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ARTICLE

How Well Can We Measure the Vertical Wind Speed? Implications for Fluxes of Energy and Mass

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Abstract Sonic anemometers are capable of measuring the wind speed in all three dimensions at high frequencies (10–50 Hz), and are relied upon to estimate eddy-covariance-based fluxes of mass and energy over a wide variety of surfaces and ecosystems. In this study, wind-velocity measurement errors from a three-dimensional sonic anemometer with a non-orthogonal transducer orientation were estimated for over 100 combinations of angle-of-attack and wind direction using a novel technique to measure the true angle-of-attack and wind speed within the turbulent atmospheric surface layer. Corrections to the vertical wind speed varied from −5 to 37 % for all angles-of-attack and wind directions examined. When applied to eddy-covariance data from three NOAA flux sites, the wind-velocity corrections increased the magnitude of CO_2 fluxes, sensible heat fluxes, and latent heat fluxes by ≈11 %, with the actual magnitude of flux corrections dependent upon sonic anemometer, surface type, and scalar. A sonic anemometer that uses vertically aligned transducers to measure the vertical wind speed was also tested at four angles-of-attack, and corrections to the vertical wind speed measured using this anemometer were within ±1 % of zero. Sensible heat fluxes over a forest canopy measured using this anemometer were 15 % greater than sensible heat fluxes measured using a sonic anemometer with a non-orthogonal transducer orientation. These results indicate that sensors with a non-orthogonal transducer orientation, which includes the majority of the research-grade three-dimensional sonic anemometers currently in use, should be redesigned to minimize sine errors by measuring the vertical wind speed using one pair of vertically aligned transducers.

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1 Introduction

Statistics related to the vertical component of the wind vector (w) are important for describing turbulent transport processes throughout the atmospheric boundary layer. In the 1960s, measurements of turbulence, especially the vertical component, were mainly obtained using three-dimensional propeller anemometer systems. The characterization of the behaviour of the anemometer (cosine response) was critical (Hicks 1972) for obtaining accurate measurements of turbulence statistics including vertical turbulent fluxes using eddy-covariance techniques. In the 1970s sonic anemometers became the instrument of choice for measuring the turbulent statistics in the atmospheric boundary layer. Nearly all sites that are part of long-term flux monitoring networks (Baldocchi et al. 2001) employ sonic anemometers as part of the eddy-covariance system to determine vertical turbulent fluxes.

As with propeller systems, it has been shown that the components of the wind vector obtained from sonic anemometers may require corrections that are dependent both on the wind direction and the angle-of-attack (Christen et al. 2000; Gash and Dolman 2003; van der Molen et al. 2004; Nakai et al. 2006), where the angle-of-attack is defined as the angle between the horizontal plane and the wind vector. When applied to the Gill R2 sonic (Gill Instruments, Lymington, UK), the correction factors obtained from wind-tunnel studies (laminar flow) increased vertical turbulent fluxes by 5–10 %. However, for field conditions where the flows are highly turbulent, the corrections may not necessarily be the same, and corrections may also be dependent on the type of sonic anemometer used. For example, the transducer wakes of non-orthogonal sonic anemometers (Fig. 1a) affect the measurement volume differently than the transducer wakes of orthogonal sonic anemometers (Fig. 1b).

In this paper, we describe a field methodology for evaluating the potential measurement errors of the wind vector, for both positive and negative angles-of-attack. A correction matrix that is dependent on both wind direction and angle-of-attack is obtained. Raw high-frequency

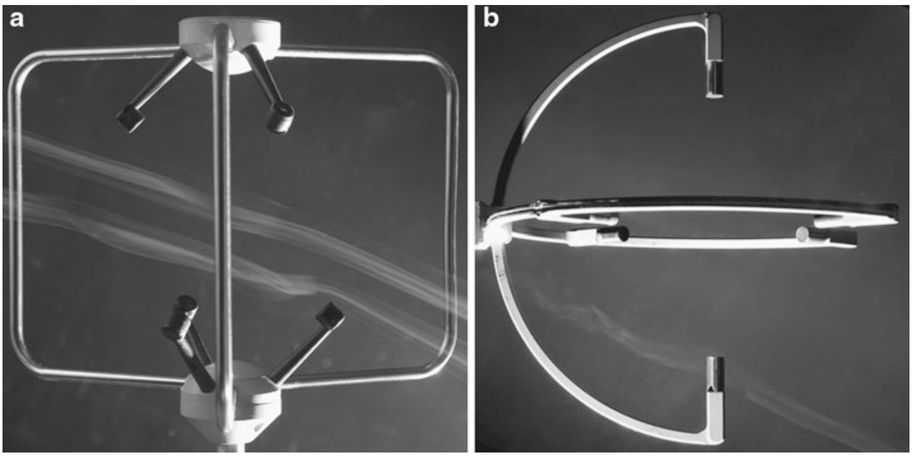

Fig. 1 Wind-tunnel photographs of transducer wakes across the R.M. Young (**a**) and the ATI (**b**) transducers in laminar flow

data (10 Hz) obtained from three different field sites of varying surface roughness were corrected using the experimentally determined matrix. Turbulent statistics, including the vertical turbulent fluxes of momentum, sensible heat, latent heat, and CO_2 are compared with the original "uncorrected" data.

2 Methods

2.1 Primary Experiment

2.1.1 Field Measurements

The primary experiment was performed in a managed grassland in Oak Ridge, Tennessee, U.S.A. (35.9843°N, 84.2184°W), where the canopy height varied between 0.1 and 0.5 m seasonally and with periodic mowing. The upwind fetch was uniform for over 150 m in the prevailing south-west and north-east wind directions. The terrain was flat and sloped ≈3.5° downwards towards the south-east.

