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An inter-comparison between Gill and Campbell sonic anemometers

Taro Nakai[a,b,c,*], Hiroki Iwata[d], Yoshinobu Harazono[c], Masahito Ueyama[e]

[a] Hydrospheric Atmospheric Research Center, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8601, Japan
[b] Graduate School of Bioagricultural Sciences, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8601, Japan
[c] International Arctic Research Center, University of Alaska Fairbanks, 930 Koyukuk Drive, Fairbanks, AK 99775-7340, USA
[d] Graduate School of Agriculture, Kyoto University, Kitashirakawa Oiwake-cho, Sakyo-ku, Kyoto, Kyoto 606-8502, Japan
[e] Graduate School of Life and Environmental Sciences, Osaka Prefecture University, 1-1 Gakuen-cho, Nakaku, Sakai, Osaka 599-8531, Japan

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ABSTRACT

Inter-comparison measurements of the Gill WindMaster and Campbell CSAT3 ultrasonic anemometers were conducted in a burned black spruce forest in interior Alaska, in order to clarify the effects of correction to Gill sonic anemometer angle of attack errors on flux data comparison. A certain version of WindMaster (Pro) proved to require the correction of high-frequency signal loss in cospectra, due to the rolling average feature, resulting in a 6.5–14.2% increase in fluxes. Before the correction of angle of attack errors was applied to the WindMaster data, eddy fluxes measured by the WindMaster were 14.3–24.0% smaller than those from CSAT3. Applying this correction to WindMaster data, we found that the scalar fluxes measured by WindMaster and CSAT3 were nearly the same, while momentum flux was somewhat underestimated by WindMaster compared to CSAT3, even after corrected. Though the underestimation of fluxes by non-orthogonal sonic anemometers compared with orthogonal anemometers has been pointed out, and both WindMaster and CSAT3 are non-orthogonal, the inter-relationships of various types of sonic anemometers are still unclear. At this stage, therefore, our results may support the most reliable data comparisons between sites where Gill and Campbell CSAT3 anemometers are adopted by applying the correction of angle of attack errors to the data of Gill anemometers.

1. Introduction

The measurement of sensible and latent heat fluxes and CO_2 flux by eddy covariance technique is essential for understanding heat, water, and carbon cycling between terrestrial ecosystems and the atmosphere. According to the FLUXNET website (ORNL DAAC, 2011), over 500 flux tower sites are operated on a long-term and continuous basis at present. The data from these sites have been used not only for site-specific research but also for intersite comparison studies and integration analyses, such as analyses of CO_2 balance (e.g. Luyssaert et al., 2007; Hirata et al., 2008; Ueyama et al., 2013) and energy balance closure (e.g. Wilson et al., 2002; Hendricks Franssen et al., 2010). These kinds of studies are based on accurate and reliable measurements of fluxes by eddy covariance technique.

In the past decade, however, Gill ultrasonic anemometers have been shown to suffer errors due to angle of attack (van der Molen et al., 2004; Nakai et al., 2006; Nakai and Shimoyama, 2012); angle of attack is defined as the angle between the wind vector and the horizontal plane. Nakai and Shimoyama (2012) confirmed that angle of attack errors occurred even under turbulent conditions, and also provided improved calibration functions for correcting such errors under turbulent conditions by using the calculation method proposed by Nakai et al. (2006). This correction resulted in increases in eddy fluxes by about 14% over meadow (Nakai and Shimoyama, 2012). Recently, Kochendorfer et al. (2012) reported that the Model 81000 ultrasonic anemometer (R.M. Young, Traverse City, Michigan, USA) also showed underestimation of vertical wind speed due to angle of attack errors, and they developed look-up tables for the correction of vertical and horizontal wind speeds. These studies imply that angle of attack errors can occur in other ultrasonic anemometers as well, especially if the transducers of the anemometer are non-orthogonally oriented. Here it is worth noting that Kochendorfer et al. (2012) confirmed that angle of attack errors from the ATI Vx-style ultrasonic anemometer (SATI/3Vx, Applied Technologies, Inc., Longmont, CO, USA), which has the orthogonal transducer orientation, were negligibly small. In addition, Frank et al. (2013) showed that the Campbell CSAT3 underestimated

* Corresponding author at: Hydrospheric Atmospheric Research Center, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8601, Japan.
Tel.: +81 52 789 3439; fax: +81 52 789 3439.
E-mail address: taro.nakai@gmail.com (T. Nakai).
URL: http://sites.google.com/site/micrometeorologist/ (T. Nakai).

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Table 1
Ultrasonic anemometers employed by AmeriFlux sites, according to the previous FLUXNET website (as of January 2012, currently unavailable from the renewed website, http://fluxnet.ornl.gov/).

