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Publication Date
2019-02-01

DOI
10.1016/j.agrformet.2018.11.010

Peer reviewed

Effects of the Gill-Solent WindMaster-Pro “w-boost” firmware bug on eddy covariance fluxes and some simple recovery strategies

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Abstract

In late 2015 and early 2016, work done by the AmeriFlux Management Project Technical Team (amerilfux.lbl.gov) helped to uncover an issue with Gill WindMaster and WindMaster Pro sonic anemometers used by many researchers for eddy covariance flux measurements. Gill has addressed this issue and has since sent out a notice that the vertical wind speed component (a critical piece of all eddy covariance fluxes) was being erroneously computed and reported. The problem (known as the “w-boost” bug) resulted in positive (upward) wind speeds being under-reported by 16.6% and negative (downward) wind speeds being under-reported by 28.9%. This has the potential to cause similar under estimates in fluxes derived from measurements using these instruments. Additionally, the bug affects corrections for angle of attack as derived by Nakai and Shimoyama, rendering them invalid. While the manufacturer has offered a firmware upgrade for existing instruments that will fix this issue, many existing data sets have been affected by it and are currently in use by the scientific community. To address the issue of affected data, currently in use, we analyzed multi-year and short-term data sets from a variety of ecosystems to assess methods of correcting existing flux data. We found that simple multiplicative correction factors (~1.18) may be used to remove most of the “w-boost” bias from fluxes in existing data sets that do not include angle of attack corrections.

Keywords: Eddy covariance, Flux, Sonic anemometer

1. Introduction

The importance of sonic anemometry to the eddy covariance technique is well known. It is at the heart of this method which is widely used to estimate the exchange of matter and energy between the land surface and the atmosphere. The accuracy and precision of vertical wind speed measurements directly affects the quality of calculated fluxes (Baldocchi et al., 1988; Lee et al., 2004; Aubinet et al., 2012). In the last 40 years, much effort has been expended to refine and improve sonic anemometry with the goal of reducing biases and uncertainties in eddy covariance fluxes (Wyngaard and Zhang, 1985; Nakai et al., 2006; Kochendorfer et al., 2012; Nakai and Shimoyama, 2012; Frank et al., 2013; Horst et al., 2015). Many of these works have focused on topics related to instrument geometry and transducer-induced flow distortions, and they all share the common assumption that the tested instruments correctly report wind velocity components as defined by the instrument specifications. This assumption is made based on the fact that all manufacturers test and calibrate instruments (individually or by model representatives) in wind tunnels.

Field researchers also rely on this assumption, but at typical installations, there is usually no opportunity to verify it by comparison with a second instrument. In this respect, the AmeriFlux Management Project (AMP) Technical Team (ameriflux.lbl.gov/tech) is in a unique position. One of the main functions of the Tech Team is to maintain and improve data quality from network sites through an on-going inter−COmparison campaign (ameriflux.lbl.gov/site-visits). During these exercises, Tech Team members deploy a well vetted, portable eddy covariance flux system adjacent to a client system for an observation period of about 10 days. Results from both systems are then compared and differences are assessed. In late 2015 and early 2016, the Tech Team identified anomalous wind velocity behavior during several flux site comparisons, all of which involved the same model and vintage Gill sonic anemometer (WindMaster and WindMaster Pro). A Gill distributor in the U.S. (LI−COR Biosciences, Lincoln, NE) and the manufacturer (Gill Solent, Lymington, UK), investigated this and discovered that between 2006 and 2015, this specific sonic anemometer model suffered from a firmware error that resulted in an asymmetric under estimation of vertical wind speeds. This flaw caused a 16.6% under estimation of positive (or upward) vertical wind speeds and a 28.9% under estimation of negative (or downward) vertical wind speeds and became known as the “w-boost” bug. Gill further confirmed that this issue was isolated to the vertical wind velocity component, did not affect the horizontal velocity components or the sonic temperature measurements, and was only present in the WindMaster and WindMaster Pro models manufactured between 2006 and 2015. This error has since been fixed in new units and Gill offers several remedies for owners of affected instruments (Gill-Solent website, 2016).

The manufacturer has identified specific firmware versions and serial number blocks which allow identification of potentially affected instruments (see the Appendix). This method however, is not an infallible indicator of whether or not the “w-boost” bug has propagated into public data sets derived from them. In the simplest case, the dataoriginator may be unaware of the “w-boost” bug, or may not have an opportunity to modify their sonic anemometer or their post-processing work flow. This will result in publicly available flux data that is affected by the “w-boost” bug and is associated with metadata necessary to detect the situation. In other cases, the effects may have been corrected in the post-processing work flow, but non-updated metadata (instrument serial number or firmware version) could indicate that the data still contains the “w-boost” bias.