Two sonic anemometers (Model 81000VRE, R.M. Young, Traverse City, Michigan) levelled using a digital protractor (Model Pro 360, Mitutoyo, Kawasaki, Japan) with a maximum error of 0.2° were mounted 1.2 m apart above a small tripod-type tower, at a height of 2.5 m above the soil surface. A third R.M. Young anemometer (also model 81000VRE) was installed between these two anemometers using additional hardware that allowed this centre anemometer to be tilted while maintaining the 2.5-m measurement height (Fig. 2a). The tilt angle of the centre sonic anemometer was also determined using the digital protractor, with the cylindrical body of the anemometer used as the reference surface for levelling and tilting. The wake corrections included in the R.M. Young anemometer firmware were activated because this is the mode in which these anemometers are normally used. These R.M. Young wake corrections include corrections to the vertical wind speed that are proprietary. Measurements were recorded from all three sonic anemometers simultaneously at 10 Hz, and were post-processed using computer software designed in-house as described below.

The primary goal of the experiment was to develop a table of corrections for the vertical and horizontal wind speeds for a single R.M. Young sonic anemometer. Based on flux-angle distribution measurements made over both rough and smooth surfaces (Weiss and Allen 1976; Motha et al. 1980; Gash and Dolman 2003), nine angles-of-attack were tested (−30°, −15°, −10°, −5°, 5°, 10°, 15°, 30°, and 45°), and at each angle-of-attack 12 wind

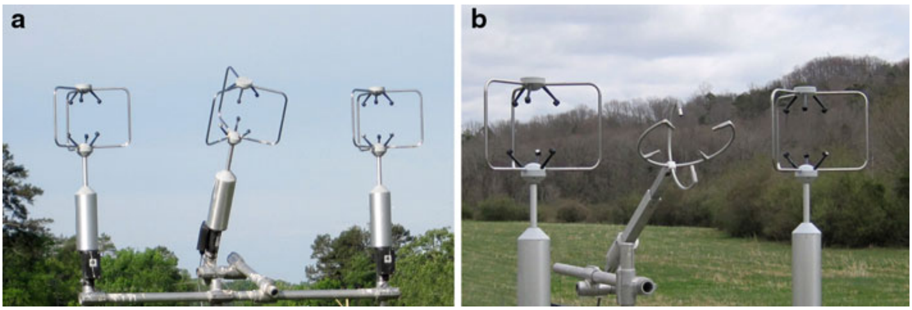

Fig. 2 Photographs of the R.M. Young (**a**) and ATI (**b**) sonic anemometers during the experiment

directions were tested (every 30° from 0° through 330°). This portion of the experiment began in June 2009 and ended in March 2010. The same sonic anemometer was then re-tested at nine orientations that were randomly selected from the 108 combinations of angle-of-attack and wind direction previously tested. A different anemometer of the same make and model and a CSAT3 three-dimensional sonic anemometer (Campbell Scientific, Logan, Utah) were also tested at sub-selected orientations, and an ATI (Applied Technologies, Inc., "Vx" Style Probe) three-dimensional sonic anemometer was tested at four angles-of-attack (−30°, −15°, 15°, and 30°) from one wind direction (Fig. 2b).

The ATI transducer wake corrections are based on the work of Kaimal et al. (1990), and are applied to the three axes of the sensor separately, without consideration for the more complicated effects of shadowing from one transducer pair on the path of another transducer pair. These corrections are therefore best suited for anemometers such as the ATI "K" Style probe, which has a large measurement volume with significant spatial separation between the three measurement axes, and was specifically designed to minimize the effects of flow distortion (Kaimal et al. 1990). In the results presented below, data from the more compact ATI "Vx" Style probe was limited to ideal wind directions, chosen to minimize interference from the horizontal transducers and their supports, allowing the ATI firmware to effectively correct the effects of transducer wakes within the relatively small measurement volume of the "Vx" Style probe. Like the "K" Style probe, the "Vx" Style probe's vertical velocity measurement is made by one pair of vertically oriented transducers, which makes it possible to estimate the vertical velocity in a volume that is unaffected by the wakes of other transducers. The CSAT3 does not include any corrections for the effects of transducer wakes.

2.1.2 Theory and Data Analysis

Based on the measurements recorded by the levelled anemometers, 10-Hz data were sub-selected for the following criteria: wind directions within ±10° of perpendicular to the lateral axis of the anemometer array, wind speeds greater than 1 m s^{-1}, angles-of-attack less than 0.5°, and close agreement between the two levelled sonic anemometers regarding the angle-of-attack, wind speed, and wind direction. After a minimum of 1,000 acceptable 10-Hz samples were recorded, statistics were generated from the sub-sampled data, and the mean wind velocity of the tilted sonic anemometer was compared to the mean wind velocity recorded simultaneously by the vertical sonic anemometers. The tilted sonic anemometer was then realigned to continue testing the next orientation. Whenever necessary, the entire sonic array was also reoriented into the prevailing wind direction. With strong winds and a steady wind direction, 1,000 acceptable samples could be recorded in less than a day. When winds were light and variable, more time was required. The sample size of 1,000 was determined by plotting cumulative mean statistics vs. the number of samples, as all the initial cases plotted this way (15) converged on a stable average (<1 % variation) within 1,000 samples.

The actual mean vertical wind speed (W_{act}) in the coordinate system of the tilted sonic anemometer was estimated using

$$W_{\mathrm{act}} = U \sin\alpha + W \cos\alpha \tag{1}$$

where α is the angle of the anemometer tilted from vertical, with α positive when it is tilted away from the prevailing wind direction, W is the sub-selected mean vertical velocity measured by the two level sonic anemometers, and U is the mean of the sub-selected horizontal wind speed from the two level sonic anemometers

$$U = \overline{(u_{\mathrm{a}} + u_{\mathrm{b}})/2} \tag{2}$$

where the overbar denotes averaging of all of the available samples, and u_a and u_b are the horizontal wind speeds from the two vertically oriented sonic anemometers, estimated from $\sqrt{u_x^2 + u_y^2}$, with u_x and u_y symbolizing the two horizontal components of the individual 10-Hz wind vector measurements. In practice, the $W \cos\alpha$ term in (1) was excluded from the estimate of W_{act} because its magnitude was negligible for the sub-selected data, in which W was negligible because the angle-of-attack was less than 0.5°. The mean vertical velocity from the tilted anemometer (W_t) was compared to W_{act} to create error estimates and corrections. For example, the correction to the vertical wind speed (C_w) measured by the tilted sonic anemometer at a given angle-of-attack and wind direction is described by

