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Underestimates of sensible heat flux due to vertical velocity measurement errors in non-orthogonal sonic anemometers☆

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ABSTRACT

Sonic thermometry and anemometry are fundamental to all eddy-covariance studies of surface energy balance. Recent studies have suggested that sonic anemometers with non-orthogonal transducers can underestimate vertical wind velocity (w) and sensible heat flux (H) when compared to orthogonal designs. In this study we tested whether a non-orthogonal sonic anemometer (CSAT3, Campbell Scientific, Inc.) measures lower w and H than an orthogonal sonic anemometer (SATI/3Vx, Applied Technologies, Inc.) and through experimental manipulation we tested if this difference can be attributed to errors in the CSAT3. Four CSAT3s and one SATI/3Vx were mounted symmetrically in a horizontal array on top of the Glacier Lakes Ecosystem Experiments Site (GLEES) AmeriFlux scaffold (southeastern Wyoming, USA) and in close enough proximity to allow covariance measurements between neighboring sonic anemometers. The CSAT3s were paired and measurements of the three orthogonal wind velocities (u, v, and w) were tested by alternatively rotating each sonic anemometer 90° around its u-axis, essentially forcing the sonic v-axis transducer system to measure w. Analysis was performed on data corresponding to gusts of wind located within the 15° cone defined around the u-axis to ensure operation within manufacturer specifications. We found that the CSAT3 measured 8% lower H than the SATI/3Vx and that was associated with a 6–12% lower measurement of w. From the CSAT3 manipulations we found w was underestimated by 6–10% which led directly to an 8–12% underestimate of the kinematic heat flux, the fundamental covariance of H. These results have implications for ecosystem flux research and the energy imbalance problem considering the prevalence of the CSAT3 and the non-orthogonal sonic anemometer design.

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1. Introduction

Within the micrometeorological community a reoccurring theme is the lack of energy balance closure at individual sites, across sites, and across networks where a common thread is turbulent energy fluxes underestimate the available energy (Foken, 2008; Franssen et al., 2010; Oncley et al., 2007; Stannard et al., 1994; Twine et al., 2000; Wilson et al., 2002). Many plausible explanations for this have been proposed ranging from uncertainties in radiation or eddy-covariance flux measurements, the mismatch of measurement areas between flux components, the neglect of energy storage terms, advective flux divergence, and incorrect coordinate systems (Leuning et al., 2012; Mahrt, 1998; Wilson et al., 2002). The role of sonic anemometry as a potential source of the lack of closure has also been investigated. Mauder et al. (2007) and Loescher et al. (2005) examined the relative difference between instrument models and manufacturers while Gash and Dolman (2003) investigated the role of turbulent wind caused (co)sine errors where the instruments operate at attack angles outside of their optimal range. Unfortunately, for most flux sites few of these explanations can account for the typical 20% biased underestimate of the turbulent flux components of the energy balance (Leuning et al., 2012).

Another possible explanation for the energy balance closure problem could be due to differences in vertical wind velocity (w) and sensible heat-flux (H) measurements between orthogonal and non-orthogonal sonic anemometers (Kochendorfer et al., 2012). In the traditional orthogonal design the sonic anemometer transducer pairs are 90° to each other and the vertical measurements are truly vertical, while in the non-orthogonal type all transducers are tilted and clustered such that none of the actual measurements, including w, are simply horizontal or vertical (Fig. 1). Though there are advantages to both designs, orthogonal sonic anemometers are increasingly rare and account for only 13% of the available AmeriFlux network level 2 sites (http://ameriflux.ornl.gov/). Orthogonal sensors have been observed to 'overestimate' w and H (Mauder

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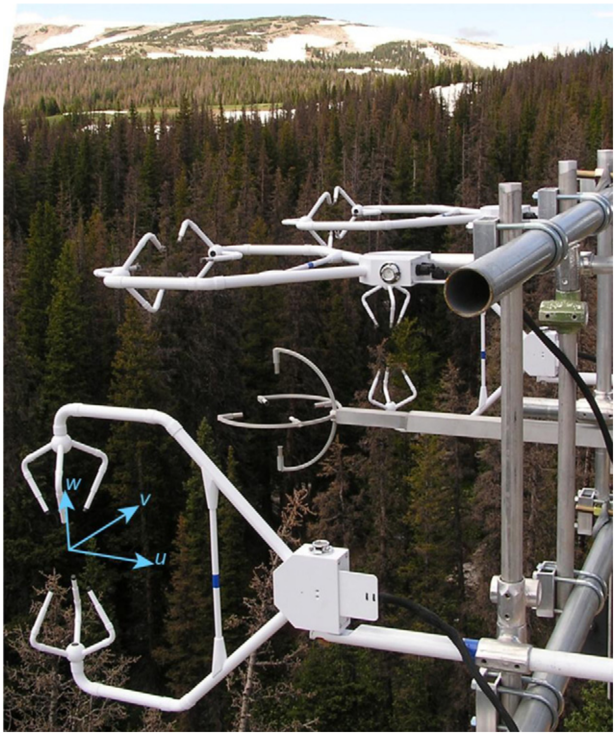

Fig. 1. Photograph of the experimental setup. Position 1 is in the bottom left. The CSAT3 sonic anemometers in positions 2 and 4 are mounted in the horizontal orientation. The u, v, and w axes are shown in light blue for position 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2007) when compared to a non-orthogonal standard. But with no compelling evidence to suggest that the orthogonal w measurement is erroneous, it is entirely possible that instead the majority of eddy-covariance systems which employ the non-orthogonal sonic anemometer underestimate w and H.