Aside from these direct effects, the “w-boost” bug can be manifested in other flux corrections derived from affected instruments. One notable case concerns the application of the transducer flow distortion (“angle of attack” or AoA) corrections calculated by Nakai and Shimoyama (2012). These algorithms were derived from data produced by affected sonic anemometers, and did not include compensation for the (then undiscovered) “w-boost” bug. The resulting AoA corrections effectively mix unaffected u and v wind speeds with affected w ones. Because of this, application of the Nakai and Shimoyama (2012) AoA correction will produce erroneous results in all cases, and is not recommended. Unfortunately, this algorithm has been incorporated into widely used, raw data processing streams (e.g., LiCor’s EddyPro), and it is likely that data sets with this secondary error have been made available to the public. Also, because the essential geometry of the Windmaster/ Windmaster Pro sonic anemometers is shared with the Gill R3 and R3- 50 models, it is possible that some data-originators have applied the Nakai and Shimoyama (2012) AoA correction to these instruments as well, creating yet another class of affected data. In all, we recognize five potential cases of data that are directly or indirectly affected by the “wboost” bug:

1 Fluxes from affected Windmaster and Windmaster Pro sonic anemometers where no corrections have been applied.

2 Fluxes from affected Windmaster and Windmaster Pro sonic anemometers where only the “w-boost” bug correction has been applied.

3 Fluxes from affected Windmaster and Windmaster Pro sonic anemometers where only the erroneous Nakai and Shimoyama (2012) AoA correction has been applied.

4 Fluxes from affected Windmaster and Windmaster Pro sonic anemometers where both the Nakai and Shimoyama (2012) AoA and the “w-boost” corrections have been applied

5 Fluxes from unaffected (R3, R3-50, or repaired or older WindMaster and WindMaster Pro) sonic anemometers where the Nakai and Shimoyama (2012) AoA correction has been applied.

It appears that data-originators may have unknowingly yet systematically calculated and shared under estimated values for eddy covariance fluxes derived from both affected and unaffected instruments and that researchers have been using these biased data sets for other studies. Two challenges therefore emerge regarding historical observations: first, the development and implementation of simple and practical correction strategies and second, a method to unambiguously identify affected data sets.

The first challenge is itself twofold. First a method of correcting fluxes for the “w-boost” bug must be developed and second, a method of removing the erroneous AoA correction is needed.

Because of the nature of the eddy covariance process, it is not obvious that a simple multiplicative factor will adequately correct existing fluxes for the “w-boost” bug, or what that factor might be. The ideal solution of course is to correct and re-process raw instrument data (LICOR website, 2016). In practice, this solution could be difficult and inconvenient for many data providers to implement, due to its laborintensive nature and will often be impossible for data users and archive managers since the raw data streams are not usually available. A more feasible approach would be the development and use of a simple mathematical transform that employs only variables commonly available to end-users which can be applied directly to affected fluxes.

Regarding the indirect effects of the “w-boost” bug that are propagated through the Nakai and Shimoyama (2012) AoA corrections, we expect the two to be independent, but without access to the original high-speed data used to calculate the AoA corrections, we cannot exactly determine the magnitude of the effect that the “w-boost” bug had on them, nor can we modify the algorithms. We can, however attempt to develop a simple strategy to effectively remove the AoA correction from existing data sets similar to the one outlined above.

A similar approach could be taken to address the second issue (identification of affected data sets). Commonly available variables could be compared to expected values for flux sites to determine if an affected sonic anemometer was present. Alternatively, and perhaps more reliably, efforts could be made (by data users or network data curators) to reach out to data-originators and determine directly, whether an affected instrument was used to produce the data set in question and whether or not corrections have been applied.

The AmeriFlux Tech Team launched an effort to explore these options and determine which if any are practical for wider use. Our unique position allowed us to obtain long-term and short-term, raw data sets from eddy covariance flux sites in a variety of ecosystems. From an analysis of exactly corrected fluxes with respect to uncorrected fluxes, we have developed a simple correction strategy for removal of the “wboost” bug that can be used by the flux community.

2. Methods and study sites

From the beginning, we adopted the restriction that any correction scheme must rely only on variables that are commonly available from the large data archives (e.g., AmeriFlux, FluxNet, ARM, etc.). This precluded any method that would rely on original, high-speed data which might only be available from the data originator and would not be commonly available from public archives. For our purposes, these data included fluxes, mean wind velocity components, and simple statistical moments (e.g., standard deviations or variances) over the flux averaging period (typically but not limited to 30 min). We settled on four metrics to test: 1.) sensible heat flux [H], 2.) latent heat flux [LE], 3.) CO_2 flux [f CO_2], and 4) CH_4 flux [f CH_4] (where available). We rejected: mean vertical wind speed since the un-rotated form is not commonly available, all second statistical moments since they do not preserve the sign of the argument, and momentum flux since it is not commonly available in historical data. Friction velocity was however, retained in our analysis since it was deemed useful for calculation of other parameters.