$$C_w = W_{act}/W_t. \tag{3}$$

The theory behind this approach is based on the accuracy of this type of sonic anemometer at negligible angles-of-attack, and the technique and resultant C_w were first presented by Meyers and Heuer (2006). All of the sonic anemometers had been factory calibrated in a wind tunnel before the field experiment, and our method relied upon the assumption that these calibrations were valid for measurements in the turbulent surface layer when the angle-of-attack was negligible. As is typical, the manufacturer's wind-tunnel calibrations were performed with the anemometers oriented vertically. The post-calibration wind-speed measurements were accurate within the manufacturer's stated 1 % or 0.05 m s^{-1}. In the field experiment, the vertical wind speed at the centre anemometer, which was tilted at a known angle, was estimated using the horizontal wind speed measured by the vertically oriented anemometers when the angle-of-attack was less than 0.5°.

The correction to the horizontal wind speed (C_u), which is also called the cosine correction because the horizontal wind speed is a function of the cosine of the angle-of-attack, was estimated using a similar methodology. The actual mean horizontal wind speed at the tilted sonic anemometer (U_{act}), in the tilted frame of reference, was estimated from

$$U_{act} = U \cos\alpha + W \sin\alpha \tag{4}$$

where U was estimated from the vertically oriented sonic anemometers (2). In practice, the $W \sin\alpha$ term was negligible, because W was negligible in the sub-selected data due to the angle-of-attack selection criteria. C_u was estimated from

$$C_u = U_{act}/U_t \tag{5}$$

where U_t is the mean horizontal wind speed measured by the tilted sonic anemometer.

2.2 Statistical Analysis

The effects of orientation (both wind direction and angle-of-attack) and sonic anemometer on C_w and C_u were tested using two-way ANOVA (SAS PROC MIXED, SAS Institute, Cary, North Carolina, USA) on a subset of the data including only the nine retested orientations for the two R.M. Young sonic anemometers. The effects of wind direction, angle-of-attack, sonic anemometer, and the presence of a transducer directly upwind of the measurement volume (hereafter referred to as transducer-shadowed orientations) on C_w and C_u were tested with a backward-eliminated linear model using ANOVA (SAS PROC MIXED) on all of the R.M. Young data. To further explore uncertainties in C_w, individual 0.1-s C_w values were estimated for all the available data, and the interquartile range was calculated.

Table 1 Energy balance instrumentation

Sensor	Variables	Mfg., make and model	Output frequency
3D sonic anemometer	u, v, w and sonic temperature	R.M. Young 81000VRE	10 Hz
Infrared gas analyzer	CO_2 and H_2O density	LiCor LI-7500	10 Hz
Net radiometer	Net radiation	Kip&Zonen CNR1	30-min average

2.3 Angle-of-Attack Corrections

A look-up table of corrections to the vertical wind speed was developed for the primary R.M. Young sonic anemometer tested. Before using the table to correct measured wind velocities, the angles-of-attack used in the table were adjusted to account for differences between the measured angles-of-attack and the actual angles-of-attack, as the measured angles-of-attack were normally less than the actual angles-of-attack due to the underestimation of the vertical wind speed. The look-up table was then used to correct past data by reprocessing 10-Hz data from three NOAA flux sites as follows. Using software developed in-house, for every recorded 0.1-s sample the wind direction and the angle-of-attack were calculated from the recorded horizontal and vertical wind components, and the vertical wind speed was then multiplied by the look-up table C_w value that corresponded most closely in orientation with the actual orientation of the wind vector. The coordinate system was then rotated, and the turbulent statistics and the fluxes of sensible heat (H), latent heat (LE), and CO_2 (F_c) were calculated every 30 min. Sensible heat fluxes were calculated from $\overline{w'T'}$, where w is the vertical wind speed, T is the temperature calculated from the sonic anemometer after correcting the sonic temperature for the effects of water vapour (Schotanus et al. 1983), primes denote deviations from the 30-min centred box-car or sliding mean, and the overbar denotes a 30-min mean. A two-dimensional coordinate rotation was applied to the turbulent statistics and the sensible heat fluxes, aligning $\overline{u}$ with the mean streamline and forcing $\overline{w}$ to zero (Massman and Lee 2002). The density effects of water vapour and air temperature on the open-path gas analyzer measurements (LiCor, Lincoln, Nebraska, Model 7500) of CO_2 and water vapour density were also corrected following Webb et al. (1980). Data processing and flux calculations are described in more detail in Meyers (2001).

2.4 Flux-Tower Sites

The Chestnut Ridge NOAA/ATDD flux tower site is located in Oak Ridge, Tennessee (35.9311°N, 84.3323°W), in a deciduous, mixed-hardwood forest. The canopy height is approximately 25 m, the maximum one-sided leaf area index (LAI) is ≈5, and the height of the eddy-covariance measurements is 43 m. The eddy-covariance and radiation balance measurements at this and the other sites presented here are described in Table 1. This site is described in more detail in Wilson and Meyers (2007). In 2009, which was the year used to examine the effects of angle-of-attack corrections, 10-Hz eddy-covariance measurements were available for 94 % of the year.

The Brookings, South Dakota, NOAA/ATDD flux tower site (44.3453°N, 96.8358°W) is grassland with an LAI that varies seasonally from 0.2 to 3 (Gilmanov et al. 2010). The canopy height is 0.2–0.4 m, and the measurement height of the eddy-covariance sensors is 4 m. In 2009, 10-Hz eddy-covariance measurements were available for 95 % of the year.

