

All Sonic Anemometers Need to Correct for Transducer and Structural Shadowing in Their Velocity Measurements*

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ABSTRACT

Sonic anemometry is fundamental to all eddy-covariance studies of surface energy and ecosystem carbon and water balance. Recent studies have shown that some nonorthogonal anemometers underestimate vertical wind. Here it is hypothesized that this is due to a lack of transducer and structural shadowing correction. This is tested with a replicated intercomparison experiment between orthogonal (K-probe, Applied Technologies, Inc.) and nonorthogonal (A-probe, Applied Technologies, Inc.; and CSAT3 and CSAT3V, Campbell Scientific, Inc.) anemometer designs. For each of the 12 weeks, five randomly selected and located anemometers were mounted both vertically and horizontally. Bayesian analysis was used to test differences between half-hourly anemometer measurements of the standard deviation of wind (σ_u , σ_v , and σ_w) and temperature, turbulent kinetic energy (TKE), the ratio between vertical/horizontal TKE (VHTKE), and sensible heat flux (H). Datasets were analyzed with various applications of transducer shadow correction. Using the manufacturer's current recommendations, orthogonal anemometers partitioned higher VHTKE and measured about 8%–9% higher σ_w and ~10% higher H . This difference can be mitigated by adding shadow correction to nonorthogonal anemometers. The horizontal manipulation challenged each anemometer to measure the three dimensions consistently, which allowed for testing two hypotheses explaining the underestimate in vertical wind. While measurements were essentially unchanged when the orthogonal anemometers were mounted sideways, the nonorthogonal anemometers changed substantially and confirmed the lack of shadow correction. Considering the ubiquity of nonorthogonal anemometers, these results are consequential across flux networks and could potentially explain half of the ~20% missing energy that is typical at most flux sites.

1. Introduction

Sonic anemometry is the fundamental tool for conducting all micrometeorological studies of energy and mass exchange between ecosystems and the atmosphere (Lee et al. 2004b). Recent studies have proposed that sonic anemometry errors in vertical wind velocity (Frank et al. 2013; Kochendorfer et al. 2012; Nakai and

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Shimoyama 2012) lead to errors in sensible heat flux and play an important role in closing the energy balance (Leuning et al. 2012; Stoy et al. 2013; Wilson et al. 2002). These studies suggest the following question, Is there is a fundamental difference in vertical wind velocity measurements between orthogonal and nonorthogonal sonic anemometers? Currently, there is no consensus on whether differences occur (Beyrich et al. 2002; Frank et al. 2013; Horst et al. 2015; Kochendorfer et al. 2012, 2013; Mauder et al. 2007) or do not (Foken et al. 1997; Loescher et al. 2005; Mauder 2013).

If such a difference exists, then what is the reason for it? Kochendorfer et al. (2012) suggested with one sonic anemometer design that wakes across the sonic transducer can cause flow distortions, or shadowing, within the sonic path. Horst et al. (2015) similarly proposed that in another nonorthogonal anemometer the cause is a lack of correction for flow distortion due to transducer shadowing. The history and development of the sonic anemometer followed numerous technical advancements with particular attention directed toward minimizing flow distortion (Kaimal 2013). Through a combination of empirical wind tunnel-derived transducer and shadow correction algorithms (Kaimal 1979; Wyngaard and Zhang 1985) and an orthogonal geometry arranged to minimize interference between the three perpendicular and independent transducer axes, the K-probe [Applied Technologies, Inc. (ATI)] was effective at mitigating flow distortion (Kaimal et al. 1990). Around the same time a new arrangement emerged to eliminate shadowing altogether by moving all transducers out of the horizontal plane and into a vertical nonorthogonal geometry separated by 60°, which made them no longer independent (Zhang et al. 1986). This University of Washington (U.W.) sonic anemometer eventually led to the CSAT3 (Campbell Scientific, Inc.) (Foken et al. 1997), which has become ubiquitous in recent decades (Nakai et al. 2014) following the expansion of eddy-covariance technology and global flux networks (Baldocchi 2003).

Here, we present results from a field experiment conducted to answer the questions posed above. We evaluate three competing hypotheses:

- A) There are no differences in vertical wind measurements between orthogonal and nonorthogonal sonic anemometers.
- B₁) Nonorthogonal anemometers underestimate vertical wind because of a one-dimensional error correlated only with the w axis.
- B₂) Nonorthogonal anemometers underestimate vertical wind because of a three-dimensional error due to the lack of a correction for transducer and structural shadowing.

We evaluate these through a two-part experiment with first, an intercomparison between orthogonal and non-orthogonal anemometers; and second, an internal consistency test where instruments were mounted on their side. The intercomparison is used to test whether there was a difference in vertical wind measurements (hypothesis A vs B₁ or B₂) as well as to provide a metric to quantify the magnitude of the difference. The internal consistency test is used to evaluate the cause of the underestimate (hypothesis B₁ vs B₂) by comparing 1D and 3D predicted errors to observations.

2. Methods

a. Experimental setup

From 14 June to 24 September 2013, we conducted a sonic anemometer intercomparison and manipulation experiment on the AmeriFlux scaffold at the Glacier Lakes Ecosystem Experiments Site (GLEES) (41°21.992'N, 106°14.397'W; 3190 m MSL). GLEES is a high-elevation subalpine forest in the Rocky Mountains of southeastern Wyoming (Frank et al. 2014; Musselman 1994). We tested four sonic anemometer designs representing orthogonal (K-probe) and nonorthogonal (A-probe, ATI; CSAT3 and CSAT3V, Campbell Scientific, Inc.) transducer arrangements. The CSAT3V is a modified CSAT3 with transducer pair A (along the u axis) located in front of the anemometer and oriented vertical (Fig. 1a). There were three replicate units of each design (serial numbers for K-probe = 130401, 130402, and 911202; A-probe = 20301, 070301, and 130403; CSAT3 = 1046, 1206, and 1455; CSAT3V = 01, 02, and 03). Firmware varied across designs and their replicates: K-probe has one unit with version 1.3.4 and two units with version 2.1.4, A-probe has two units with 1.3.4 and one unit with version 2.1.7, CSAT3 has all units with version 4.0, and CSAT3V has all units with version 3.0. The date of the last calibration or factory service also varied across designs and their replicates: K-probe had two units in 2013 and one unit unknown; A-probe had all units in 2013; CSAT3 had one unit in 2005, one unit in 2006, and one unit in 2007; and CSAT3V had one unit in 2012 and two units in 2013.

We installed a mounting jig to accommodate five anemometers at an average height of 24.5 m above the ground. The average canopy height of the forest is 9.3 m (Bradford et al. 2008), reaching a maximum of 18 m. A majority of the largest trees were recently dead and needleless following a spruce beetle epidemic (Frank et al. 2014). All anemometers were oriented with their azimuth pointed west, and with the five positions staggered among two rows to allow the closest arrangement

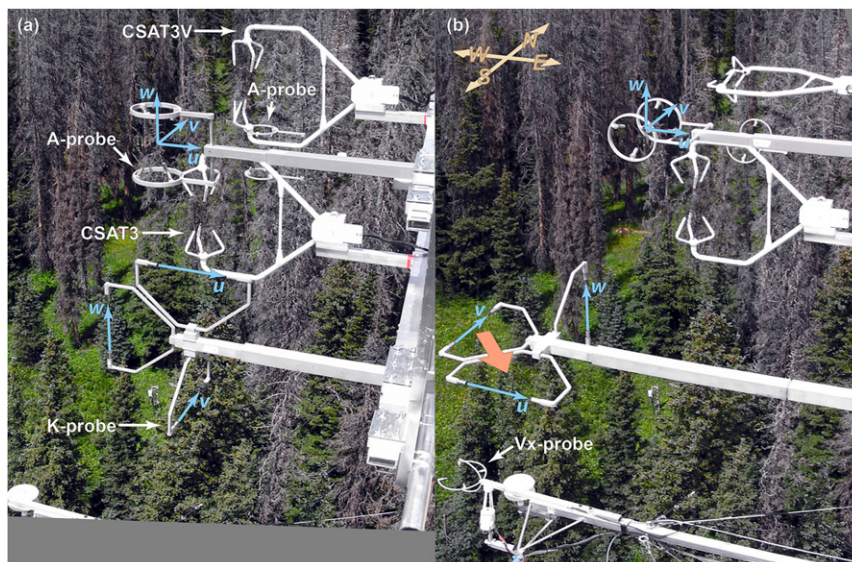


FIG. 1. Photographs of the experiment with the sonic anemometers mounted (a) vertically and (b) horizontally and highlighting some of the sonic coordinate axes (u , v , and w ; blue arrows). The Vx-probe associated with the GLEES AmeriFlux eddy-covariance system is visible in (b). The thick orange arrow illustrates structural shadowing in the K-probe u -axis measurement introduced by the horizontal manipulation. Images were taken during week 7 (Table 1).

while reducing crosswind interference, such that position 1 was the farthest south in the bottom row, position 2 was 0.35 m north and 0.35 m above, position 3 was 0.70 m north, position 4 was 1.05 m north and 0.35 m above, and position 5 was 1.40 m north (Fig. 1a). The jig was constructed so that regardless of the anemometer design or vertical/horizontal mounting, the center of the vertical measurement path at each position remained constant (Fig. 1b). The sonic north–south and east–west axes were adjusted to an average tilt of $0.2^\circ \pm 0.14^\circ$ (mean $\pm$ standard deviation, maximum equals 0.6° , measured with a digital level), while azimuth was aimed toward a known 270° reference point on the nearby Snowy Range Mountains 4 km away to an estimated accuracy of at least 0.5° .

The experiment was divided into 12 individual weeks. For each week five anemometers were randomly selected from the pool of 12 anemometers, subject to these restrictions: 1) one from each of the four designs was represented at all times, and hence the fifth sonic was considered a wildcard; and 2) each sonic was selected five times (i.e., four times representing its design and once as a wild card). The positions of the anemometers were randomly assigned, except the sonic representing the CSAT3, which was always mounted in the center (position 3) to be used as a control during the horizontal manipulation. The 12 weeks were assigned before the experiment, and we ordered the weeks to minimize the

exchange of equipment up and down the scaffold. All units were deployed with each other at least once, with the exceptions of C7 versus C8, V10 versus V11, and V10 versus V12 (lost due to sensor damage) (Table 1). Halfway through each week, all instruments except the CSAT3 in the center position were manipulated and mounted horizontally (Fig. 1b).