To construct an appropriate “w-boost” correction scheme for existing fluxes, we considered three approaches. First was a simple average of the two individual factors for upward (1.166) and downward (1.289) wind speeds (as determined by Gill). The second approach was a linear transformation, determined from analysis of corrected and uncorrected fluxes. The third approach was to derive a correction function from the uncorrected fluxes or other mean (half-hourly) quantities, commonly available from typical data archives. To evaluate each of these approaches, we performed linear regressions between corrected and uncorrected fluxes calculated from raw data sets obtained directly from flux site investigators (the data originators). To avoid biases due to individual site characteristics, the data sets came from towers located in a variety of ecosystems.

Since our evaluation required calculation of fluxes from corrected and uncorrected raw data, both the first and second approaches were straight forward and only involved linear regressions between the resulting quantities. The third approach, however, required development of a correction function. Because the corrections determined by Gill were simple multipliers for upward and downward wind speeds, we chose a simple weighted average of these values where the weights were determined by the fraction of positive and negative values of the chosen metric. The hope was that the weighting factors would preserve the original distribution of positive and negative vertical wind speeds. The functional form of this correction is given by:

$$Corr = \left(\frac{n_+}{n_+ + n_-}\right)1.166 + \left(\frac{n_-}{n_+ + n_-}\right)1.289 \qquad (1)$$

where n_+ is the number of positive values of the chosen metric and n- is the number of negative values. The weighting factors (in parenthesis) were evaluated either for the total duration of the data set (short-term sites) or for yearly periods (long-term sites).

To detect the presence or absence of the “w-boost” bug in any data set, we examined several parameters for “universality” across sites and years. Again, a key criterion was that these metrics must be included in, or calculable from typical on-line data sets. The metrics tested were: 1.) Monin-Obukhov stability parameter (z/L), 2.) the vertical wind speed universality function ($\varphi_w = \sigma_w/u^*$) and, 3.) the uw correlation coefficient ($r_{uw} = (u^*)^2/\sigma_u\sigma_w$) (Kaimal and Finnigan, 1994). The goal of this analysis was to determine if there were any absolute levels that could be used as indications of an affected sonic anemometer, independently of site, flux, or time of year.

The first step in our analysis was to create “corrected” raw data sets. This was done by simply multiplying all of the positive (or upward) vertical wind values by 1.166 and the negative (or downward) ones by 1.289 to correct for the “w-boost” bug, and of using the code from Nakai’s web site to correct for AoA (Nakai and Shimoyama, 2012). This resulted in raw data sets that were: 1.) uncorrected (U), 2.) corrected for the “w-boost” bug only (W), 3.) corrected for AoA only (A), or 4.) corrected for both the “w-boost” bug, and for AoA (AW). We then processed all of the raw data using identical work flows. This was done using either our in-house processing package, HuskerProc (Billesbach et al., 2004) or the freely available EddyPro® software package (https://www.licor.com/env/products/eddy_covariance/eddypro.html) (Note: in the case of EddyPro processing, we used the built-in AoA corrections). QA/QC procedures appropriate to each site were also applied to the data. These data scenarios represent the four potential cases that are directly or indirectly affected by the “w-boost” bug. We then used these data sets to evaluate our correction and detection strategies.

The sites selected for this study were chosen for their verified use of an affected Gill sonic anemometer, availability of high-frequency raw data, membership in one or more flux networks or data archives, and for variety in ecosystem and climatic representation. Details of the sites are contained in Table 1.The first two sites are part of the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM), Climate Research Facility and are located at Barrow and Point Oliktok, in the North Slope Borough of Alaska, USA. These sites are Arctic coastal tundra and several years of high-frequency data were available, typically collected between early-spring and late-fall. The third site (FluxNet, GH-Ank) is located in Ghana, Africa near the Atlantic coast and is an equatorial forest. Slightly less than one year of raw data was available from this site. The fourth site (AmeriFlux, US-SP1) is located in Florida, USA and is a slash pine forest with slightly less than one year of available data. The last two sites contributed short term (~2 weeks) high-frequency data sets from deployments of the AmeriFlux reference flux systems. One, US-Myb, is a recovered wetland in the SacramentoSan Joaquin River Delta near Sacramento, California USA, and the other, US-StJ, is a tidal salt marsh in the Saint Jones Reserve near Dover, Delaware, USA. These sites represent both tall and short-stature ecosystems; cold, temperate, and warm climates; and northern, midlatitude, and equatorial locations.