The Bondville, Illinois, NOAA/ATDD flux tower site (40.0062°N, 88.2904°W) is located within a no-till managed agricultural field that alternates annually between soybean and maize (Meyers and Hollinger 2004; Wilson and Meyers 2007). The measurements presented here were recorded during the period from May 1 (DOY 120) to May 31 (DOY 150), 2011. The site was planted with maize on DOY 130. The canopy height was approximately 0.25 m on DOY 150. The eddy-covariance measurement height was 4 m, and the net radiometer was at a height of 5.6 m. Three soil heat-flux probes (in-house design) were used to measure the soil temperature at a depth of 0.02, 0.05, 0.1, 0.2, 0.5, and 1 m below the soil surface. The soil thermal conductivity was measured with three-needle heat pulse sensors (Bristow et al. 1994; Ochsner et al. 2007). The measured thermal conductivities and volumetric heat capacity were used to compute the soil heat flux and soil heat storage using the measured temperatures and gradients from the 0.02- and 0.05-m soil temperature observations.

2.5 Side-by-Side Anemometer Comparison

From 19 April 2011 through 6 May 2011 the ATI sonic anemometer was operated adjacent to an R.M. Young (Model 81000VRE) anemometer, collecting wind velocity and sonic temperature data at 10 Hz on the Chestnut Ridge flux tower above a 25-m tall forest, at a height of 43 m above the soil surface. The separation distance between the two anemometers was 0.75 m, and the data were selected for wind speeds greater than 0.75 m s^{-1} and wind directions between 190° and 230°. This wind-direction sector included the prevailing wind direction, and was free from all obstructions such as the tower and the sonic anemometers themselves. Based on these selection criteria, 211 of the 810 available 30-min data periods were included in the analysis. The sensible heat flux and turbulent statistics were estimated without the application of any angle-of-attack corrections.

3 Results and Discussion

3.1 Wind-Velocity Corrections

A table of C_w for the R.M. Young sonic anemometer was generated from all of the orientations examined (Table 2). The mean C_w for all angles-of-attack and wind directions tested was 1.12, which indicates that within typical flux-angles-of-attack, w is underestimated by ≈12 %. There was significant variation between orientations, with a standard deviation of all C_w of 0.09, or 9 %. The ANOVA results demonstrated that wind direction and transducer-shadowed orientations were not significant predictors of C_w ($p = 0.79$, $p = 0.12$, respectively), but that angle-of-attack was significantly correlated with C_w ($p < 0.0001$, Fig. 3). We hypothesize that changes in the effects of the wakes formed downwind of all three of the transducer pairs contributed to the variability in C_w (Fig. 1a, b) and to the lack of a transducer-shadowed orientation effect. This is presumably because w is calculated simultaneously from the three separate non-orthogonal sonic transducer paths. The measured errors in w were also affected by proprietary corrections to the vertical wind speed included in the sensor firmware by the manufacturer. An additional source of uncertainty was the magnitude of errors in C_w at small angles-of-attack, which increased as the magnitude of w decreased (Fig. 4). For example, at a tilt angle of 5°, an error of 0.5° in the measured tilt angle of the anemometer would create an error in C_w of 11 %, which is nearly equal to the average magnitude of the correction. At 15°, the same 0.5° measurement error causes an error in C_w of only 3 %. An error of 0.5° in the measured tilt angle is unrealistically large, but it demonstrates the vulnerability

Table 2 R.M. Young vertical wind-speed corrections (C_W) for all angles-of-attack (α) and wind directions tested

Direction	α	−30°	−15°	−10°	−5°	5°	10°	15°	30°	45°	Mean
0°	C_W	1.24	1.07	1.11	1.10	1.06	1.02	1.01	1.16	1.22	1.11
30°		1.25	1.09	1.10	1.14	*1.12*	*1.02*	*1.02*	*1.10*	*1.25*	1.12
60°		1.24	1.07	1.17	1.14	1.07	1.01	0.99	1.12	1.19	1.11
90°		*1.23*	*1.09*	*1.20*	*1.30*	0.93	0.98	1.01	1.11	1.11	1.11
120°		1.27	1.07	1.14	1.18	1.03	0.99	0.96	1.13	1.22	1.11
150°		1.25	1.07	1.14	1.06	*1.19*	*1.03*	*0.99*	*1.10*	*1.27*	1.12
180°		1.26	1.07	1.11	0.94	1.25	1.00	1.01	1.09	1.18	1.10
210°		*1.25*	*1.08*	*1.13*	*1.11*	1.27	1.03	1.01	1.13	1.13	1.13
240°		1.26	1.05	1.04	1.17	1.08	0.97	1.00	1.11	1.23	1.10
270°		1.25	1.06	1.16	1.11	*1.22*	*1.02*	*1.01*	*1.11*	*1.29*	1.14
300°		1.24	1.04	1.15	1.25	1.25	1.14	1.02	1.14	1.22	1.16
330°		*1.16*	*1.06*	*1.13*	*1.39*	1.09	1.17	1.01	1.14	1.17	1.15
	Mean	1.24	1.07	1.13	1.16	1.13	1.03	1.00	1.12	1.21	1.12

Italics indicate corrections calculated at transducer-shadowed orientations

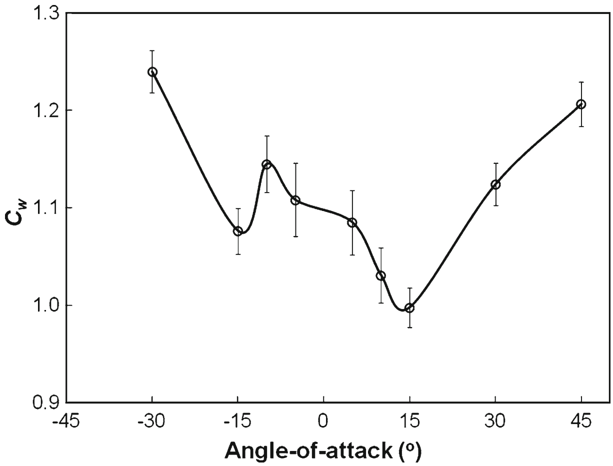

Fig. 3 Corrections to the vertical velocity (C_W) averaged by angle-of-attack. *Error bars* indicate the standard error of the 12 C_W estimates available for every angle-of-attack

of our results to tilt-angle and wind-velocity errors at small angles-of-attack. For example, a small error in w measured by the two sonic anemometers could also affect the results at small angles-of-attack. The effects of vertical velocity offset errors, which can change with air temperature, also increase as the angle-of-attack diminishes. This may explain why C_W varied more at low angles-of-attack (Table 2; Fig. 4), but of course large percentage errors in C_W at small angles-of-attack do not necessarily result in large absolute errors because the vertical velocity is small.

