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Examining the utility of satellite-based wind sheltering estimates for lake hydrodynamic modeling

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ABSTRACT

Satellite-based measurements of vegetation canopy structure have been in common use for the last decade but have never been used to estimate canopy's impact on wind sheltering of individual lakes. Wind sheltering is caused by slower winds in the wake of topography and shoreline obstacles (e.g. forest canopy) and influences heat loss and the flux of wind-driven mixing energy into lakes, which control lake temperatures and indirectly structure lake ecosystem processes, including carbon cycling and thermal habitat partitioning. Lakeshore wind sheltering has often been parameterized by lake surface area but such empirical relationships are only based on forested lakeshores and overlook the contributions of local land cover and terrain to wind sheltering. This study is the first to examine the utility of satellite imagery-derived broad-scale estimates of wind sheltering across a diversity of land covers. Using 30 m spatial resolution ASTER GDEM2 elevation data, the mean sheltering height, h_s, being the combination of local topographic rise and canopy height above the lake surface, is calculated within 100 m-wide buffers surrounding 76,000 lakes in the U.S. state of Wisconsin. Uncertainty of GDEM2-derived h_s was compared to SRTM-, high-resolution G-LiHT lidar-, and ICESat-derived estimates of h_s, respective influences of land cover type and buffer width on h_s are examined; and the effect of including satellite-based h_s on the accuracy of a statewide lake hydrodynamic model was discussed. Though GDEM2 h_s uncertainty was comparable to or better than other satellite-based measures of h_s, its higher spatial resolution and broader spatial coverage allowed more lakes to be included in modeling efforts. GDEM2 was shown to offer superior utility for estimating h_s compared to other satellite-derived data, but was limited by its consistent underestimation of h_s, inability to detect within-buffer h_s variability, and differing accuracy across land cover types. Nonetheless, considering a GDEM2 h_s-derived wind sheltering potential improved the modeled lake temperature root mean square error for non-forested lakes by 0.72 °C compared to a commonly used wind sheltering model based on lake area alone. While results from this study show promise, the limitations of near-global GDEM2 data in timeliness, temporal and spatial resolution, and vertical accuracy were apparent. As hydrodynamic modeling and high-resolution topographic mapping efforts both expand, future remote sensing-derived vegetation structure data must be improved to meet wind sheltering accuracy requirements to expand our understanding of lake processes.

1. Introduction

Lakes and reservoirs play a small but important role in the global carbon cycle, individually acting as a sink or source of carbon depending on the metabolic balance between primary producers and respiration (Cole et al., 2007; McDonald, Stets, Striegl, & Butman, 2013; Raymond et al., 2013; Tranvik et al., 2009). The rate of gaseous carbon exchange (e.g., fluxes of CH_4 and CO_2) between lakes and the atmosphere is mediated by water temperature, which controls solubility, and near-surface turbulence in the water column (Zappa et al., 2007). Lake water temperature and near-surface turbulence are influenced by complex interactions between regional and local drivers (e.g., climate and hydrology) with lake-specific properties such as wind sheltering (i.e., the reduction of over-lake wind speeds via interference from surrounding topography and terrain features; Markfort et al., 2010; Read et al., 2012). Accounting for the influence of wind sheltering effects on gas exchange is especially important for small lakes since they contribute more to carbon cycling

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than larger lakes (Downing, 2010; Downing et al., 2008; Kankaala, Huotari, Tulonen, & Ojala, 2013; Roehm, Prairie, & Del Giorgio, 2009) and are more sensitive to shoreline wind sheltering (Markfort et al., 2010).

Although seldom considered, recent research (e.g., Markfort et al., 2010) has highlighted the importance of including the additive effects of topographic height (h_t) and canopy height (h_c) relative to the lake surface elevation (z_{lake}) – referred to here as the "sheltering height" (h_s) – to parameterize the local wind sheltering coefficient (W_{st}) in hydrodynamic models (Read et al., 2014; Fig. 1) and models of gas transfer (Read et al., 2012). Lacking direct measurements at a given lake, "typical" h_c values for specific land covers have been used in place of h_s (Read et al., 2012; Table 1) or, more commonly, W_{st} has simply been assumed to be a function of lake surface area (Hondzo & Stefan, 1993). However, such a simplified parameterization of wind sheltering overlooks the role of (and variation in) local topography and canopy height as mediators of lake temperature and near-surface turbulence. For example, a small lake surrounded by flat agricultural land experiences a much lower degree of wind sheltering compared to a similarly sized lake surrounded by steep, sloping terrain and forested land cover (Fig. 2).