3. Results

Our first task was to determine if a simple, linear transform could be used to compensate for the “w-boost” bug and/or AoA correction in existing flux data sets. We arbitrarily set the criterion that if linear regressions between corrected and uncorrected fluxes showed little scatter about regression lines (R^2 values greater than 0.9), the relationship would be considered linear. Fig. 1 shows comparisons between “w-boost” corrected (W) and uncorrected (U) fluxes for one siteyear of data (2015) from the Point Oliktok site. These results were typical for all regressions from all sites. Not only were R^2 values very high, but offsets were negligible (less than 0.5% of the maximum data range). Points falling away from the main data trend were determined to be questionable fluxes that were not filtered out by our QA/QC routine. This confirms that a simple multiplicative factor can be used as a “w-boost” correction. The high degree of linearity and small scatter about the regression lines for entire years also indicate that factors such as wind speed and direction, seasonality, stability class, and other environmental and temporal variables had little or no effect. As a result, we did not run separate regressions on sub-groups of our fluxes and took this as evidence that a single multiplier can be used to correct fluxes over long time periods.

Regression results (i.e. slopes) between corrected (W) and not corrected (U) data are listed in Table 2. Between all sites, fluxes, and years, the correction factors ranged between 1.206 and 1.130, a range of less than 7% and were clearly different than the simple average of the upward and downward, instantaneous correction factors (1.228). If we disregard friction velocity which is complicated by the need to square the regression slope, the range was 1.199 to 1.140 (a range of about 5%). The average correction for the different fluxes across sites and years varied between 1.171 and 1.187, while the average corrections for all fluxes varied between 1.200 and 1.142 across all sites and years. The average of all correction factors across all sites, years, and fluxes was 1.176. While this removes a bias of almost 18% in typical data sets, it is possible that (based on the range of calculated corrections listed here) application of this factor could add up to 3% additional uncertainty to long-term budget calculations.

To consider the secondary effects of applying (or not) the erroneous AoA corrections, we considered three combinations: AoA corrected (A) versus completely uncorrected data (U), AoA corrections applied to “wboost” corrected data (AW) versus data only corrected for the “w-boost bug (W), and AoA only corrected data (A) versus data corrected only for the “w-boost bug (W). Tables 3, 4, and 5 show the regression slopes for these combinations respectively. As before, the R^2 values were higher than our criterion and the intercepts were small, and we again focused only on the regression slopes. In all cases we see (as illustrated in Fig. 2) that the behavior of the tropical rainforest (GH-Ank) is significantly different from the two Arctic tundra sites. Table 3 shows that application of the AoA correction (A) increases uncorrected (U) fluxes by 6% to 11% at the Arctic sites with an average flux correction factor (ignoring u^{*2}) of 1.086. At the rainforest site the increases were between 20% and 24% with an average correction factor of 1.226. This configuration is typical of some older, standard processing work flows that are not aware of the “w-boost” bug but do apply the AoA correction. Table 4 shows that application of the AoA correction to data corrected for the “w-boost” bug (AW) compared to “w-boost” bug only corrected (W) data again increases fluxes by similar amounts. This situation corresponds to more recent processing work flows that are aware of the “wboost” bug, but are not aware of the errors in the Nakai and Shioyama (2012) AoA correction. Together, these two results suggest that the two corrections (“w-boost” and AoA) are independent. Table 5 shows the comparison of AoA corrected only data (A) to “w-boost” bug only corrected data (W). This combination illustrates the implications of using an older processing work flow (AoA correction only) as a surrogate for the “w-boost” bug correction. We see in this case that the Arctic sites are significantly under corrected while the rainforest site is moderately over corrected. This suggests that the erroneous AoA correction partially compensates for the “w-boost” error, but that the magnitude of the compensation is site-dependent.

Table 1
Site information.

Site	Network	Lat.	Lon.	Elev. (m)	Ecosystem type	Duration	Canopy Height (m)	Tower Height (m)
Barrow	ARM	71°19’28”N	156°36’54”W	3	Arctic coastal tundra	~3 years	~10cm	4m
Pt. Oliktok	ARM	70°29’43”N	149°52’56”W	5	Arctic coastal tundra	~1 year	~10cm	4m
GH-Ank	FluxNet	05°16’07”N	002°41’39”E	124	Equatorial rain forest	~1 year	~35m	~65m
US-SP1	AmeriFlux	29°44’17”N	082°13’98”W	50	Slash pine forest	~1 year	~25m	~31m
US-Myb	AmeriFlux	38°02’59”N	121°45’54”W	−1	Wetland	~2 weeks	~2m	~5m
US-StJ	AmeriFlux	39°05’18”N	075°26’14”W	7	Atlantic coastal salt marsh	~2 weeks	~1.5m	~3.6m

Our second task was to evaluate available variables as surrogates for instantaneous (high-frequency) vertical wind speed in calculating “wboost” correction factors using Eq. (1). These results are listed in Table 6. We see that in all cases, the proposed correction algorithm overestimated fluxes when compared to the exact method. This disagreement was not unexpected as there is no a-priori reason that the raw vertical wind speed distribution would be preserved in the data products tested. This implies that commonly available, uncorrected variables do a worse job of predicting” w-boost” correction factors than a simple, fixed multiplier.