Manufacturer	Sites	Percentage	Model	Sites
Campbell Scientific, Inc.	88	57.5%	CSAT3	88
Gill Instruments Ltd.	40	26.1%	WindMaster Pro	20
			R2	8
			R3	10
			R3A	1
			HS	1
R.M. Young Company	9	5.9%	81000V	8
			81000VRE	1
Applied Technologies, Inc.	9	5.9%	SWS-211/3K	3
			SATI/3K	4
			SATI/3Sx	1
			SATI/3Vx	1
No information	7	4.6%		
Total	153	100%		146

fluxes compared to SATI/3Vx, though they did not clarify whether such underestimation was due to angle of attack errors.

Although there are various types of ultrasonic anemometers, Campbell and Gill ultrasonic anemometers are the most commonly employed instruments at FLUXNET sites. For example, 55.7% of AmeriFlux sites have adopted Campbell CSAT3, and Gill anemometers accounted for 26.1% (Table 1), as of January 2012. However, though inter-comparisons of ultrasonic anemometers have been made in several studies (e.g. Loescher et al., 2005; Mestayer et al., 2005; Mauder et al., 2007; El-Madany et al., 2013), the effects of angle of attack errors have not been considered in such studies, and thus how the corrections of angle of attack errors of Gill ultrasonic anemometers affect the inter-comparison of fluxes with other anemometers is still unknown.

A comparison of the performances of Gill and Campbell ultrasonic anemometers, considering the effects of the correction of angle of attack errors, is thus of great importance for a multi-site analysis of eddy covariance fluxes over FLUXNET sites. The objective of this study has been to explore the effects of these corrections to the Gill anemometer by Nakai and Shimoyama (2012) (hereafter AoA correction) upon the inter-comparison of eddy covariance calculations between Campbell and Gill anemometers by a field experiment.

2. Measurements and data post-processing

Measurements were conducted from August 25 to September 12, 2011, in a burned black spruce forest on a hilltop at the Poker Flat Research Range (PFRR), University of Alaska Fairbanks (65°08′N, 147°26′W, 491 m a.s.l.), where ongoing year-round flux observation is conducted (Iwata et al., 2011). Instruments were installed within burned black spruce stands (ca. 4 m tall), with ground surface partly covered by short vegetation such as white birch, trembling aspen, Labrador tea, bog blueberry, sedge, fireweed, and mosses (Iwata et al., 2011). Fractional vegetation cover of these understory plants was about 70–80%, with plant height not more than 0.5 m around the measurement site (Nakai et al., 2011). This site was located on a north-facing slope, and the ground surface was slightly slanted to the north, with its slope less than 4.2 degrees.

In this study, WindMaster ultrasonic (Gill Instruments, Lymington, UK) and CSAT3 sonic anemometers (Campbell Scientific, Logan, UT, USA) were compared (Fig. 1). The recommended operating range (i.e., the application limit for accuracy specifications) of the angle of attack was ±30° for the WindMaster, and ±20° for the CSAT3. Variables measured by these anemometers included horizontal wind components u (m s^{-1}) and v (m s^{-1}), vertical component w (m s^{-1}), and sonic virtual temperature T_{sv} (K).

Fig. 1. Photographs of the front and side views of the experimental design in this study.

Concentration of water vapor, ρ_v (mg m^{-3}), and CO_2, ρ_c (mg CO_2 m^{-3}) were measured by LI-7500 open-path infrared gas analyzer (LI-COR, Lincoln, NE, USA) and these data were logged in a CR3000 data logger (Campbell Scientific, Logan, UT, USA) at 10 Hz. The WindMaster, CSAT3, and LI-7500 were arranged so that the centers of their paths were equal in height (2.6 m above the ground). The LI-7500 was placed between the two anemometers, and the distances between each anemometer and the LI-7500 were about 20 cm.

Friction velocity u_* (m s^{-1}), sensible heat flux $\overline{w'T'}$ (K m s^{-1}), latent heat flux $\overline{w'\rho_v'}$ (mg m^{-2} s^{-1}), and CO_2 flux $\overline{w'\rho_c'}$ (mg CO_2 m^{-2} s^{-1}) were used for data comparisons between the two anemometers. These were calculated using the eddy covariance method, and the following concerns were considered when processing data. Data spikes were removed according to Vickers and Mahrt (1997). The double-rotation method was applied so that the mean lateral and vertical wind speeds equaled zero (McMillen, 1988). Detrending was not applied, though frequency response correction was considered (see Section 3.1). Since the sonic virtual temperatures of the WindMaster and CSAT3 were both corrected internally for crosswind, only the humidity correction (Schotanus et al., 1983) was applied to calculate air temperature T (K). The zero wind speed test was conducted by enclosing anemometers in a plastic bag, and the obtained offsets were taken into account. The u, v, w offsets of the WindMaster and CSAT3 were 0.001, 0.002, 0.030 and 0.001, −0.064, −0.003 m s^{-1}, respectively.

Delay times t_d (s) between the LI-7500 and the anemometers (WindMaster, CSAT3) were calculated using a dynamic delay correction (Nakai et al., 2011), expressed as follows:

$$t_d = -\frac{l}{\overline{U}} \cos(\gamma - b) + d, \quad (1)$$