All data were collected on a CR3000 Micrologger (Campbell Scientific, Inc.). The datalogger was responsible for triggering all anemometers at 20 Hz. The CSAT3 and CSAT3V were set up to group trigger. The K-probe and A-probe independently sample at 200 Hz, and both were set up to output the median of 9 samples (total time sampled ≈ 45 ms) when externally triggered; this was an adjustment following week 1, when 10 samples (total time sampled ≈ 50 ms) caused intermittent communication errors. We inspected the correlation of 20-Hz data between the sonic anemometers to reasonably confirm optimal synchronization. If too many sequential missing communications occurred from any of the K-probes or A-probes, then the CR3000 power cycled and rebooted those anemometers. The CR3000 recorded the wind velocities along the orthogonal axes (u , v , and w) and sonic virtual temperature (T) from each anemometer, the CSAT3/CSAT3V diagnostics, and the number of missing communications with each K-probe/A-probe. All data were processed and analyzed in cardinal coordinates (u = east, v = north, w = west). For all

TABLE 1. Summary of experimental setup. Abbreviations for designs are K stands for K-probe, A stands for A-probe, C stands for CSAT3, V stands for CSAT3V. Units are labeled 1–12. Sonic anemometers in position 3 were not manipulated horizontally.

Week	Dates vertical	Dates horizontal	Position				
			1	2	3	4	5
1	14–18, and 21–24 Jun	18–21 Jun	V12	K2	C8	V11*	A5
2	24–28 Jun	28 Jun–2 Jul	K2*	K3	C8	A5	V11
3	2–5 Jul	5–9 Jul	K1	K3*	C7	A5	V11
4	9–12 Jul	12–16 Jul	V12*	A4	C7	K1	V11
5	16–19 Jul	19–23 Jul	A4	V12**	C7	K3	V10*
6	23–26 Jul	26–30 Jul	C8*	A4	C9	V10	K3
7	30 Jul–2 Aug	2–6 Aug	K1	A5	C9	V10	A4*
8	6–9 Aug	9–13 Aug	A5*	V10	C9	A6	K1
9	13–17 Aug	17–20 Aug	V10	K1*	C8	A6	K2
10	20–23 Aug	23–27 Aug	K2	A6	C8	V11	C9*
11	27–30 Aug	30 Aug–3 Sep	A6*	K2	C7	V12	A4
12	3–6 Sep	6–24 Sep	K3	A6	C9	C7*	V12

* A wildcard.

** Sensor damage; data omitted from analysis.

vertically mounted anemometers this was equivalent to sonic coordinates. For anemometers mounted horizontally, the data were transposed (i.e., $v = -w$ and $w = v$) (Fig. 1). We processed the 20-Hz time series data by applying a median despiker (Frank et al. 2014) to remove outliers. Then, we evaluated each half hour of data for quality assurance, quality control (QA/QC) based on summary statistics (mean, standard deviation, skewness, kurtosis, and missing data) (Vickers and Mahrt 1997) and removed all data from an anemometer for each half hour deemed questionable from our analysis. In preliminary analysis of the half-hour data, we observed that model residuals were biased from easterly winds through the scaffold and mounting structure. To minimize the influence of adjacent anemometers and the scaffold on wind flow, we omitted wind from these directions and performed all analyses on data with a half-hour average wind direction between 210° and 330° . For these remaining half hours, we inspected the power spectra of u , v , w , and T for increased high-frequency energy or a knee associated with wakes caused by the scaffold and mounting structure (Barthlott and Fiedler 2003). We calculated the sensible heat flux (H) for each sonic anemometer using the planar fit rotation (Lee et al. 2004a) and buoyancy correction (Massman and Lee 2002) with all ancillary meteorological measurements, including vapor flux, taken from the nearby GLEES AmeriFlux site (Frank et al. 2014).

b. Shadow correction

All sonic anemometers were operated without shadow correction. For the K-probe this required turning off shadow correction in the internal settings. For the others, there are no shadow correction algorithms

available within the instruments. Transducer shadowing for orthogonal anemometers is typically characterized as a linear drop as the wind becomes parallel to the acoustic path (Kaimal 1979; Wyngaard and Zhang 1985). The K-probe has a transducer pathlength $L = 148$ mm and diameter $d = 9.6$ mm with $L/d = 15$. The equation currently implemented by the manufacturer is slightly different from the one originally proposed for the K-probe (Kaimal et al. 1990) or for $L/d = 15$ (Kaimal 1979) and is defined as $U_{\text{meas}} = (1 - 0.16 + 0.16\theta/70)U$ for $\theta \leq 70^\circ$ and $U_{\text{meas}} = U$ for $\theta > 70^\circ$, where U and U_{meas} are the original and measured wind velocities, respectively, and θ is the angle between the wind and the acoustic path. We refer to this as the Kaimal correction. We created a second dataset where we applied this correction to every 20-Hz measurement for the K-probe, while leaving the other anemometers unchanged.

There is no consensus on how to characterize shadowing in nonorthogonal sonic anemometers. Because the A-probe is constructed with the same transducer diameter and pathlength as the K-probe, we assumed that shadowing in the A-probe could to a first approximation be characterized by applying the Kaimal correction to the three nonorthogonal transducer pairs. Horst et al. (2015) proposed that variations on this correction might be appropriate for the CSAT3. The CSAT3 has $L = 116$ mm, $d = 6.4$ mm, $L/d = 18$, which from Kaimal (1979) corresponds to $U_{\text{meas}} = (1 - 0.16 + 0.16\theta/75)U$ for $\theta \leq 75^\circ$ and $U_{\text{meas}} = U$ for $\theta > 75^\circ$. We chose to use the 70° formulation for the CSAT3 and CSAT3V, and created a third dataset where we applied the same Kaimal correction to every 20-Hz measurement for all anemometers.

The original Kaimal (1979) correction addresses shadowing from a single transducer pair, and in the case

of the K-probe, which was designed with maximum separation between pairs, the shadowing from the other transducers was considered negligible. This might not be the case with nonorthogonal designs, where all pairs are clustered close together, creating the possibility of cross-transducer shadowing or shadowing from the network of support arms. Knowledge of how to characterize this is limited. Instead, we propose that doubling the Kaimal correction could roughly approximate the true combined shadowing of both transducers and the support structure in a nonorthogonal anemometer. We define the double-Kaimal correction as $U_{\text{meas}} = (1 - 0.32 + 0.32\theta/70)U$ for $\theta \leq 70^\circ$ and $U_{\text{meas}} = U$ for $\theta > 70^\circ$, and created a fourth dataset where we applied the Kaimal correction to the K-probe and the double-Kaimal correction to the others for all 20-Hz measurements.

c. Analysis

1) INTERCOMPARISON (HYPOTHESIS A VS B₁ OR B₂)

Our first analysis was an intercomparison between the different designs of sonic anemometers, focusing only on the part of the experiment when the instruments were vertically mounted. We tested the standard deviations of wind velocities along the orthogonal axes (σ_u , σ_v , and σ_w) and sonic virtual temperature (σ_T), turbulent kinetic energy [$\text{TKE} = (\sigma_u^2 + \sigma_v^2 + \sigma_w^2)/2$], the ratio of vertical to horizontal TKE [$\text{VHTKE} = \sigma_w^2/(\sigma_u^2 + \sigma_v^2)$], and H . Considering the complexity of the experimental setup, the unbalanced nature of only deploying 5 of the 12 units at a time, and the objective of both testing and quantifying the differences between designs, we analyzed the intercomparison using a set of Bayesian models (see supplemental text). Instead of directly comparing all combinations of sonic anemometers to each other, the models normalized each half hour by a pooled reference parameter and then estimated the percent difference between each anemometer from the average of all instruments. The models fit the measured data against categorical data for unit, position, and time in a manner similar to an ANOVA or generalized linear model (GLM) with categorical data (Kruschke 2010). The pooled reference is the model parameter associated with time and represents what the average measurement would have been had every sonic anemometer been deployed at the same time (Fig. 2). Clark (2005) pointed out that a strength of hierarchical Bayesian analysis is that it can account for variation that cannot be measured directly. In our case this applies to the fact that no absolute standard exists to measure the true wind velocity; instead, the Bayesian model uses the pooled reference parameter to account for this stochastic variation from half hour to half hour. To mitigate the possibility of

unequal measurements due to flow distortions from the scaffold or mounting hardware, the models were adjusted for each position. Finally, the results from each unit were hierarchically combined to determine the percent difference for each sonic anemometer design from the average of all instruments.

To improve our interpretation of the K-probe results, we added a 13th sonic anemometer to the intercomparison analysis, a single Vx-probe (Applied Technologies Inc., serial number 971202) associated with the GLEES AmeriFlux eddy-covariance system (Frank et al. 2014). The Vx-probe is an orthogonal sonic anemometer similar to the K-probe, with the only significant differences being that all paths share the same volume and that the u and v axes are rotated 45° (Fig. 1b). This instrument was located 1.7 m below the bottom row and was operated independent of the experiment. Consistent with the experiment, it was aimed west, its level checked for $\leq 0.2^\circ$ accuracy, its system clock synchronized to within a few seconds, and because of its geometry, its original σ_u and σ_v measurements were rotated 45° . The Vx-probe was always operated with shadow correction on.

To investigate the impact of shadow correction, we ran the set of models on four distinct datasets: 1) with shadow correction applied only to the Vx-probe, 2) shadow correction applied only to orthogonal sonic anemometers (K-probe and Vx-probe) reflecting manufacturers' current recommendations for all instruments, 3) with shadow correction applied to all instruments, and 4) with shadow correction applied to all instruments but with double-Kaimal shadow correction applied to nonorthogonal instruments. Dataset 2 was specifically used to test hypothesis A versus B₁ or B₂. Datasets 1, 3, and 4 were used to explain hypothesis B₁ versus B₂ by demonstrating the impact that omission/addition of shadow correction has on measurements.