The third and final task was to evaluate three commonly available metrics for their ability to predict if a given data set was affected by the “w-boost” bug. To do this, we calculated half-hourly values for the three chosen metrics (z/L, φ_w, and r_{uw}), and averaged them over an entire year for three of our long-term data sets. These three were deemed to represent the greatest differences in mean atmospheric conditions and ecosystem type. The results are shown in Fig. 3. It is obvious from the figure that none of these metrics can be used as a blind test of whether or not the “w-boost” bug is present or absent in a data set. While there is similar behavior between the two Arctic tundra sites (Barrow and Point Oliktok), it should be noted that they have almost identical terrain and canopy structure, and the flux tower structures are of identical design and construction.

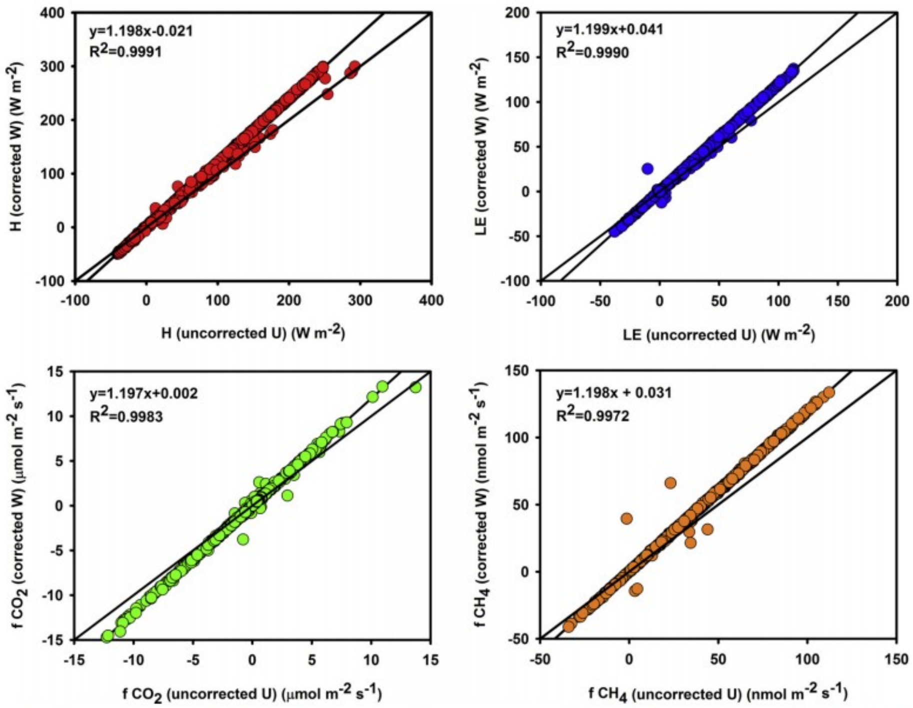

Fig. 1. Typical regressions between uncorrected, 2015 Typical regressions between uncorrected (U) and "w-boost" corrected (W) data from Point Oliktok, 2015.

4. Discussion

Considering the direct effects of the "w-boost" bug, there clearly exists a bias in eddy covariance fluxes obtained from affected sonic anemometers. While random uncertainties in fluxes are often between 10% and 15% (Billesbach, 2011; Richardson et al., 2012); they will tend to cancel out in long term averages. The "w-boost" bug, however, produces a bias (15% to 18%) and has the potential to significantly impact annual budgets of carbon, water and energy. Ideally, all affected raw data should be reprocessed, but due to the extended existence (at least 9 years) of the "w-boost" bug, this would require a major effort from the entire community.

Table 2
Exact "w-boost" (W) correction factors for individual fluxes, derived from raw, high-frequency data.

Flux	Barrow 2012	Barrow 2014	Barrow 2015	Oliktok 2015	GH-Ank 2011	US-SP1 2015	US-Myb 2015	US-StJ 2015	Average
H	1.187	1.171	1.186	1.198	1.193	1.16	1.17	1.16	1.178
LE	1.195	1.188	1.190	1.199	1.192	1.17	1.18	1.14	1.182
Flux CO_2	1.180	1.146	1.177	1.197	1.195	1.18	1.15	1.14	1.171
Flux CH_4	1.198	1.165	1.186	1.198	NA	NA	NA	NA	1.187
$(u^*)^2$	1.183	1.162	1.182	1.206	1.161	1.17	1.19	1.13	1.173
Average	1.189	1.166	1.184	1.200	1.185	1.170	1.172	1.142	1.176

Table 3
AoA (A) versus uncorrected (U) regression slopes.