The sensitivity of C_W to the minimum wind-speed criterion was examined by incrementally increasing the 1 m s^{-1} lower wind-speed limit by 0.5 m s^{-1}. The resultant C_W estimates

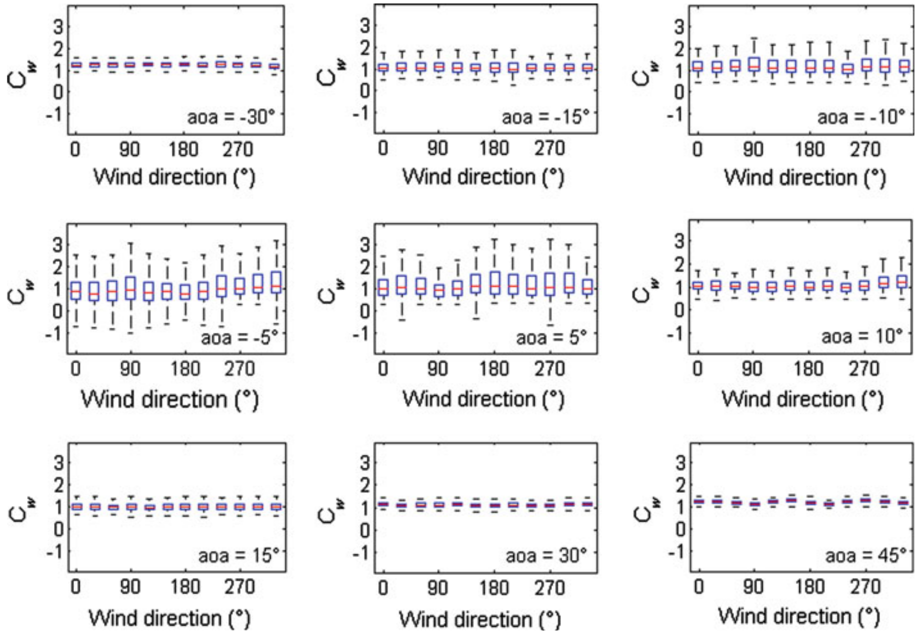

Fig. 4 Distribution of the 0.1-s values of C_W. *Box plots* indicate the interquartile range (IQR) and *whiskers* indicate the 1.5 IQR minimum/maximum

did not change significantly, nor was there any significant relationship between the mean C_w and the magnitude of the minimum wind-speed selection criterion.

A table of C_u was also generated from all of the orientations tested (Table 3). With the exception of the largest angle-of-attack tested (45°), angle-of-attack errors to the horizontal wind speed, or cosine errors, were small. The average of all the estimated C_u was 1.01, but the effects of shadowing from individual transducers were more apparent for C_u than for C_W. This may be because when the wind direction is aligned with one pair of transducers, after correcting for w, the horizontal component of the wind velocity is calculated primarily by the pair of transducers aligned with the flow, while all three transducer pairs are relied upon to calculate w. Wind direction was a significant predictor of C_u ($p = 0.0012$) but ultimately backward eliminated from our statistical model because only one comparison (240° vs. 330°) was moderately significant (Tukey–Kramer adjusted $p = 0.0252$). Angle-of-attack was a significant predictor of C_u, and transducer-shadowed orientations were also significantly correlated with C_u ($p < 0.0001$) for angles-of-attack with magnitudes ≥30° (Tukey–Kramer adjusted $p < 0.0192$).

After the initial round of testing, the same sonic anemometer was re-tested at nine orientations, and the original C_w estimates proved to be repeatable, with an average error in C_w of 4 %. Excluding the two orientations with an angle-of-attack of 5°, the average error in C_w was only 2 %.

Another R.M. Young sonic anemometer, also model 81000VRE, was then tested at the same nine orientations. The mean C_w for these orientations ($C_{w\,other}$) was similar to the original R.M. Young mean C_w ($C_{w\,orig}$) for these orientations ($C_{w\,other} = 1.08$, $C_{w\,orig} = 1.10$), but at a given orientation the C_w estimates from the two R.M. Young anemometers tested were significantly different ($p \leq 0.0005$) when individual orientations (based on the

Table 3 R.M. Young horizontal wind-speed corrections (C_u) for all angles-of-attack (α) and wind directions tested

Direction	α	−30°	−15°	−10°	−5°	5°	10°	15°	30°	45°	Mean
0°	C_u	0.95	0.96	0.98	0.95	0.98	1.00	0.98	0.94	1.00	0.97
30°		0.91	0.96	0.98	0.97	*0.99*	*1.00*	*1.00*	*1.03*	*1.13*	1.00
60°		0.93	0.97	0.97	0.97	0.98	1.00	0.97	0.98	1.08	0.98
90°		*1.02*	*0.98*	*1.00*	*0.98*	0.99	1.00	1.02	0.96	1.02	1.00
120°		0.96	0.99	1.01	1.00	1.01	1.02	1.02	1.00	1.04	1.00
150°		0.93	0.99	1.02	1.00	*1.01*	*1.02*	*1.04*	*1.08*	*1.27*	1.04
180°		0.97	1.00	1.03	1.00	1.01	1.01	1.02	1.03	1.13	1.02
210°		*1.06*	*1.03*	*1.04*	*1.02*	1.02	1.02	1.02	0.98	1.06	1.03
240°		0.98	1.00	1.03	1.02	1.02	1.02	1.02	1.07	1.05	1.02
270°		0.93	1.00	1.00	1.01	*1.01*	*1.02*	*1.02*	*1.07*	*1.25*	1.03
300°		0.96	1.00	1.01	1.00	1.00	0.99	1.00	0.99	1.09	1.00
330°		*1.03*	*0.99*	*1.01*	*0.99*	1.00	0.97	0.99	0.94	0.98	0.99
	Mean	0.97	0.99	1.01	0.99	1.00	1.00	1.01	1.01	1.09	1.01