We evaluated the Bayesian models using Markov chain Monte Carlo (MCMC) methods (Kruschke 2010). Each MCMC analysis contained three independent chains of 100 000 steps each: 1000 steps to adapt the chain, 24 000 for burn-in, and 75 000 to construct posterior distributions. One in every 50 steps was saved to remove autocorrelation, or in total: 1500 steps per chain or 4500 steps per analysis. Chains were evaluated for convergence by examining trace plots, density plots, effective size, Gelman–Rubin diagnostic, and autocorrelation. We conducted all analyses using R (version 3.1.0, R Core Team 2015) with packages CODA (Plummer et al. 2006) and rjags (Plummer 2015) within RStudio (version 0.98.953, RStudio Team 2015) and implementing MCMC analysis with JAGS (version 3.4.0, Plummer 2003). Finally, we present testable

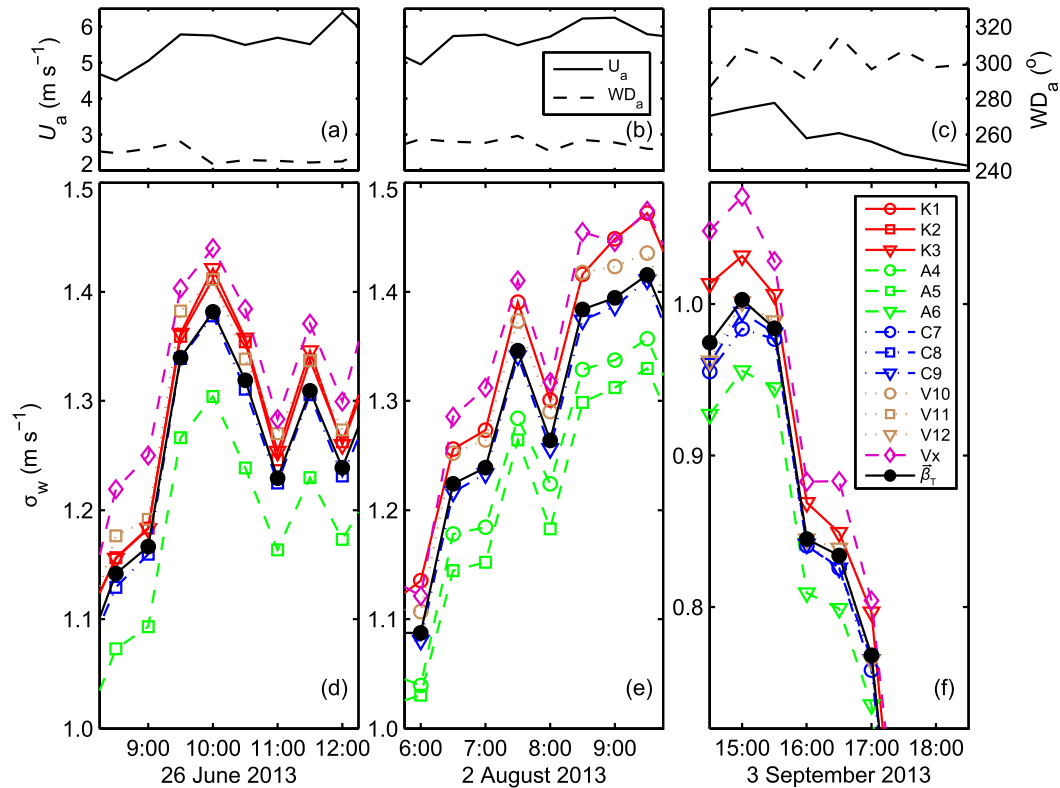


FIG. 2. Illustrative time series of (a)–(c) average half-hour wind velocity (U_a) and direction (WD_a) and (d)–(f) σ_w relating five sonic anemometers under test (K = K-probe, A = A-probe, C = CSAT3, V = CSAT3V; units labeled 1–12), and the GLEES AmeriFlux Vx-probe. The pooled reference β_r is a Bayesian model parameter and is a combined average of measurements and predictions for all 13 sonic anemometers. Data are from weeks (a) 2, (b) 7, and (c) 12 (Table 1). Values are associated with the analysis of Table 3, where shadow correction was applied only to orthogonal sonic anemometers (K-probe and Vx-probe) reflecting manufacturers' current recommendations for all instruments. Mountain standard time (MST) is used throughout.

differences between Bayesian posterior parameter distributions as odds ratios, defined as the probability that parameter $A > \text{parameter } B$ divided by the probability that parameter $A \leq \text{parameter } B$. Unlike traditional statistical analysis, with Bayesian analysis the difference between two model parameters can be tested by directly comparing their posterior probability distributions; the resulting odds ratio represents a simple yet statistically meaningful metric to judge the strength of that difference. We avoid declaring statistical significance, though we interpret odds less than 4:1 as little or no evidence and greater than 5:1 as strong evidence (Kass and Raftery 1995).

2) INTERNAL CONSISTENCY (HYPOTHESIS B_1 VS B_2)

Our second analysis was a test of the internal consistency of each sonic anemometer design in order to answer the question of whether each design treats the three dimensions equally, and if not, can this be explained by hypothesis B_1 or B_2 . Here the dataset was expanded to

include data from both vertically and horizontally mounted instruments. The first step was to predict the impact of shadow correction on the internal consistency of each design. This analysis quantified the difference in datasets between 1) without and with shadow correction applied to all instruments and 2) without and with shadow correction applied to all instruments but with double-Kaimal shadow correction applied to non-orthogonal instruments. We achieved this by using a set of simpler Bayesian models (supplemental text). Only one in 75 steps was saved, or in total: 1000 steps per chain or 3000 steps per analysis.

Next, we analyzed the observed change when the anemometers were manipulated horizontally. This was done with a similar analysis to the intercomparison, with the most important change in the structure of these Bayesian models being the addition of parameters related to the mounting orientation (supplemental text). Similar to the other models, three independent MCMC chains of 100 000 steps per run, and one in 75 steps were saved, or in total, 1000 steps per chain or 3000 steps per

analysis. We ran the set of models on two distinct datasets: 1) without and 2) with shadow correction applied to all instruments.

3. Results

a. Turbulent mixing near the sonic anemometers

Throughout the experiment, the sonic anemometers were exposed to strong turbulence characterized by large eddies with minimal flow distortions from the scaffold. The GLEES AmeriFlux site (Frank et al. 2014) measured the mean friction velocity (u_*) for all analyzed half hours at 0.60 m s^{-1} , with 85% of the half hours experiencing greater than the 0.20 m s^{-1} threshold empirically determined for the site (Frank et al. 2014); this was different between day (97% of half hours $> 0.20 \text{ m s}^{-1}$) and night (72% of half hours $> 0.20 \text{ m s}^{-1}$). Below this threshold, eddies may not sufficiently mix within the canopy, resulting in questionable ecosystem flux measurements, but turbulence around the anemometers can still be sufficient for a valid intercomparison. The eddies at the height of the sonic anemometers were large, with analysis of planar fit rotated u , v , w , and T spectral and u_* and H cospectra revealing median normalized peak frequencies (η_x) between 0.09 and 0.42 (Massman and Clement 2004), which translate using Taylor's hypothesis to length scales between 53 m (for w) and 263 m (for u). These eddies are much larger than the distance between anemometers in the jig (1.4 m) or to the Vx-probe (1.7 m). Even though we only considered half-hourly data with average winds between 210° and 330° , the scaffold and mounting structure could still cause flow distortions (Wieringa 1980; Wyngaard et al. 1982) that can be evaluated by the presence of high-frequency distortions or knees in the spectral (Barthlott and Fiedler 2003). Spectral analysis of individual half hours for each sonic anemometer (supplemental Figs. 1–4) showed minimal evidence of wakes in the u or w measurements, with the notable exception of a plateau of high-frequency energy visible in the CSAT3V u spectra, which is most likely attributable to low signal-to-noise ratio in that dimension for the design. Distortions or knees occurred more often in the v spectra, which is possibly due to wakes caused by wind blowing laterally across the sonic anemometers within the jig, though we estimate that this occurred in less than 5% of the spectra. Almost every T spectrum has a high-frequency plateau, which may reflect a fundamental limit to the signal-to-noise ratio in sonic thermometry rather than flow distortion. Finally, for each analysis the Bayesian model did estimate slightly different slope parameters for each position

(supplemental text). The standard deviation among all β_{1p} for σ_v and σ_w was 0.8%, while for σ_u it was 2.1%. This suggests that mean flow distortions were greater for winds that flowed through the scaffold (i.e., along the u axis), though the Bayesian model accounts for these differences. Based on these metrics, there is a reasonable expectation that all sonic anemometers were subjected to the same turbulent conditions for each half hour.

b. Intercomparison

A total of 11 349 sets of measurements from the 13 sonic anemometers distributed over 1968 half hours were considered for the intercomparison. Restricting the average wind direction to between 210° and 330° reduced the data to between 8423 and 8460 sets and 1498 and 1508 half hours, depending on the nuances in wind directions produced after the application of the various shadow correction algorithms.

1) NO SHADOW CORRECTION

When no shadow correction was applied, the K-probe had low measurements of σ_u , σ_v , and TKE; the A-probe had low measurements of σ_w and H ; and the two orthogonal probes had higher partitioning of vertical to horizontal TKE (Table 2). The K-probe had lower measurements of σ_u , σ_v , and TKE than all the other anemometers, with the smallest odds ratio among all comparisons being 14.6:1 (at least 94% probable). The A-probe measured the lowest σ_w and H (minimum odds of 5.6:1, or 85% probable). There was a minimum of 12.2:1 odds (92% probable) that the orthogonal anemometers had the highest VHTKE, though the K-probe and Vx-probe were quite different (49.6:1 odds or 98% probable). There was no obvious difference ($<1\%$) between the virtual temperature measurements among the replicated anemometers (maximum odds of a difference of 1.4:1 or 59% probable).

2) SHADOW CORRECTION APPLIED TO ORTHOGONAL ANEMOMETERS

When shadow correction was applied only to the orthogonal anemometers, there were fewer obvious differences between anemometers for σ_u or σ_v ; some nuanced differences between σ_w , H , and TKE; and an obvious separation between orthogonal versus nonorthogonal anemometers in how they partition vertical to horizontal TKE (Table 3). The maximum difference between all measurements of σ_u and σ_v was 4%, though some differences among the anemometers were strongly supported by odds ratios as high as 18.1:1, or 95% probable. The differences in σ_w and TKE were a little more varied, though the A-probe was fairly low for both, and of note the

TABLE 2. Intercomparison of sonic anemometer designs with shadow correction (bold) applied only to Vx-probe. This is the relative percent difference between each anemometer from the average of all instruments as determined from the Bayesian model parameter β'_{lp} (see the online supplement). Vertically mounted sensors only. Half-hour standard deviations (σ) of the three dimensions of wind velocity (u , v , and w), and sonic anemometer virtual temperature (T), turbulent kinetic energy (TKE), the ratio of vertical to horizontal (VHTKE), and sensible heat flux (H). Bayesian posterior distributions for relative differences summarized as mean $\pm$ standard deviation. Ratios refer to the odds that the slope for the design listed in a row is greater than the slope for the design listed in a column.