A vs U	Barrow 2015	Oliktok 2015	GH-ank 2011
H	1.0952	1.0780	1.2399
LE	1.1122	1.0758	1.2338
Flux CO_2	1.0732	1.0649	1.2046
Flux CH_4	1.1041	1.0856	
$(u^*)^2$	1.0115	0.9965	1.2037

Table 4
AoA and "w-boost" corrected (AW) versus only "w-boost" corrected (W) regression slopes.

AW vs W	Barrow 2015	Oliktok 2015	GH-ank 2011
H	1.1102	1.0919	1.2519
LE	1.1273	1.0911	1.2431
Flux CO_2	1.0897	1.0783	1.2173
Flux CH_4	1.1159	1.1014	
$(u^*)^2$	1.0454	1.0145	1.2113

Instead, approximate corrections can be applied in some cases to affected fluxes in archival sources as a more expedient and easier approach. Our linear regression results from multiple sites, over multiple years indicate that a simple average of the instantaneous up/down correction factors (1.228) overcorrects. The same results do, however show that simple multipliers can be used to correct fluxes for the direct effect of the "w-boost" bug, and that external factors (wind direction, wind speed, stability class, etc.) have little effect on the magnitude of the corrections. The data in Table 2 suggest that a value of 1.176 can be universally used to correct all fluxes from any site or year for the "wboost" bug if no AoA correction was applied. The important impact of this issue is that existing (uncorrected) fluxes from affected sonic anemometers have been under estimated by up to 18%. Correction factors for sites, years, and fluxes shown in Table 2 differ from the suggested value by at most 3% to 4%, and their use might reduce the overall bias. From this small sample of sites however, it is questionable whether or not these site or flux specific factors will further refine values or if they will add overall noise to a data set. In other words, a simple multiplicative factor of 1.176 will remove most of the bias induced by the "w-boost" bug in any flux at any site, but any remaining bias may be somewhat random. Further refinement would require analysis of a larger ensemble of sites.

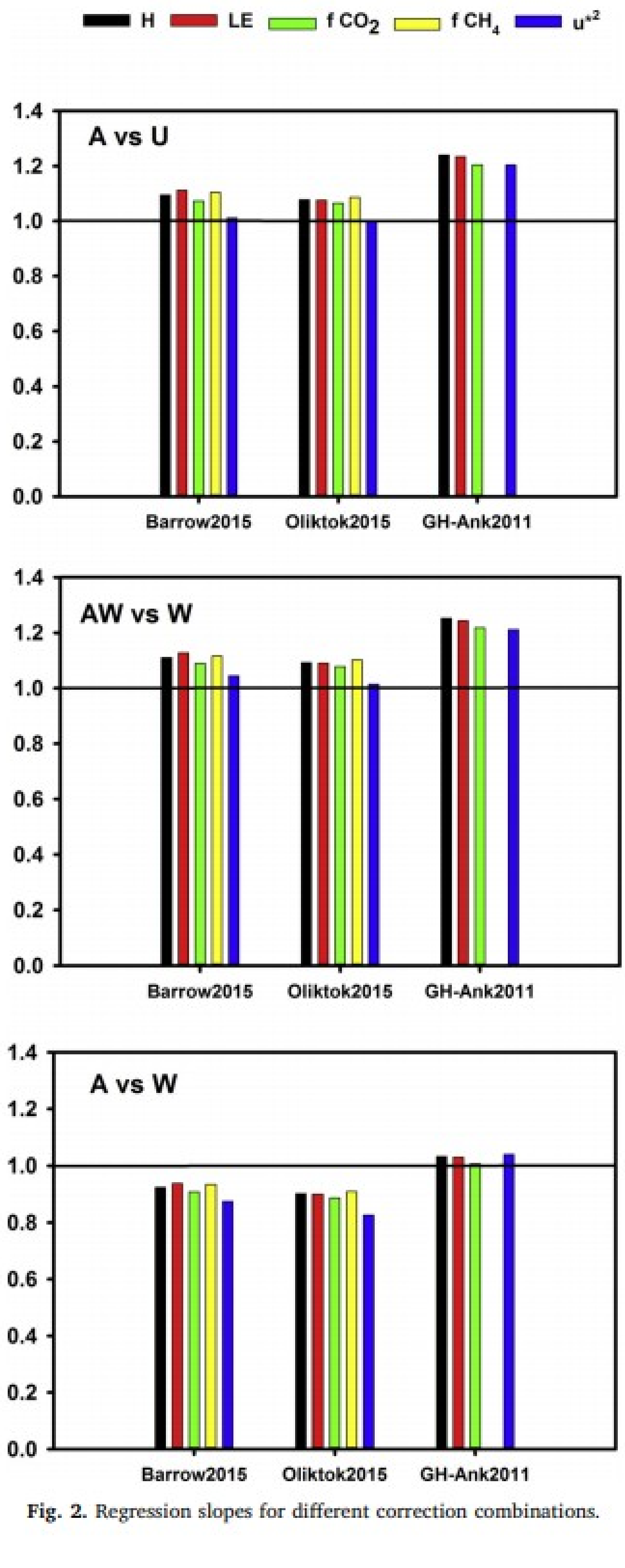

Fig. 2. Regression slopes for different correction combinations.