Italics indicate corrections calculated at transducer-shadowed orientations

combination of wind direction and angle-of-attack) were compared. However, there was no difference between anemometers ($p > 0.84$) when orientations were generalized by only angle-of-attack or wind direction. These results indicate that, although C_w estimates are repeatable with an individual sonic anemometer and the mean C_w of different anemometers are similar, significant anemometer-to-anemometer variations may exist at a given orientation, even when the same model anemometer is used. This has important implications for correcting past data, as corrections for w based on specific angle-of-attack and wind direction vary significantly from sensor to sensor, and calibrating every sonic anemometer individually may not be feasible due to the time and resources required. This work demonstrates that sonic anemometer measurement errors are important, but the reader should note that only one sonic anemometer was thoroughly tested and more studies, both theoretical and experimental, are needed before the application of such corrections can be applied defensibly to past sonic anemometer and eddy-covariance data. The ANOVA results indicate that C_w can be estimated based simply on angle-of-attack (Fig. 3), and C_u can be estimated based on angle-of-attack by treating orientations that are either downwind or not downwind of transducers separately (Fig. 5). The ANOVA results also support the application of these generalized corrections to other sonic anemometers of the same make and model, but more testing and analysis are needed to strengthen this finding due to the limited extent of the testing performed on the second anemometer.

The CSAT3 sonic anemometer results from the selected orientations were similar to the R.M. Young results. Although the CSAT3 has smaller transducers than the R.M. Young sonic anemometer, the mean CSAT3 C_w was 1.14. This is supported in Frank and Massman (2011), who found discrepancies of ≈10 % between measurements made with a CSAT3 and an ATI sonic anemometer. As with the two R.M. Young anemometers tested, there was considerable variation in the CSAT3 C_w between different orientations. The standard deviation in the CSAT3 C_w was 8 % and the standard deviation calculated excluding the 5° angle-of-attack orientations was 6 %.

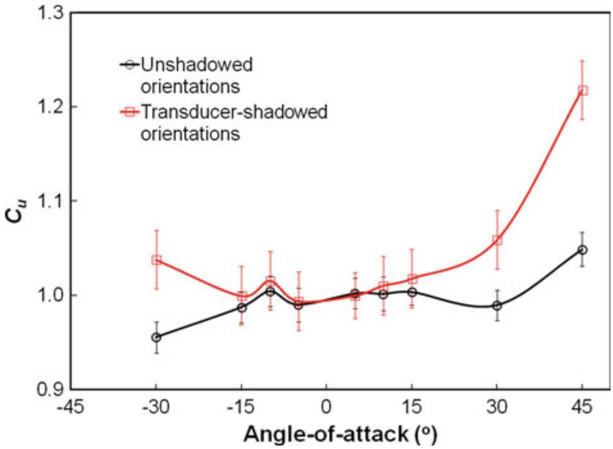

Fig. 5 Corrections to the horizontal velocity (C_u) averaged by angle-of-attack, with C_u estimates from orientations with a transducer directly upwind of the measurement volume (transducer-shadowed orientations, *red with squares*) and from unshadowed orientations (*black with circles*) plotted separately. *Error bars* indicate the standard error of the C_u estimates used to calculate the mean values

ATI sonic anemometer testing at four angles-of-attack ($-30°, -15°, 15°$, and $30°$) resulted in a mean C_w of 1.00 and a standard deviation of 1.5 %, or 0.015. This indicates that angle-of-attack errors can be eliminated by proper instrument design, and that the methods used to measure w in this experiment were sound. The ATI was only tested at one wind direction, which corresponded to the airflow coming directly into the sensor. This minimized the effects of wakes created by the transducers used to measure the horizontal wind speed.

3.2 Corrected Measurements

All of the available 2009 flux measurements from the Brookings flux tower and the Chestnut Ridge flux tower were re-evaluated to examine the effects of angle-of-attack corrections on turbulent statistics and the fluxes of energy and mass. Two weeks of data from the Bondville flux tower were also re-evaluated. The 30-min standard deviations of the vertical wind speed (σ_w) and the Reynolds stresses ($-u'w'$) at the forest, grassland, and maize sites were augmented by 7–10 % through the application of angle-of-attack corrections (Fig. 6). The fluxes of energy and CO_2 were more variable, with increases in energy fluxes over the forest and maize sites of up to 13 % (Fig. 7). The increase in fluxes over the grassland was smaller due to the prevalence of lesser angles-of-attack over the smoother surface. At the maize site proximity to the canopy may have compensated for the decrease in canopy roughness relative to the forest site, resulting in comparable flux-angle distributions and angle-of-attack corrections. Linear regressions were not forced through the origin, but the offsets for all regressions were negligible because corrected near-zero fluxes and statistics remained near-zero.

As an alternative to the angle-of-attack and wind-direction specific corrections, a mean correction was applied to the same dataset from the three sites by multiplying w by the average C_w of 1.12. These data are not shown, but they resulted in regression slopes of 1.12 for all the variables shown in Figs. 6 and 7. The very small regression errors were due only to variations in the coordinate system rotation due to the change in w, but the effects of these regression errors on the fluxes and statistics were negligible, as they were much smaller than errors in C_w and other errors in the measured statistics and fluxes. Indeed, the reason these