Measurement	Design	Relative diff (%)	Odds ratio (row > column)				
			K-probe	A-probe	CSAT3	CSAT3V	Vx-probe*
σ_u	K-probe	$-11\% \pm 3.6\%$	—	0.0	0.0	0.1	0.0
	A-probe	$+1\% \pm 6.5\%$	30.0	—	0.2	0.4	0.3
	CSAT3	$+4\% \pm 7.2\%$	47.9	4.6	—	1.0	4.0
	CSAT3V	$+5\% \pm 13.5\%$	14.6	2.5	1.0	—	1.9
	Vx-probe*	$+2\% \pm 0.1\%$	186.5	3.9	0.3	0.5	—
σ_v	K-probe	$-6\% \pm 5.1\%$	—	0.1	0.0	0.0	0.0
	A-probe	$-0\% \pm 4.5\%$	15.0	—	0.1	0.1	0.6
	CSAT3	$+3\% \pm 3.4\%$	31.6	10.8	—	1.7	20.7
	CSAT3V	$+3\% \pm 10.0\%$	22.9	7.0	0.6	—	11.1
	Vx-probe*	$+0\% \pm 0.2\%$	27.5	1.5	0.0	0.1	—
σ_w	K-probe	$+1\% \pm 4.7\%$	—	13.1	2.8	0.6	0.0
	A-probe	$-5\% \pm 5.8\%$	0.1	—	0.1	0.1	0.0
	CSAT3	$-0\% \pm 5.9\%$	0.4	9.7	—	0.3	0.0
	CSAT3V	$+2\% \pm 4.1\%$	1.8	15.9	3.9	—	0.0
	Vx-probe*	$+6\% \pm 0.1\%$	36.5	62.4	35.3	30.9	—
TKE	K-probe	$-13\% \pm 3.7\%$	—	0.0	0.0	0.0	0.0
	A-probe	$-1\% \pm 5.9\%$	33.4	—	0.1	0.2	0.1
	CSAT3	$+6\% \pm 8.6\%$	49.0	7.7	—	0.7	3.7
	CSAT3V	$+7\% \pm 13.1\%$	22.8	5.5	1.5	—	3.1
	Vx-probe*	$+3\% \pm 0.1\%$	154.2	14.8	0.3	0.3	—
VHTKE	K-probe	$+21\% \pm 7.5\%$	—	34.7	103.7	30.0	49.6
	A-probe	$-8\% \pm 12.8\%$	0.0	—	0.8	0.7	0.1
	CSAT3	$-8\% \pm 1.8\%$	0.0	1.3	—	0.8	0.0
	CSAT3V	$-7\% \pm 13.3\%$	0.0	1.3	1.2	—	0.1
	Vx-probe*	$+4\% \pm 0.4\%$	0.0	13.1	749.0	12.2	—
H	K-probe	$+2\% \pm 7.3\%$	—	7.9	4.1	1.3	0.1
	A-probe	$-5\% \pm 7.2\%$	—	—	0.2	0.1	0.0
	CSAT3	$-1\% \pm 4.4\%$	0.2	5.6	—	0.1	0.0
	CSAT3V	$+2\% \pm 3.8\%$	0.8	12.1	7.0	—	0.0
	Vx-probe*	$+9\% \pm 0.1\%$	18.5	51.9	70.4	63.3	—
σ_T	K-probe	$+0\% \pm 7.2\%$	—	1.4	1.2	1.4	0.2
	A-probe	$-1\% \pm 7.0\%$	0.7	—	0.8	0.9	0.1
	CSAT3	$-0\% \pm 4.3\%$	0.8	1.2	—	1.2	0.1
	CSAT3V	$-0\% \pm 4.9\%$	0.7	1.2	0.9	—	0.0
	Vx-probe*	$+3\% \pm 0.3\%$	6.0	8.6	13.4	24.7	—

* Unreplicated instrument from nearby eddy-covariance system.

A-probe was 8% lower than the K-probe in σ_w (odds of 23.6:1 or 96% probable) and 6% lower than the CSAT3 in TKE (odds of 8.5:1 or 89% probable). The K-probe had higher H than the nonorthogonal anemometers, measuring 12% higher than the A-probe (odds of 8.6:1 or 90% probable) and 7% higher than the CSAT3 or CSAT3V (minimum of 5.4:1 odds or 84% probable). The VHTKE separated into two groups: orthogonal (odds of a difference between K-probe and Vx-probe of 2.9:1 or 74% probable) and nonorthogonal (maximum odds of a difference between any of the three of 1.3:1 or 57% probable) with the orthogonal anemometers partitioning at least 11% higher VHTKE (minimum odds of 7.6:1 or 88% probable).

3) SHADOW CORRECTION APPLIED TO ALL ANEMOMETERS

Once the Kaimal shadow correction was applied to all of the anemometers, there were fewer differences: the ATI anemometers measured lower σ_u , σ_v , and TKE; the A-probe measured lower σ_w and H ; and the orthogonal anemometers partitioned more vertical than horizontal TKE, though that difference was lessened (Table 4). The ATIs measured 4% less σ_u and σ_v and 7% less TKE than the CSAT3s (minimum odds of 4.6:1 or 82% probable), with the exception of comparing to the CSAT3V σ_u , which was too noisy due to the design's loss of sensitivity

TABLE 3. Intercomparison of sonic anemometer designs with shadow correction (bold) applied only to orthogonal sonic anemometers (K-probe and Vx-probe) reflecting manufacturers' current recommendations for all instruments. This is the relative percent difference between each anemometer from the average of all instruments as determined from the Bayesian model parameter β'_{1_b} (see the online supplement). Vertically mounted sensors only. Half-hour standard deviations (σ) of the three dimensions of wind velocity (u , v , and w), turbulent kinetic energy (TKE), the ratio of vertical to horizontal TKE (VHTKE), and sensible heat flux (H). Bayesian posterior distributions for relative differences summarized as mean $\pm$ standard deviation. Ratios refer to the odds that the slope for the design listed in a row is greater than the slope for the design listed in a column.

Measurement	Design	Relative diff (%)	Odds ratio (row > column)				
			K-probe	A-probe	CSAT3	CSAT3V	Vx-probe*
σ_u	K-probe	-1% $\pm$ 2.9%	—	1.5	0.2	0.4	0.2
	A-probe	-2% $\pm$ 6.5%	0.7	—	0.2	0.4	0.3
	CSAT3	+2% $\pm$ 6.8%	5.2	4.2	—	1.0	4.2
	CSAT3V	+2% $\pm$ 12.9%	2.3	2.3	1.0	—	1.8
	Vx-probe*	-0% $\pm$ 0.1%	6.5	3.5	0.2	0.5	—
σ_v	K-probe	-1% $\pm$ 1.6%	—	2.9	0.1	0.1	5.4
	A-probe	-2% $\pm$ 5.1%	0.3	—	0.1	0.1	0.5
	CSAT3	+2% $\pm$ 4.3%	8.2	7.1	—	0.9	13.8
	CSAT3V	+2% $\pm$ 1.8%	18.1	12.4	1.1	—	47.9
	Vx-probe*	-1% $\pm$ 0.2%	0.2	1.9	0.1	0.0	—
σ_w	K-probe	+3% $\pm$ 3.4%	—	23.6	9.3	4.5	0.1
	A-probe	-5% $\pm$ 5.2%	0.0	—	0.1	0.1	0.0
	CSAT3	-1% $\pm$ 5.4%	0.1	8.8	—	0.2	0.0
	CSAT3V	+1% $\pm$ 4.2%	0.2	15.1	4.3	—	0.0
	Vx-probe*	+6% $\pm$ 0.1%	17.8	57.4	39.2	29.0	—
TKE	K-probe	-1% $\pm$ 3.3%	—	7.8	0.2	0.2	0.1
	A-probe	-4% $\pm$ 5.1%	0.1	—	0.1	0.2	0.1
	CSAT3	+2% $\pm$ 8.1%	5.0	8.5	—	0.6	3.3
	CSAT3V	+4% $\pm$ 12.0%	4.1	6.6	1.6	—	3.3
	Vx-probe*	-0% $\pm$ 0.1%	9.8	15.4	0.3	0.3	—
VHTKE	K-probe	+8% $\pm$ 7.8%	—	7.8	30.9	7.6	0.3
	A-probe	-4% $\pm$ 13.3%	0.1	—	0.8	0.8	0.1
	CSAT3	-3% $\pm$ 2.4%	0.0	1.3	—	0.8	0.0
	CSAT3V	-3% $\pm$ 12.5%	0.1	1.3	1.2	—	0.1
	Vx-probe*	+9% $\pm$ 0.4%	2.9	11.9	320.4	12.2	—
H	K-probe	+5% $\pm$ 7.3%	—	14.7	10.5	5.6	0.1
	A-probe	-6% $\pm$ 6.9%	0.1	—	0.2	0.1	0.0
	CSAT3	-2% $\pm$ 4.3%	0.1	5.9	—	0.1	0.0
	CSAT3V	+1% $\pm$ 3.6%	0.2	12.9	7.0	—	0.0
	Vx-probe*	+8% $\pm$ 0.1%	7.3	54.6	89.0	87.2	—

* Unreplicated instrument from nearby eddy-covariance system.

(posterior standard deviation of 12.6%) for meaningful comparisons. The A-probe measured at least 3% less σ_w than any other anemometer (minimum odds of 5.3:1 or 84% probable) and measured 6% less H than the K-probe (odds of 4.0:1 or 80% probable). And the grouping in VHTKE partitioning was still apparent between orthogonal versus nonorthogonal, though the orthogonal anemometers were only 5% higher on average with some odds ratios as low as 2.8:1 (74% probable).