Secondary effects of the "w-boost" bug are manifest in the AoA (Nakai and Shimoyama, 2012) correction. The similarity of the corrections shown in

Tables 3 and 4 indicate that the direct and secondary effects are relatively independent of each other (as would be expected), but both move flux values in the same direction and that the AoA correction may partially correct for the “w-boost” bug in some cases. We also note the large difference in correction factors between the Arctic tundra sites (short towers and canopy structure) and the equatorial forest site (tall tower and high canopy) which points out that the amount of compensation the erroneous AoA correction produces in any given data set is not predictable. This further suggests that construction of a universal scheme to compensate for the erroneous AoA correction is not possible from this small sampling of sites. Again, this is not unexpected since the AoA correction relies on wind speed, wind direction, turbulence intensity, and the relative orientation of the sonic anemometer structure, all of which will differ at various sites.

Table 5
AoA (A) versus “w-boost” (W) corrected regression slopes.

A vs W	Barrow 2015	Oliktok 2015	GH-ank 2011
H	0.9244	0.9024	1.0317
LE	0.9381	0.9007	1.0295
Flux CO_2	0.9091	0.8870	1.0073
Flux CH_4	0.9346	0.9097	
$(u^*)^2$	0.8755	0.8267	1.0387

Table 6
Estimated “w-boost” (W) correction factors derived from various metrics using Eq. (1).

Metric	Barrow 2012	Barrow 2014	Barrow 2015	Oliktok 2015	GH-Ank 2011	US-SP1 2015
H	1.216	1.213	1.212	1.205	1.236	1.235
LE	1.192	1.198	1.193	1.193	1.218	1.188
Flux CO_2	1.228	1.225	1.230	1.240	1.228	1.217
Flux CH_4	1.204	1.190	1.228	1.179	NA	NA
Exact (ave)	1.189	1.166	1.184	1.200	1.185	1.170

Before applying any corrections however, the end user is cautioned to first verify that the data in question are actually affected by the “wboost” bug and which (if any) corrections have already been applied. Our attempt to identify an indicator of whether or not the “w-boost” bug is present in any given data set did not yield a universally applicable metric. While there are definite differences between corrected and uncorrected values of the three variables tested, the variability between sites was larger. While it may be possible to use one or more of these variables to determine if an affected sonic anemometer was installed at a specific site, they do not seem to offer a detection solution in a more general setting. A larger sampling of sites and further analyses of the behaviors of these variables may, yield a useful method for identifying affected data and we strongly encourage more discussion and research into their use. Because of this, the only definitive method to determine what if any corrections should be applied to existing flux data is to consult with the data originator regarding what corrections are present in the data, if (and when) the instrument firmware has been corrected, and whether or not these conditions are reflected in any metadata associated with the data set.

Finally, we bring attention to Appendix A of Nakai and Shimoyama (2012) which suggests that their "angle of attack" correction may be applied to other models of Gill sonic anemometers, that are not affected by the "w-boost" bug (i.e. R3, R3-50, HS, and others). This raises the possibility that archival flux data (available to the public) from a wider range of instruments may be indirectly affected as suggested by our analysis.

5. Conclusions and Recommendations

There is a firmware bug in many Gill-Solent WindMaster and WindMaster Pro sonic anemometers (manufactured between 2006 and October 2015) that can directly cause under estimation of fluxes by about 18% and can also introduce biases indirectly through an angle-ofattack (AoA) correction (Nakai and Shimoyama, 2012). The direct effect can be exactly compensated in the raw, high-frequency data by multiplying all positive (or upward) wind speeds by 1.166 and all negative (or downward) wind speeds by 1.289 and re-calculating all fluxes. Alternatively, fluxes can be approximately corrected by a multiplicative factor of 1.176 when raw data are not available and when the AoA correction has not been applied during flux processing.

There does not appear to be a simple, universal method to undo the effects of the erroneous application of the AoA correction for either affected or unaffected sonic anemometer models. In cases where the AoA correction has been applied, we propose that fluxes must be recalculated from the original data.

There does not appear to be a simple, universal indicator to test whether existing fluxes have been directly (or indirectly) affected by the "w-boost" bug. While instrument serial numbers and firmware versions provide clues, the only method to unambiguously determine if the "w-boost" bug is present in flux data is through consultation with the data originator. Care must therefore be exercised before applying any correction to assure that the sonic anemometer in question has indeed been affected by the "w-boost" bug, that it has not been repaired, and that the bias has not already been removed (entirely or partially) from the fluxes in the processing work flow.