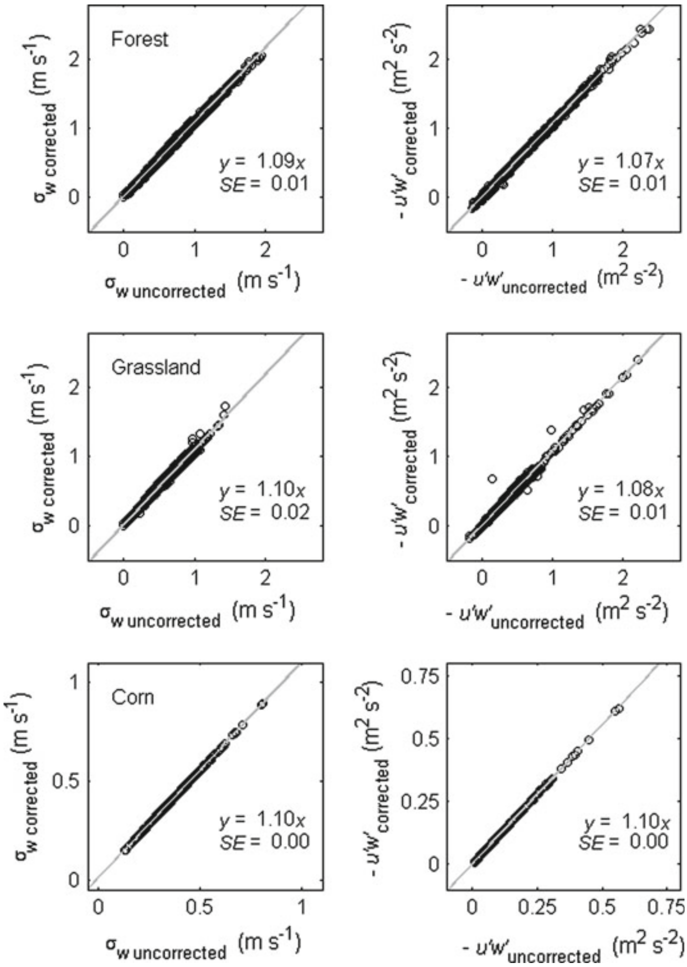

Fig. 6 Comparison of uncorrected and corrected 30-min standard deviations of the vertical wind speed (σ_{W}) and Reynolds stresses ($-u'w'$) at the Chestnut Ridge (*forest*), Brookings (*grassland*), and Bondville (*maize*) flux towers. The standard error (*SE*) and the slope of linear regressions are also shown

data and regressions are not shown is because they vary from each other only in the scale and units on their axes, and all were essentially a straight line with a slope of 1.12 and a standard error of zero. It is worth noting that *LE* and F_c, which were estimated from measurements recorded using an open-path CO_2/H_2O gas analyzer, were also linearly affected by the mean correction. This is because the density corrections applied to the fluxes of CO_2 and water vapour changed linearly with the fluxes of sensible heat and water vapour (Webb et al. 1980). In this special case where all fluxes are affected equally by the same mean correction to the vertical wind speed, the density correction does not contribute any additional non-linearity to the resultant corrected fluxes. This indicates that a mean correction to the vertical wind speed can be applied directly to past fluxes without introducing any additional significant errors, other than the errors in the correction itself. Comparison of fluxes estimated using the mean correction and fluxes estimated using the angle-of-attack and wind-direction specific corrections yielded maximum differences of up to 2 % for the forest and the grassland sites.

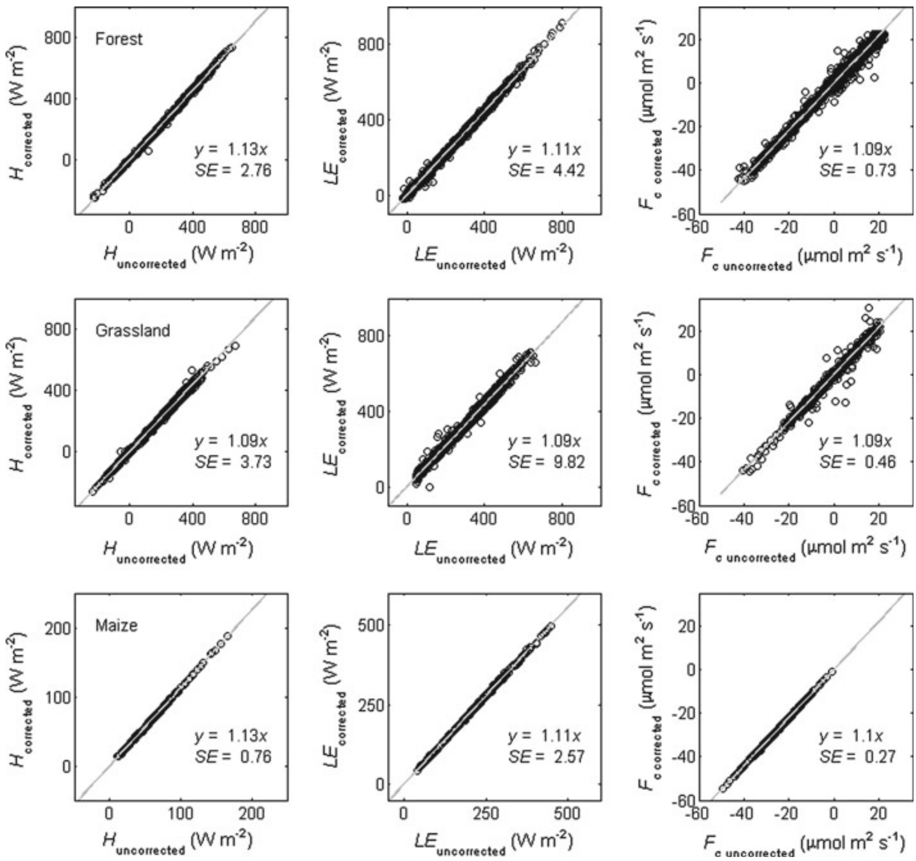

Fig. 7 Comparison of uncorrected and corrected 30-min fluxes of sensible heat (H), latent heat (LE), and CO_2 (F_c) at the Chestnut Ridge (*forest*), Brookings (*grassland*), and the Bondville (*maize*), flux towers

In consideration of the significant sensor-to-sensor variability demonstrated in the angle-of-attack and wind-direction specific C_w, more research is required to show that the application of a wind-direction/angle-of-attack specific correction is significantly more accurate than a mean correction. Some middle ground between the re-analysis of 10-Hz data and the application of a gross correction may also be possible, where corrections are applied based on measured turbulent statistics such as $\sigma_w/\overline{u}$ and skewness ($w'w'w'$ for example) that indicate the dominant angles-of-attack and flux-angle distribution in a given 30-min period. These suggestions are presented in part because not all researchers permanently record their high-frequency measurements, rendering the re-analysis of past high-frequency data impossible.