4) DOUBLE-KAIMAL SHADOW CORRECTION APPLIED TO NONORTHOGONAL ANEMOMETERS

Two distinctions emerge after applying the double-Kaimal shadow correction to the nonorthogonal anemometers: the ATIs measure less TKE than the CSAT3s and there is no longer a separation between orthogonal

versus nonorthogonal in the partitioning of vertical and horizontal TKE (Table 5). The minimum odds that the ATIs measure less TKE are 5.0:1 (83% probable). The ATI measurements of σ_u , σ_v , and σ_w follow a similar trend when compared to the CSAT3 (minimum odds of 5.3:1 or 84% probable) though much of the evidence when compared to the CSAT3V was weak. There were no obvious patterns of grouping in the VHTKE partitioning, with the maximum odds of any difference being 4.9:1 (83% probable) and the CSAT3 having the highest VHTKE, though this was weakly supported (minimum odds of 1.4:1 or 58% probable).

c. Internal consistency

A total of 19 588 sets of measurements from the 12 sonic anemometers distributed over 4158 half hours

TABLE 4. Intercomparison of sonic anemometer designs with shadow correction (bold) applied to all instruments. This is the relative percent difference between each anemometer from the average of all instruments as determined from the Bayesian model parameter β'_{1p} (see the online supplement). Vertically mounted sensors only. Half-hour standard deviations (σ) of the three dimensions of wind velocity (u , v , and w), turbulent kinetic energy (TKE), the ratio of vertical to horizontal (VHTKE), and sensible heat flux (H). Bayesian posterior distributions for relative differences summarized as mean $\pm$ standard deviation. Ratios refer to the odds that the slope for the design listed in a row is greater than the slope for the design listed in a column.

Measurement	Design	Relative diff (%)	Odds ratio (row > column)				
			K-probe	A-probe	CSAT3	CSAT3V	Vx-probe*
σ_u	K-probe	-2% $\pm$ 3.5%	—	0.7	0.1	0.5	0.1
	A-probe	-1% $\pm$ 6.0%	1.4	—	0.2	0.6	0.5
	CSAT3	+3% $\pm$ 7.2%	7.6	4.6	—	1.6	6.9
	CSAT3V	+1% $\pm$ 12.6%	1.9	1.6	0.6	—	1.5
	Vx-probe*	-1% $\pm$ 0.1%	6.9	1.9	0.1	0.7	—
σ_v	K-probe	-3% $\pm$ 1.5%	—	0.1	0.0	0.0	6.7
	A-probe	-1% $\pm$ 3.9%	7.0	—	0.1	0.0	13.0
	CSAT3	+2% $\pm$ 3.7%	23.7	11.2	—	0.7	34.2
	CSAT3V	+3% $\pm$ 1.1%	94.7	28.0	1.5	—	408.1
	Vx-probe*	-3% $\pm$ 0.1%	0.1	0.1	0.0	0.0	—
σ_w	K-probe	-0% $\pm$ 3.0%	—	5.3	0.2	0.4	0.1
	A-probe	-3% $\pm$ 6.1%	0.2	—	0.1	0.1	0.1
	CSAT3	+2% $\pm$ 4.3%	4.1	8.3	—	3.0	0.3
	CSAT3V	+1% $\pm$ 2.7%	2.4	8.0	0.3	—	0.0
	Vx-probe*	+3% $\pm$ 0.1%	16.6	18.7	3.8	21.2	—
TKE	K-probe	-4% $\pm$ 3.0%	—	0.3	0.1	0.1	0.1
	A-probe	-3% $\pm$ 5.4%	3.6	—	0.1	0.2	1.0
	CSAT3	+4% $\pm$ 7.9%	15.2	10.3	—	1.2	14.2
	CSAT3V	+4% $\pm$ 11.0%	8.2	5.9	0.8	—	7.1
	Vx-probe*	-3% $\pm$ 0.1%	11.8	1.0	0.1	0.1	—
VHTKE	K-probe	+3% $\pm$ 5.8%	—	2.8	7.5	3.9	0.3
	A-probe	-1% $\pm$ 14.0%	0.4	—	0.8	1.2	0.2
	CSAT3	-1% $\pm$ 3.8%	0.1	1.2	—	1.6	0.0
	CSAT3V	-2% $\pm$ 12.8%	0.3	0.9	0.6	—	0.2
	Vx-probe*	+5% $\pm$ 0.4%	3.0	4.2	45.4	6.1	—
H	K-probe	+1% $\pm$ 7.2%	—	5.1	1.5	2.2	0.1
	A-probe	-4% $\pm$ 7.9%	0.2	—	0.2	0.2	0.0
	CSAT3	+1% $\pm$ 6.2%	0.7	6.0	—	1.9	0.0
	CSAT3V	-0% $\pm$ 4.4%	0.5	5.5	0.5	—	0.0
	Vx-probe*	+5% $\pm$ 0.1%	7.8	20.8	22.6	36.8	—

* Unreplicated instrument from nearby eddy-covariance system.

were considered for the internal consistency test. Restricting the average wind direction to between 210° and 330° reduced the data to between 14 310 and 14 371 sets and between 3096 and 3100 half hours, depending on the nuances in wind directions produced after the application of the various shadow correction algorithms.

1) PREDICTED CHANGE WHEN MANIPULATED

The first part of the internal consistency test was to predict the relative change in slope following the manipulation. For hypothesis B₁, we formulated predictions based on deduction (Table 6). First, we predicted that there would be no changes in the K-probe. Second, because B₁ predicts a 1D error associated with the non-orthogonal w axis, we predicted that any error in σ_w would be transposed into σ_v when the sonic is rotated

around the u axis. Similarly, as the error is moved into σ_v , we predicted that σ_w would increase by a corresponding amount. Based on the -8% difference in σ_w measured with the A-probe relative to the K-probe (Table 3), we predicted for the A-probe and CSAT3 that σ_v would decrease 8% while σ_w increased 8%. The CSAT3V was modified to potentially eliminate the measurement errors in w . Because we do not know if this modification was successful, we allowed for two possible predictions: either there would be no change similar to the K-probe or the response would be the same as the other nonorthogonal sensors.

We used hypothesis B₂ to predict how much the wind measurements for each vertically mounted sonic anemometer were underestimated due to transducer/structural shadowing. This was done by comparing the original dataset to versions with various implementations

TABLE 5. Intercomparison of sonic anemometer designs with shadow correction (**bold**) applied to all instruments; double-Kaimal shadow correction applied to nonorthogonal instruments (*italics*). This is the relative percent difference between each anemometer from the average of all instruments as determined from the Bayesian model parameter β_{1D}^I (see the online supplement). Vertically mounted sensors only. Half-hour standard deviations (σ) of the three dimensions of wind velocity (u , v , and w), turbulent kinetic energy (TKE), the ratio of vertical to horizontal TKE (VHTKE), and sensible heat flux (H). Bayesian posterior distributions for relative differences summarized as mean $\pm$ standard deviation. Ratios refer to the odds that the slope for the design listed in a row is greater than the slope for the design listed in a column.

Measurement	Design	Relative diff	Odds ratio (row > column)				
			K-probe	A-probe	CSAT3	CSAT3V	Vx-probe*
σ_u	K-probe	$-2\% \pm 4.8\%$	—	0.2	0.1	0.5	0.1
	A-probe	$-1\% \pm 5.4\%$	4.1	—	0.2	0.9	2.6
	CSAT3	$+4\% \pm 7.0\%$	10.7	5.3	—	2.4	11.7
	CSAT3V	$+0\% \pm 12.8\%$	2.0	1.1	0.4	—	1.5
	Vx-probe*	$-1\% \pm 0.1\%$	7.0	0.4	0.1	0.7	—
σ_v	K-probe	$-5\% \pm 1.9\%$	—	0.0	0.0	0.0	5.3
	A-probe	$-1\% \pm 1.9\%$	38.5	—	0.1	0.0	85.5
	CSAT3	$+3\% \pm 4.0\%$	43.6	15.3	—	0.6	59.8
	CSAT3V	$+4\% \pm 2.0\%$	106.1	39.2	1.5	—	224.0
	Vx-probe*	$-5\% \pm 0.1\%$	0.2	0.0	0.0	0.0	—
σ_w	K-probe	$-3\% \pm 3.3\%$	—	0.2	0.0	0.1	0.1
	A-probe	$-0\% \pm 6.2\%$	4.8	—	0.1	1.1	1.2
	CSAT3	$+4\% \pm 5.1\%$	25.6	8.3	—	20.8	24.4
	CSAT3V	$-1\% \pm 1.4\%$	12.6	0.9	0.0	—	1.6
	Vx-probe*	$-1\% \pm 0.1\%$	17.1	0.8	0.0	0.6	—
TKE	K-probe	$-7\% \pm 1.9\%$	—	0.0	0.0	0.1	0.0
	A-probe	$-1\% \pm 2.4\%$	50.7	—	0.1	0.2	63.3
	CSAT3	$+7\% \pm 9.5\%$	29.4	12.3	—	2.6	30.0
	CSAT3V	$+3\% \pm 9.5\%$	17.4	5.0	0.4	—	16.0
	Vx-probe*	$-6\% \pm 0.1\%$	20.2	0.0	0.0	0.1	—
VHTKE	K-probe	$-1\% \pm 6.4\%$	—	0.6	0.2	1.9	0.3
	A-probe	$+1\% \pm 12.6\%$	1.7	—	0.7	2.2	1.2
	CSAT3	$+2\% \pm 5.4\%$	4.3	1.4	—	4.4	4.9
	CSAT3V	$-3\% \pm 10.7\%$	0.5	0.5	0.2	—	0.3
	Vx-probe*	$+1\% \pm 0.4\%$	3.2	0.8	0.2	3.7	—
H	K-probe	$-2\% \pm 7.0\%$	—	0.9	0.1	0.9	0.1
	A-probe	$-1\% \pm 9.3\%$	1.1	—	0.2	1.1	0.2
	CSAT3	$+4\% \pm 4.8\%$	8.2	6.0	—	16.9	5.6
	CSAT3V	$-1\% \pm 3.2\%$	1.1	0.9	0.1	—	0.0
	Vx-probe*	$+2\% \pm 0.1\%$	8.1	5.4	0.2	33.4	—

* Unreplicated instrument from nearby eddy-covariance system.

of the Kaimal and double-Kaimal corrections for each anemometer. Assuming the Kaimal equation correctly predicts shadowing for the K-probe, σ_u , σ_v , σ_w , and H were inaccurate by -11.7% , -6.3% , -2.3% , and -3.2% , respectively. For the nonorthogonal anemometers, we proposed that shadowing could be predicted by either the Kaimal correction or the double-Kaimal correction. For the A-probe, this means that σ_u , σ_v , σ_w , and H were wrongly measured between -0.8% , -2.3% , -5.1% , and 5.1% (Kaimal correction) and -2.0% , -5.0% , -10.5% , and -10.2% (double-Kaimal correction), respectively. For the CSAT3, σ_u , σ_v , σ_w , and H were erroneous between -1.2% , -2.8% , -5.3% , and -5.3% (Kaimal correction) and -2.7% , -6.2% , -10.7% , and -10.5% (double-Kaimal correction), respectively. Finally, for the CSAT3V, σ_u , σ_v , σ_w , and H

were incorrectly measured between $+1.1\%$, -2.9% , -2.3% , and -2.3% (Kaimal correction) and $+1.7\%$, -6.0% , -4.2% , and -3.6% (double-Kaimal correction), respectively.

