U_{10}^{3} \Delta = W_{str} \sum_{As} 0.000292 \rho_a^{\frac{3}{2}} \rho_w^{\frac{-1}{2}} U_{10}^{1.275} \Delta A \]

At 10 meters where \( U_{10} \geq 4 \) m/s

\[ TKE = W_{str} \sum_{As} \left( -8.34022 \times 10^{-7} U_{10}^{2} + 7.60691 \times 10^{-5} U_{10} + 6.53167 \right) \times 10^{-4} \rho_a^{\frac{3}{2}} \rho_w^{\frac{1}{2}} U_{10}^{3} \Delta A \]

We can calculate TKE for the airport and site using site specific \( U_{10} \). In both cases \( W_{str} \) would be 1 because \( U_{10} \) will be the actual measured wind, which implicitly accounts for any sheltering effects. Then to calculate \( W_{str} \) for the lake:

\[ W_{str} = \frac{TKE_{sheltered}}{TKE_{unsheltered}} \]