The 30-min sums of H, LE, and G were compared to the net radiation (R_n) from the Bondville flux tower (Fig. 8). Soil heat fluxes were computed by measuring the soil thermal properties with a dual-heat probe heat-pulse method (Bristow et al. 1994) at three locations. The measurements of the soil thermal conductivity and soil heat capacity (at 50 mm) were combined with observations of the vertical temperature profile at three locations to obtain the total soil heat flux, including the heat storage (see Ochsner et al. 2007). Net radiation, measured with a model CRN1 (Kipp and Zonen, Delft, The Netherlands) has measurement uncertainties of about 5 % (Blonquist et al. 2009). Maximum soil heat fluxes were on the order

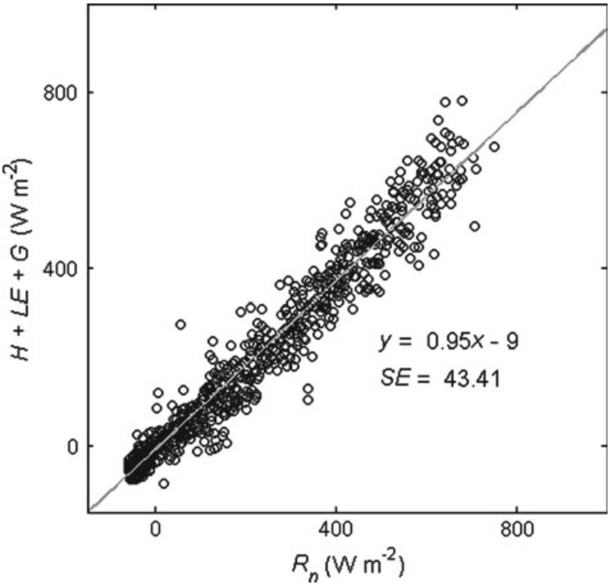

Fig. 8 Sensible heat fluxes (H) plus latent heat fluxes (LE) plus ground heat fluxes (G) of maize plotted against the net radiation (R_n) at the Bondville flux tower from 19 July 2011 through 1 August 2011

of 150 W m^{-2} and the coefficient of variation was about 24 % on a 30-min basis. Typically, the sum of all the heat fluxes accounts for only 70–80 % of R_n (Wilson et al. 2002b). With the inclusion of angle-of-attack corrections to the vertical velocity, heat fluxes accounted for 95 % of R_n.

3.3 Side-by-Side Anemometer Comparison

An ATI and an R.M. Young sonic anemometer were installed adjacent to each other on the Chestnut Ridge flux tower above a 25-m tall forest. The effects of angle-of-attack errors and sensor design were demonstrated by comparing sensible heat fluxes, Reynolds stresses, and σ_w derived from these measurements. The underestimated R.M. Young w caused a 10–15 % discrepancy in the measured fluxes and turbulent statistics derived from w (Fig. 9). This agrees with past research, in which the fluxes estimated from the orthogonally oriented ATI sonic anemometer measurements above a forest (Frank and Massman 2011) and cotton (Mauder et al. 2007) were ≈10 % greater than those estimated from CSAT3 measurements. In contrast to these findings, in another study that compared field measurements from a CSAT3 and an orthogonally oriented ATI sonic anemometer, the orthogonally oriented anemometer measured similar or even smaller σ_w and sensible heat fluxes than the CSAT3 (Loescher et al. 2005).

4 Conclusions

The vertical wind speed measured by the R.M. Young sonic anemometer was demonstrated to be underestimated by ≈12 %. Measurements from this and other field studies indicate that the majority of the three-dimensional sonic anemometers utilized for eddy-covariance

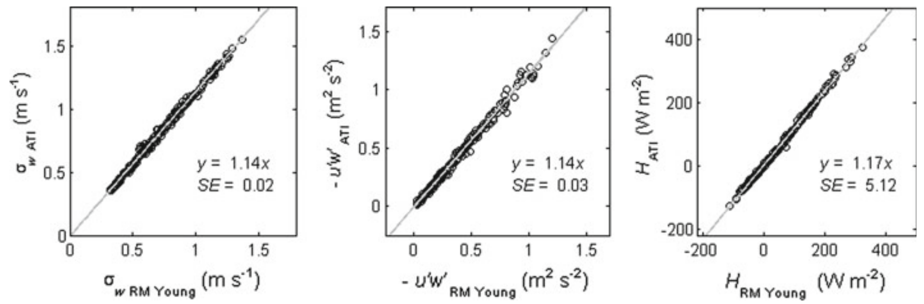

Fig. 9 Comparisons of the standard deviations of the vertical wind speed (σ_W), Reynolds stresses ($-u'w'$), and sensible heat fluxes (H) measured using R.M. Young and ATI sonic anemometers on the Chestnut Ridge flux tower above a 25 m tall forest

measurements underestimate w and the resultant fluxes of mass and energy by 10–15 %. This helps explain the lack of energy budget closure that has plagued micrometeorologists since the widespread use of non-orthogonal sonic anemometers in eddy-covariance studies began (e.g. Wilson et al. 2002a). This work also indicates that hourly, daily, and annual fluxes of CO_2 and other trace gasses have been significantly underestimated.

Past flux measurements and turbulent statistics can be corrected for angle-of-attack errors using appropriate methods, but to avoid the necessity of yet another required eddy-covariance correction, future studies should utilize sonic anemometers designed to minimize the effects of transducer shadowing on the measured vertical wind speed. The non-orthogonal transducer orientation currently in use in most research grade three-dimensional sonic anemometers is designed to measure the wind velocity when the vertical component of the wind velocity is negligible, but this orientation causes a significant underestimation of w even at small angles-of-attack. In contrast, our results indicate that a properly designed sonic anemometer that estimates w from one pair of vertically aligned transducers experiences negligible angle-of-attack errors at typical flux angles.

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