Finally, we used hypothesis B₂ to predict how much these shadowing errors would change after the sonic anemometers were manipulated horizontally. For the K-probe this results in no change in any measurement (Table 6). Depending on the nonorthogonal anemometer and whether we applied the Kaimal correction or double-Kaimal correction, the predictions were that σ_v would decrease -4% to -9% , σ_u would decrease -2% to -9% , and σ_w would change either negative or positive between -9% to $+1\%$ (Table 6). All predicted changes $\geq |1\%|$ had an infinite odds ratio of being nonzero.

TABLE 6. Internal-consistency test of sonic anemometer designs with no shadow correction applied; the percent change in half-hour measurements when manipulated from vertical to horizontal mounting. Predictions for hypothesis B₁ (i.e., errors are associated with the w -axis) are hypothetical with magnitudes based on the results for σ_w in Table 3. There are two scenarios for the CSAT3V: either the modification to a true vertical transducer path eliminates w errors (a) or the errors still persist and the response is similar to the other nonorthogonal anemometers (b). Predictions for hypothesis B₂ (i.e., errors are associated with transducer shadowing) are based on two shadow correction algorithms (Kaimal and double Kaimal) and are determined from the Bayesian model parameter β'_{1O} (see the online supplement). The observed change is determined from the Bayesian model parameter β'_{1H} (see the online supplement). The Vx-probe is not included in this analysis. Half-hour standard deviations (σ) of the three dimensions of wind velocity (u , v , and w). Bayesian posterior distributions for the change summarized as mean $\pm$ standard deviation. Ratios refer to the odds that the observed change in slope is less or greater than zero depending on the sign.

Predicted change after horizontal manipulation						
Measurement	Design	Hypothesis B ₁ (%)	Hypothesis B ₂		Observed change (%)	Odds ratio
			All with Kaimal (%)	Orthogonal = Kaimal Nonorthogonal = double Kaimal (%)		
σ_u	K-probe	0%	$-0 \pm 0.2\%$	$-0 \pm 0.4\%$	$-3\% \pm 10.8\%$	3.0
	A-probe	0%	$-2 \pm 0.2\%$	$-5 \pm 0.4\%$	$-4\% \pm 6.4\%$	12.2
	CSAT3	0%	$-4 \pm 0.3\%$	$-9 \pm 0.5\%$	$-6\% \pm 5.8\%$	22.6
	CSAT3V	0%	$-3 \pm 0.2\%$	$-7 \pm 0.3\%$	$-8\% \pm 7.5\%$	23.4
σ_v	K-probe	0%	$+0 \pm 0.2\%$	$+0 \pm 0.2\%$	$-0\% \pm 4.2\%$	1.2
	A-probe	$\sim -8\%$	$-4 \pm 0.2\%$	$-9 \pm 0.2\%$	$-11\% \pm 2.8\%$	119.0
	CSAT3	$\sim -8\%$	$-5 \pm 0.3\%$	$-8 \pm 0.4\%$	$-11\% \pm 8.1\%$	33.9
	CSAT3V	0% ^a or $\sim -8\%$ ^b	$-4 \pm 0.2\%$	$-6 \pm 0.2\%$	$-9\% \pm 5.8\%$	41.3
σ_w	K-probe	0	$+0 \pm 0.2\%$	$+0 \pm 0.5\%$	$+1\% \pm 6.0\%$	2.5
	A-probe	$\sim +8\%$	$-1 \pm 0.2\%$	$-3 \pm 0.5\%$	$-3\% \pm 6.7\%$	6.4
	CSAT3	$\sim +8\%$	$+0 \pm 0.3\%$	$+1 \pm 0.7\%$	$+0\% \pm 11.2\%$	1.3
	CSAT3V	0% ^a or $\sim +8\%$ ^b	$-4 \pm 0.2\%$	$-9 \pm 0.4\%$	$+4\% \pm 6.6\%$	9.0

2) OBSERVED CHANGE WHEN MANIPULATED

The second part of the internal consistency test was to observe the relative change in each nonshadow-corrected anemometer after the horizontal manipulation. The K-probe changed minimally in all three dimensions; we observed a maximum change of -3% in σ_u but with a maximum odds ratio of only 3.0:1 (75% probable) (Table 6). Meanwhile, σ_v decreased considerably in all of the nonorthogonal anemometers; we observed a minimum change of -9% and a minimum odds ratio of 33.9:1 (97% probable) (Table 6). The probability that the K-probe had a different σ_v response than the nonorthogonal anemometers was at minimum 21.4:1 odds (96% probable). There was a decrease in σ_u ranging from 4% to 8% in all of the nonorthogonal anemometers (minimum odds of 12.2:1, or 92% probable) (Table 6). The response in σ_w in the nonorthogonal anemometers covered all possibilities: the A-probe decreased 3% (6.4:1 odds, or 86% probable), the CSAT3 was essentially unchanged (1.3:1 odds, or 57% probable of a slight increase), and the CSAT3V increased 4% (9.0:1 odds, or 90% probable) (Table 6). There was evidence that the change in the CSAT3V was higher than that of the A-probe (8.4:1 odds, or 89% probable). Otherwise, there was minimal evidence to suggest that any other responses were different when

comparing the designs (maximum odds ratio of 4.7:1, or 82% probable).

4. Discussion

Based on the results of the intercomparison (Table 3) and the internal consistency test (Table 6), we reject hypotheses A and B₁ in favor of B₂; that is, between these orthogonal and nonorthogonal designs, there is a difference in vertical wind velocity measurements that can be explained by the lack of correction for transducer/structural shadowing in the nonorthogonal sonic anemometers.

a. Is there a difference in vertical wind measurements between orthogonal and nonorthogonal anemometers?

We argue that orthogonal sonic anemometers measure higher vertical wind velocity than nonorthogonal transducer arrangements, a distinction most clearly supported by the difference in the partitioning of vertical and horizontal TKE (Table 3). This difference can be partially obscured, though, by the differences in total TKE among instruments from different manufacturers (Table 3). When comparing orthogonal versus non-orthogonal from a single manufacturer, measurements

of horizontal wind velocity were nearly identical, while σ_w was 8% higher in the orthogonal (K-probe vs A-probe; Table 3). When differences in total TKE are taken into consideration, the differences between one manufacturer's orthogonal versus another's non-orthogonal anemometer clearly follows the same pattern; that is, horizontal wind velocity and TKE was 3% higher with the CSAT3, while σ_w was 4% higher with the K-probe (Table 3). If all measurements on the K-probe were 3% higher, then it would measure similar horizontal wind velocity as the CSAT3, but σ_w would be 7% higher. Determining the actual amount of difference in TKE between manufacturers is difficult because we argue that nonorthogonal anemometers are missing some vertical energy. A reasonable approximation is that the Campbell Scientific anemometers measure 8% higher total TKE than the ATI instruments (e.g., Table 4, where shadow correction was applied to account for missing vertical energy), which corresponds to 4% higher velocity measurements in all dimensions, which is consistent with observations of σ_u and σ_v in Table 3. Based on the intercomparison results, we reject hypothesis A.

This intercomparison study has several strengths when judged against others that have compared orthogonal versus nonorthogonal sonic anemometers (Beyrich et al. 2002; Foken et al. 1997; Horst et al. 2015; Loescher et al. 2005; Mauder 2013; Mauder et al. 2007). First, we tested three replicates of each design. This is fairly uncommon, especially for replication of all designs tested, with the notable exception of Beyrich (2000) and Beyrich et al. (2002). Mauder et al. (2007) and Horst et al. (2015) also replicated several designs, including two K-probes and three (Mauder et al. 2007) or two (Horst et al. 2015) CSAT3s. Second, as discussed by Beyrich et al. (2002), the location of each sonic anemometer within an intercomparison setup can influence results. Mitigation of this is rarely found in the literature; Mauder et al. (2007) did move one CSAT3 between test sites. In our experimental setup, each anemometer was randomly located multiple times (Table 1). A secondary benefit of this is that the slight mounting errors in azimuth and tilt should average out upon successive installations of the same unit, thus allowing us to perform our analysis in sonic coordinates that more clearly relate to the physical arrangement of each design and their geometry, transducers, and structure. Third, our intercomparison contains a fairly long data record of approximately 38 days over a 4-month period (Table 1). Most intercomparisons are less than 2 weeks, with the exception of Mauder (2013), which lasted 17 days, and Horst et al. (2015), which spanned 8 months. Finally, our Bayesian analysis offers several advantages. Unlike all

other intercomparisons, we make no arbitrary selection of a single anemometer to be the reference; all anemometers are treated equal in the analysis and all statistical inferences apply equally when comparing any two designs. This is especially important because the Bayesian model can account for uncertainty (i.e., model residuals) in each individual unit, pool that uncertainty among replicates, and produce results for a design that accurately reflect the combined uncertainty. The Bayesian model also has the power to conduct many simultaneous analyses in a hierarchical framework while accounting for replicate designs, their presence or absence on the tower, and each mounting position while producing a succinct set of results comparing each design. For example, the results for Table 3 alone represent $12 \text{ weeks} \times 6 \text{ sonic anemometers at time (i.e., 15 intercomparisons)} \times 6 \text{ measurements} = 1080 \text{ total comparisons}$.