A simplified parameterization of W_{st} that only considers h_c has often been unavoidable. There is an abundance of digital elevation models (DEMs) that estimate h_t across broad spatial extents, such as the 3 m resolution National Elevation Dataset (NED) (Gesch et al., 2002) and the 90 m resolution Shuttle Radar Topography Mission (SRTM) Version 2 (V2) DEM (Slater et al., 2006) with near-global coverage, but comparably few sources for systematically-collected measurements of h_c. Canopy height data collected through the Forest Inventory and Analysis (FIA) Program of the U.S. Forest Service (www.fia.fs.fed.us), for example, tend to be located within "representative" and continuous forest stands that are rarely in close proximity to lakes or reservoirs. Spaceborne altimeters, such as the SRTM radar or Geoscience Laser Altimeter System (GLAS) lidar, offer near-global elevation measurements with which to calculate h_s (e.g., Bolton, Coops, & Wulder, 2013; Farr et al., 2007; Wulder et al., 2012; Table 2). However, neither spaceborne radar nor lidar are well-suited to estimate h_s around diffusely distributed and often small-sized lakes given their coarse sampling or resolution (Hanson, Carpenter, Cardille, Coe, & Winslow, 2007). Canopy height products derived from spaceborne altimetry data, e.g., Lefsky (2010) and Simard, Pinto, Fisher, and Baccini (2011), offer h_c but cannot be directly used to estimate h_s since they lack a collocated measurement of h_t. Other radar altimeters, e.g., Envisat's RA-2 and Jason-1's Poseidon-2, commonly used to map global lake and reservoir surface elevations (e.g., Kouraev et al., 2007; Medina, Gomez-Enri, Alonso, & Villares, 2008; Swenson & Wahr, 2009; Wang et al., 2011) have spatial resolutions of 5 km and cannot resolve small lakes or surrounding canopy. Finally, while airborne lidar, such as G-LiHT considered below, can very accurately estimate h_c and h_t at a fine spatial detail, their limited coverage and often proprietary data keep broad-scale estimates of h_s out-of-reach.

In part because of these limitations, remotely sensed altimetry data have never before been used to calculate wind sheltering. However, the Global Digital Elevation Model Version 2 (GDEM2) generated from imagery collected by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor aboard NASA's Terra satellite presents the opportunity to assess lake-level wind sheltering across 99% of the Earth's landmass at the moderate spatial resolution of 30 m. The GDEM2 is a photogrametrically-derived DEM with elevations based on ASTER's visible and near-infrared (VNIR) band, which simultaneously acquires imagery from different look angles producing a stereographic perspective of the landscape (Toutin, 2008; Yamaguchi, Kahle, Tsu, Kawakami, & Pniel, 1998). GDEM2 elevations reflect the combined influence of topographic elevation as well as the height of terrain features such as trees or buildings, thereby offering an inherent estimate of h_s. GDEM2's absolute vertical accuracy has been measured to within 0.20 m across the continental United States (Tachikawa et al., 2011b) and has recently been shown to be acceptable for vegetation height mapping in areas of low relief (Ni, Sun, & Ranson, 2013), and this is the first study to consider the utility of GDEM2 in a wind sheltering assessment or a hydrodynamic modeling application.

Using the U.S. state of Wisconsin as a regional testbed, this study introduces a novel method to estimate h_s across a broad spatial extent using GDEM2 data. The approach is composed of three stages: first,

Table 1
Typical canopy heights (h_c) for specific land cover types. Note that many land covers with non-negligible h_c, such as wetland or urban/built-up do not have a "standard" h_c and are excluded. Adapted from Oke (1987) and Garratt (1992).

Land cover	h_c (m)
Open water	0
Ice	0
Snow	0
Bare soil	0
Turf grass	0.02–0.1
Prairie grass	0.3–1.0
Agriculture	0.2–1.4
Woodland trees	8–15
Coniferous forest	10–27
Tropical forest	32–35

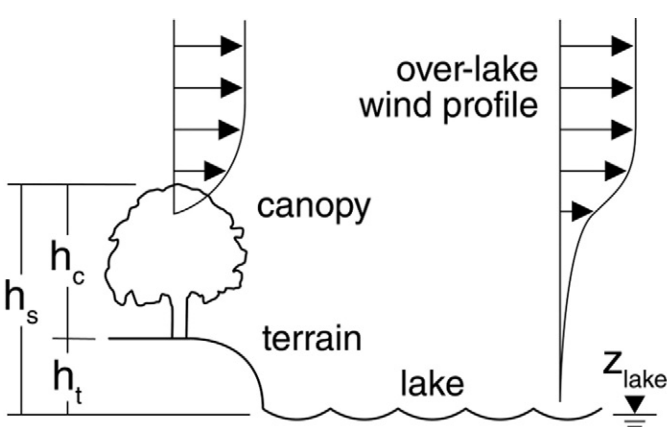

Fig. 1. Sheltering height, h_s – the sum of terrain height, h_t, and canopy height, h_c – is incorporated in a one-dimensional model of wind sheltering's effect on the wind profile over a lake surface with elevation z_{lake}. Adapted from Markfort et al. (2010, 2014).

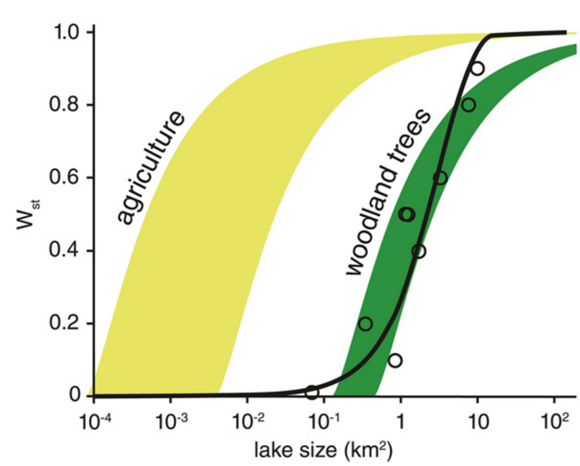

Fig. 2. Comparison of wind-sheltering coefficient (W_{st}) estimates by land cover type and W_{st} estimation methods. The ranges of W_{st} at lakes surrounded by agriculture (yellow) or woodland trees (green) were calculated using the land cover-specific h_c (see Table 1) following Markfort et al. (2010). A lake surface area-based parameterization (black line) is also represented where black circles represent calibrated W_{st} for forested lakes in Minnesota (U.S.) following Hondzo and Stefan (1993).