Here we hypothesize that a non-orthogonal sonic anemometer underestimates w and H. With this sensor we expect to observe lower w and H in comparison to an orthogonal anemometer. Through experimental manipulation of instrument orientations and consequently measurements of the three orthogonal wind velocities (u, v, and w), we predict that rotating a non-orthogonal sonic anemometer 90° around its u-axis and forcing the v-axis transducer system to measure the w wind component will increase the measurement of w. In concurrence, we also expect a corresponding decrease in the measured v wind component due to the erroneous sonic w-axis transducer system measuring the horizontal cross-wind. Finally, we predict that the underestimate in w also exists in H, thus yielding a possible explanation for the bias in energy balance closure across a majority of flux sites.

2. Methods

2.1. Site information and experimental design

Four non-orthogonal (CSAT3, Campbell Scientific Inc., Logan, UT, USA, serial numbers 1046, 1206, 1209, and 1455) and one orthogonal (SATI/3Vx, Applied Technologies Inc., Longmont, CO, USA, serial number 971204, hereafter referred to as the ATI) sonic anemometers were tested in a horizontal array at the top of the Glacier Lakes Ecosystem Experiments Site (GLEES) AmeriFlux scaffold (41° 21.992′ N, 106° 14.397′ W, 3190 m above sea level) at an average height of 24.5 m above the soil surface of an 18 m high canopy subalpine forest in southeastern Wyoming, USA described by Musselman (1994). The sonics were oriented with their azimuth pointed west (or in the case of the ATI, the boom was pointed west) and mounted in five positions located in two rows with the upper row (row 1) 0.35 m above the lower row (row 2). From south to north and relative to position 1 in the lower row, position 2 was 0.35 m north in row 1, position 3 was 0.70 m north in row 2, position 4 was 1.05 m north in row 1, and position 5 was 1.40 m north in row 2 (Fig. 1). The sonics were always mounted such that they were centered at each position and the total distance between adjacent sonic centroids was 0.50 m at a 45° diagonal. The CSAT3s were paired, such that the first pair shared positions 1 and 2 and the second pair shared positions 4 and 5; the ATI was always in position 3. The experiment comprised six stages during an eight week experiment when the pairs of sonics were alternately rotated 90° around their u-axis into a horizontal orientation such that in sonic coordinates the CSAT3 w-axis was pointing south and the v-axis was pointing up and the ATI was rotated so its w-axis was facing north (Table 1). All data are presented in cardinal coordinates ($u_{\text{cardinal}} = \text{east}$, $v_{\text{cardinal}} = \text{north}$, $w_{\text{cardinal}} = \text{up}$) hereby referred to simply as u, v, and w. The sonic north-south and east-west axes were adjusted to within 0.4° with a digital level while the direction was set by pointing the sonics within 0.5° of a known 270° reference point on the nearby Snowy Range Mountains 4 km away. We marked lines across the side of the CSAT3s for use as guides in sighting horizontally mounted instruments (e.g., the piece of tape on the vertical brace in Fig. 1). Time series data from the five sonics was recorded at 20 Hz on either a CR1000 or CR3000 (Campbell Scientific Inc., Logan, UT, USA). The complete time series was processed (QA/QC) by removing half-hours with physically unrealistic summary statistic measurements (mean, standard deviation, skewness, kurtosis, number of samples) in any of the five sonic anemometers (Vickers and Mahrt, 1997). This amount of processing was deemed sufficient to assure the quality control of the 20 Hz time series samples (Figs. 2 and 3) therefore no despiking algorithm was applied. Finally, since the focus of this study was specifically sonic anemometer measurements, no coordinate rotations, time lag corrections, spectral corrections, or buoyancy corrections were applied to the data.

Non-orthogonal sonic anemometers are most accurate measuring near horizontal winds where transducer shadowing and (co)sine errors are minimized (Gash and Dolman, 2003; Nakai et al., 2006). Similarly, the 90°-rotated horizontal sonic anemometers are most accurate with winds in the vertical plane normal to the sonic w-axis. In order to facilitate comparisons between simultaneously accurate vertical and horizontal mounted instruments the complete time series data was restricted to gusts of wind within a cone of $\pm\alpha$ around the u-axis. Though the CSAT3 has an expected accuracy of 6% for $\alpha = 20°$ (Campbell Scientific, Inc., 2012), here α was defined more conservatively at 15° following the results of Kochendorfer et al. (2012). Because many of the wind measurements within the 15° cone were fragmentary and could have been associated with eddies of short length and time scales such that they might not be simultaneously visible to all five sonics, the data was further reduced to gusts of at least a minimum length and hence a minimum time period, defined by Taylor's hypothesis as $T_i = L/U_i$ where T_i is the minimum instantaneous time period, L is the minimum length equal to twice the distance between positions 1 and 5, and U_i is the instantaneous wind velocity. Then for a series of consecutive 20 Hz sampled wind velocities within the 15° cone, only those series with a minimum of $2T_{i,\max}f_s$ elements were included in the analysis ($T_{i,\max}$ is the maximum of the T_i values within the series, f_s is the sample rate, and 2 is merely a safety factor). As an example, for a series of 32 consecutive wind velocity measurements within the 15° cone sampled at 20 Hz and U_i ranging from 3.7 m s^{-1} to 5.0 m s^{-1}, with L = 2.8 m the maximum T_i is 0.76 s, and a minimum gust size of $2 \times 0.76 \times 20 = 30$ samples would be