Are our results consistent with what was observed in previous intercomparisons? Because we know the presence/absence of shadow correction only in the ATI and CSI anemometers, we have limited our discussion to the subset of intercomparisons most similar to ours. Most relevant is Horst et al. (2015), who found that the CSAT3 measured 3.5% and 4.8% less σ_w and H (i.e., $w'T'$), respectively, than the K-probe, which compares favorably to the 3.4% and 6.4% less than we measured, respectively (Table 3). In older literature, Loescher et al. (2005) compared a K-probe, an A-probe, and a CSAT3, and observed that relative to the CSAT3, nonrotated σ_w was 0%–8% lower with the K-probe and 38%–60% lower with the A-probe and 2D rotated σ_w was 8%–17% lower on the K-probe and between 6% lower and 60% higher with the A-probe. Mauder et al. (2007) observed that planar-fit rotated σ_w was 5%–6% higher with two K-probes than a reference CSAT3 while observing little difference between two other CSAT3s. Frank et al. (2013) compared four CSAT3 to an ATI Vx-probe (a different unit than the one included in this analysis) and found σ_w was 6% higher in the Vx-probe. Kochendorfer et al. (2012) never directly compared the CSAT3 and Vx-probe but both were part of their experiment, where they observed that the Vx-probe measured higher w . Why is it difficult to synthesize all of these intercomparisons into a generalized result? We propose two reasons. First, the strengths of our intercomparison are weaknesses in these others: that is, replication, randomization and repeatability, duration, and analysis. Second, as we argue in the following sections, the errors in measuring vertical wind velocity with these non-orthogonal sonic anemometers are a function of both 1) shadowing specific to the geometry of the probe and 2) the distribution of local wind (Fig. 3). Therefore, we

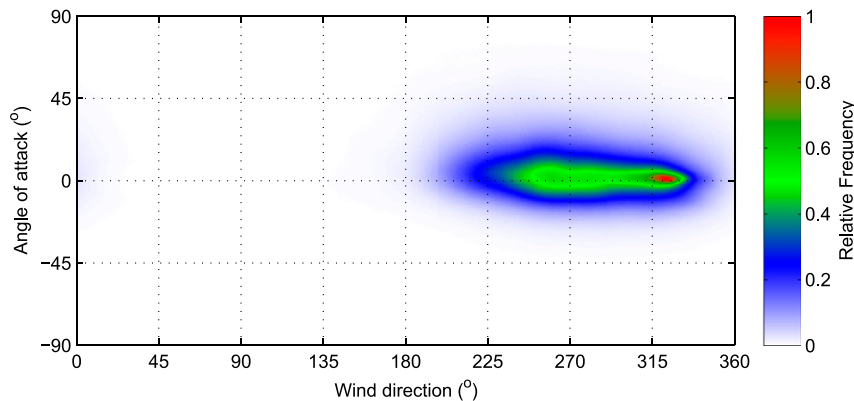


FIG. 3. Histogram of horizontal wind direction and vertical angle of attack from all 20-Hz sonic anemometer measurements used to construct the dataset analyzed in this experiment. Shadow correction was applied only to orthogonal sonic anemometers (K-probe and Vx-probe) reflecting manufacturers' current recommendations for all instruments.

expect that all intercomparison results should, in part, be site specific.

b. What is the reason for the discrepancy?

We argue that the lack of correction for transducer/structural shadowing in the nonorthogonal anemometers is the reason for this discrepancy. Recognition of the impact that shadowing has on sonic transducer measurements is nothing new. Variations of the empirical shadow correction algorithm proposed by Kaimal (1979) and confirmed by Kaimal et al. (1990) have been a mainstay of orthogonal sonic anemometers for years. Our results for the K-probe remind us that shadowing is both real and correctable. Without correction, the K-probe measured anomalously low u , v , and TKE (Table 2), a problem remedied by the Kaimal correction (Table 3). This is clearly evident in the residuals of the model, where shadowing causes a bias toward underestimating σ_u for wind directions aligned parallel to the u axis, while the Kaimal correction alleviates much of this problem (Fig. 4). That the K-probe and Vx-probe u and v transducer paths are rotated 45° from each other but measure similar wind velocities after shadow correction (Table 3) replicates and reaffirms Kaimal et al. (1990). The orthogonal transducer arrangement is not without its detriments, most importantly that the average transducer shadow correction for horizontal wind was between 6% and 12%. And specific to the K-probe, we observed possible structural shadowing in the u measurement, which became apparent when we mounted the probe horizontally and northwesterly winds (Fig. 3) blew across the support structure (Figs. 1b, 4d), which manifested as an average decrease in σ_u (Table 6). But for all of its detractors, the orthogonal transducer arrangement was predicted to have

minimum shadowing along the w axis over the course of a half hour and observed to be the most internally consistent at measuring the three dimensions of wind (Table 6).

Neither the A-probe, CSAT3, nor CSAT3V applies a shadow correction algorithm, and our implementation of the Kaimal and double-Kaimal corrections are admittedly flawed. We do propose that there is some appropriateness to these algorithms because 1) it is reasonable to assume that the transducer pairs will cause similar shadowing as the K-probe and 2) in the case of the A-probe and the CSAT3, the structure is radially symmetric, with the three transducer vectors equally pointing toward it. Regardless, our implementation of the Kaimal and double-Kaimal corrections serves as a tool for hypothesis testing. The inclusion of the Kaimal correction clearly improves the intercomparison between the orthogonal and nonorthogonal sonic anemometers by reducing the discrepancy between σ_w and the partitioning of vertical to horizontal TKE, by solidifying the total TKE difference between ATI and CSI anemometers, and by minimally affecting measurements of u and v (Table 4). By the time the double-Kaimal correction is applied, the difference between the partitioning of vertical and horizontal TKE is completely mitigated (Table 5). But, as Horst et al. (2014) rightfully pointed out, even though this can force one anemometer to look more like the other, how do we know which is more correct?

The problem is that no standard exists to know what truth is when measuring wind in the field. We argue that the shadow-corrected K-probe is the most internally consistent and accurate at measuring all three dimensions of wind. Though horizontal wind measurements with the K-probe are clearly flawed, with the

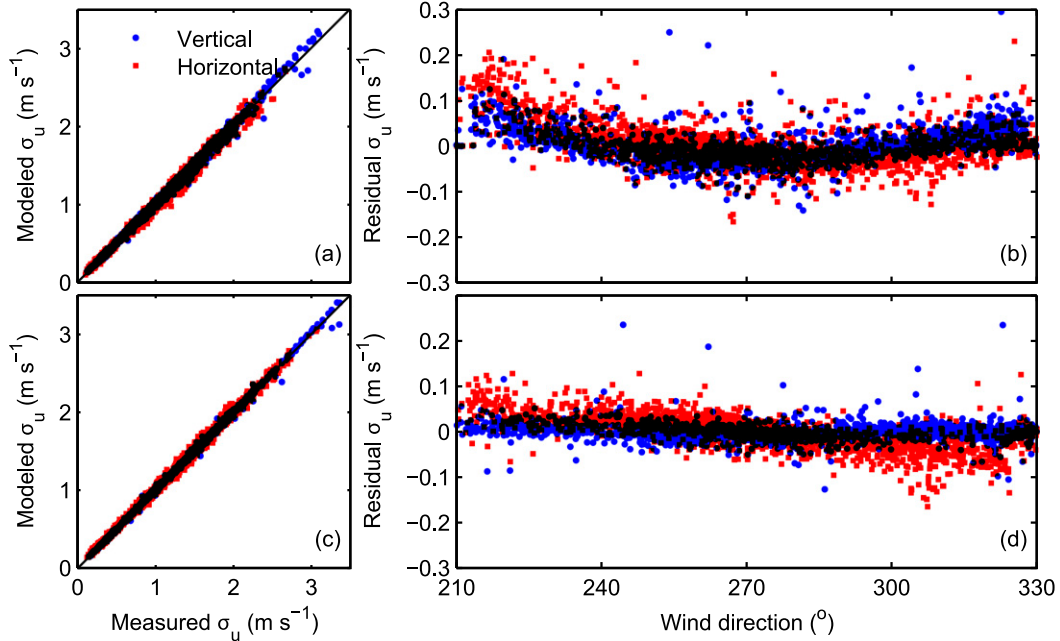


FIG. 4. (a),(c) Modeled and (b),(d) residual half-hour σ_u for the K-probe from the analysis of measurements (a),(b) without shadow correction and (c),(d) with Kaimal shadow correction. Sonic anemometers were oriented vertical (blue circles) and horizontal (red squares, dark shading represents overlap). Residuals are plotted relative to average wind direction. (b) The original measurements show similar shadowing for both vertically and horizontally oriented orthogonal sonic anemometers, with maximum shadowing (negative residuals) along the u axis at 270°. (d) Kaimal shadow correction eliminates most of the shadowing for both orientations, with the notable exception of horizontally mounted instruments, which experience additional shadowing from northwesterly wind blowing across the support structure (Fig. 1b).

Kaimal correction they are on average as accurate as those from other anemometers (Table 3; Kaimal et al. 1990). Because we both predicted and observed that the horizontal manipulation would not change any measurements (Table 6), we argue that w is also accurately measured, and by extension the partitioning between vertical and horizontal TKE. Finally, based upon the Kaimal correction, the K-probe w measurement is not only minimally shadowed but the correction is small and accurately known.

In contrast are the results for the nonorthogonal sensors, where the observations (Table 6) clearly show they treat the three dimensions differently. Thus, while horizontal wind measurements are more precisely measured with the nonorthogonal anemometers, are their vertical wind measurements accurate? Based on transducer/structural shadowing, the answer is no. The internal consistency manipulation allowed us to test two competing hypotheses that explain why these anemometers treat the three dimensions differently. We reject hypothesis B₁ (a 1D error in w) because clearly it cannot explain the observed changes in σ_u and σ_w following the horizontal manipulation (Table 6). And while our models (Kaimal and double Kaimal) for

testing hypothesis B₂ (a 3D error due to the lack of shadow correction) do not completely explain the horizontal manipulation (Table 6), they are remarkably consistent with the observations enough to suggest that this is the reason. We argue that the imperfections in predicting Table 6 are not because the lack of shadowing correction hypothesis is wrong, but rather the Kaimal and double-Kaimal corrections only approximate the true correction. These corrections correctly predict an observed decrease in σ_w . But, they also predict that while the nonorthogonal w axis is heavily shadowed when mounted vertically due to vertical wind distribution (Fig. 3), the w axis is still heavily shadowed when it is mounted horizontally by north–south winds (Fig. 3). This is illustrated by the model residuals of the CSAT3 σ_w measurement where shadowing obviously occurs in both vertically and horizontally mounted sensors, though both are due to winds from different directions (Fig. 5). In this case, the Kaimal correction can mitigate most of the shadowing (Fig. 5d). Likewise the u axis is not shadowed when mounted vertically, but due to the north–south winds blowing across the transducers, the horizontal u axis is heavily shadowed, causing the decrease in σ_u . Based upon the Kaimal and double-Kaimal

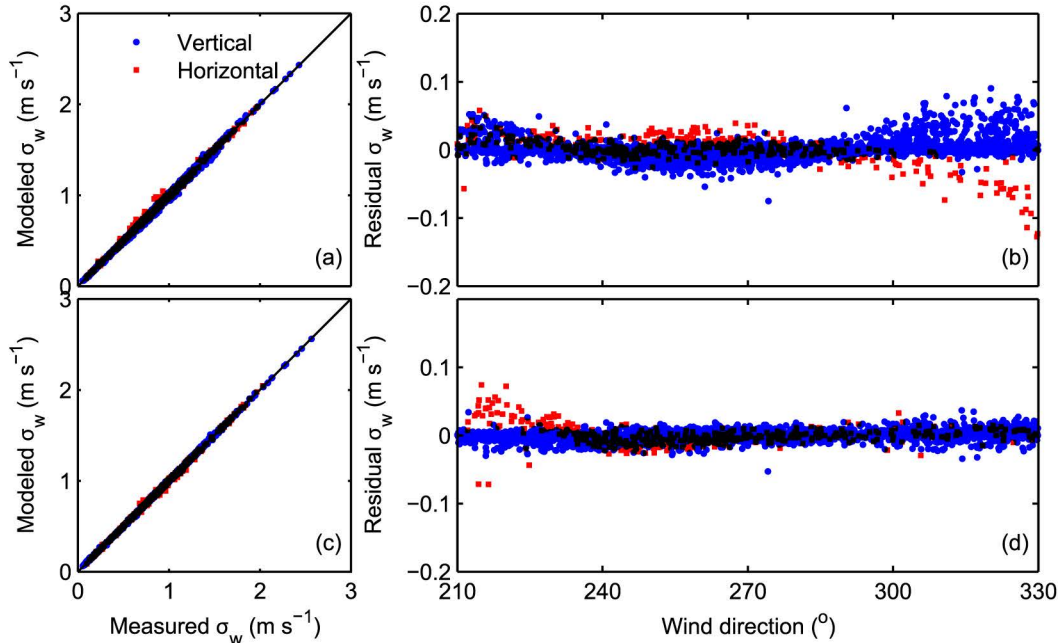


FIG. 5. (a),(c) Modeled and (b),(d) residual half-hour standard deviations of vertical wind velocity (σ_w) for the CSAT3 from the analysis of measurements (a),(b) without shadow correction and (c),(d) with Kaimal shadow correction. Sonic anemometers were oriented vertical (blue circles) and horizontal (red squares, dark shading represents overlap). Residuals are plotted relative to average wind direction. (b) Shadowing occurs at different wind directions for the two orientations; maximum shadowing (negative residuals) corresponds 1) to the west-oriented CSAT3 transducer pair in the vertical orientation and 2) with the north–south-oriented support structure in the horizontal orientation. (d) Kaimal shadow correction eliminates most of the shadowing for both orientations, though it cannot sufficiently account for shadowing from southerly wind across the horizontally mounted support structure.

corrections, the average A-probe and CSAT3 w measurements experience dramatic shadowing, but the correction is large and not accurately known.

There are strong similarities, but there are some major differences between our conclusions and those of Horst et al. (2015). First, we both agree that the reason for the observed differences in the intercomparison is because of the lack of shadow correction. We both tested similar formulations for the Kaimal correction; they found that this made the CSAT3 measure equal σ_w and only 1.3% less H than the K-probe, while we similarly found 1.8% higher σ_w and 0.6% less H . In Horst et al. (2015), the ability to mitigate the observed differences supports the proposed transducer-shadowing flow-distortion correction. We argue that Horst et al. (2015) did not recognize that ATI anemometers measure lower TKE, and that a properly corrected CSAT3 should measure higher σ_w and H than a K-probe. We introduce a unique experimental manipulation (the internal consistency test) that does not rely on comparing one design to another, but independently confirms that the actual correction should have a magnitude approximately 100% greater than the Kaimal correction. Thus, while applying the

Kaimal correction is a step in the right direction, the problem is probably not solved.

The worst prediction/observation from the horizontal manipulation—that is, the change in σ_w for the CSAT3V (Table 6)—can be explained if one considers that structural shadowing is as important as transducer shadowing for the nonorthogonal anemometers. Because the CSAT3V has a purely vertical w axis, the Kaimal correction only predicts shadowing due to the vertical transducer pair, and as such assumes that σ_w is minimally shadowed in the vertical CSAT3V, much like the K-probe. This is probably not the case, as the vertically mounted CSAT3V σ_w measurement most likely experiences significant structural shadowing. Though most winds were directed into the sensor (Fig. 3), this is caused by the close clustering of transducers, especially at the bottom (Fig. 1a), which might be analogous to increasing the apparent transducer diameter, decreasing the apparent L/d , and increasing the shadowing (Kaimal 1979). When the CSATV is rotated horizontally, the Kaimal correction predicts substantial shadowing due to north–south winds; hence, the overall prediction was that σ_w would decrease substantially when manipulated.

In reality, the vertically mounted CSAT3V is probably more shadowed along the w axis than when it is on its side, leading the observed increase (Table 6).

c. What is the magnitude of the nonorthogonal transducer/structural shadowing correction?

Though we cannot provide a definitive shadow correction algorithm for the nonorthogonal sensors, our results provide a reasonable set of indicators of the magnitude. We argue that the magnitude of the true correction is somewhere between the Kaimal correction (representing only transducer shadowing) and the double-Kaimal correction (representing transducer plus structural shadowing). First, from the intercomparison results and assuming the K-probe σ_w measurement as the standard, the A-probe would require an 8.4% correction (Table 3). And, while the CSAT3 would only require a 3.6% increase (Table 3), by taking into consideration the 4.3% higher CSAT3 TKE, it would actually require an 8.1% correction to be similar to the K-probe. The two shadow correction algorithms predict a σ_w correction between 5.4% and 12.0%, and we observed that the difference in partitioning of vertical to horizontal TKE was still evident with the Kaimal correction (Table 4) but not with the double-Kaimal correction (Table 5). Finally, we observed in the internal consistency experiment that σ_v was 12.0%–12.5% higher when mounted vertically, which is similar to that predicted by the double-Kaimal correction (Table 6). And, because the CSAT3V had an orthogonal w axis but still measured 10.3% higher σ_v when mounted vertically (Table 6), we are confident that structural shadowing is a significant contributor.

We do not advocate for the use of the Kaimal or double-Kaimal corrections to fix the problem of transducer/structural shadowing in nonorthogonal anemometers. While we have used these corrections as a diagnostic tool for testing our hypothesis about shadowing, we have also demonstrated that Kaimal correction is inadequate by as much as 100%, plus we suspect the double-Kaimal correction can degrade high-frequency (i.e., 20 Hz) measurements. We used these corrections to show that the average turbulent measurements (i.e., σ_u , σ_v , and σ_w) of these nonorthogonal anemometers are biased under the manufacturer's current recommendations, but it is also possible that implementing these corrections could add errors to the high-frequency data. Current research using computationally intensive Bayesian models to tease out a comprehensive 3D correction has shown promise to characterize not only transducer shadowing but cross shadowing between transducers. Preliminary results from this research suggest that the Kaimal correction is

inadequate because it does not account for cross shadowing; that is, transducers do not just get into their own way, but they get into each other's way too.

Finally, the magnitude of the shadow correction on turbulent statistics and ecosystem fluxes is a function of both the 3D correction around the sonic anemometer and the local wind distributions (Fig. 3). While we found that the w shadow correction was likely between 5.5% and 12.5% at our site (8%–9% based on the intercomparison), causing $\sim 10\%$ higher H , there is no guarantee that this is the case elsewhere. A reasonable estimation would be to apply the Kaimal correction at other sites, with full acceptance that the actual correction could be almost twice that.

d. What are the broader impacts?

The biggest issue with solving the networkwide bias in underestimating energy closure (Wilson et al. 2002) is the discovery of errors that are fundamentally biased. The lack of shadowing correction in the A-probe and CSAT3 represents such an error. While there certainly is not a 1:1 mapping of errors in σ_w to errors in H , any error in the vertical wind measurement will impact the measured sensible heat flux. We observed 11% higher H in the orthogonal anemometer when compared to the nonorthogonal design from the same manufacturer, and even without taking into account the differences in TKE, the K-probe measured 7% higher H than the CSAT3, which is consistent with the 8% found in Frank et al. (2013) and 8% found in the 2009 GLEES AmeriFlux intercomparison (J. Kathilankal 2010, unpublished data). The application of the Kaimal and double-Kaimal corrections increased H in the A-probe and CSAT3 by 5%–12%, which is consistent with all of these intercomparisons, and it demonstrates that it is not unreasonable to expect that these nonorthogonal anemometers underestimate H by $\sim 10\%$. Between 35% and 58% of all AmeriFlux sites use the CSAT3 (Frank et al. 2013; Nakai et al. 2014). While our results do not implicate nonorthogonal sensors from other manufacturers, other studies have brought into question the accuracy of vertical wind velocity measurements made with two other common manufacturers: Gill Instruments (Nakai and Shimoyama 2012; Nakai et al. 2014) and R. M. Young Company (Kochendorfer et al. 2012, 2013). With the inclusion of instruments from these manufacturers, 87%–90% of all AmeriFlux sites use nonorthogonal sonic anemometers (Frank et al. 2013; Nakai et al. 2014). We doubt that the lack of shadow correction in nonorthogonal sonic anemometers is entirely responsible for the $\sim 20\%$ bias in underestimating flux energy across large networks (Wilson et al. 2002). But, considering that one of the most

common anemometers underestimates the vertical wind at our site by 8%–9%, resulting in ~10% less H , the implications should be investigated across the networks as a whole.

5. Conclusions

Using results from our field experiment, we determined that there was a clear, observable difference in measurements of vertical wind velocity between orthogonal and nonorthogonal sonic anemometers (i.e., we rejected hypothesis A). This difference is not correlated with a 1D error and cannot simply be corrected by increasing the magnitude of w (i.e., we reject hypothesis B₁). Instead, this underestimate is due to the lack of correction for transducer and structural shadowing within the nonorthogonal sonic anemometer (i.e., we accept hypothesis B₂). Though we do not know the exact functional form of the shadow correction, we determined that the magnitude of the correction is probably somewhere between the Kaimal and double-Kaimal correction. The actual correction is also a function of local wind distributions, and at our site this amounted to likely an 8%–9% increase in w and ~10% increase in H . Without investigating this error at other sites, it is difficult to determine the impact across flux networks, though this has the potential to explain a large portion of the energy balance closure discrepancy and underestimates of ecosystem fluxes worldwide.

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