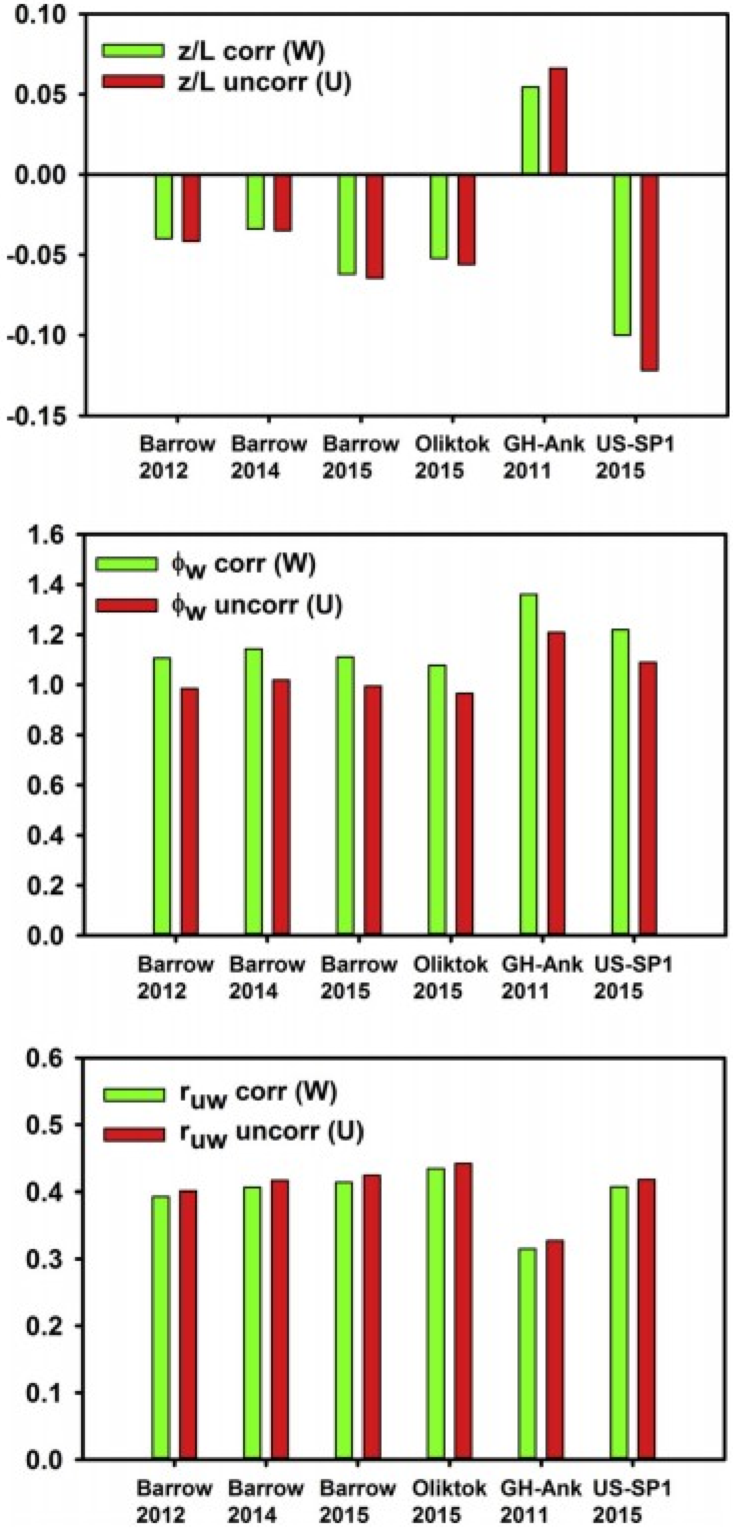

Fig. 3. Detection metrics for “w-boost” corrected (W) vs. uncorrected (U) data.

We bring attention to the importance of this issue for users of large data collections and regional data bases (e.g. AmeriFlux, FLUXNET, ARM etc.) who may not be aware of it. We encourage communication and collaboration among data users, data curators, and data originators. Furthermore, we highlight the importance of accurate and up-todate metadata as an integral part of data sets, where information about sensors and data processing workflow should be present.

We therefore recommend to the flux community, the following actions:

For data managers and data users:

1.) Examine current holdings to determine which data sets potentially are affected by either the “w-boost” bug and/or the erroneous AoA corrections.

2.) Contact data originators to determine whether or not the data in question are indeed affected.

3.) If the data are affected and the AoA corrections have NOT been applied, a simple multiplier (1.176) can be used to approximately correct the fluxes.

4.) If the AoA correction has been applied, work with the data originators to correct the fluxes.

5.) Managers of large regional databases should coordinate the collection of metadata including sensor model, serial number, firmware versions and processing applied to help in identifying potentially affected fluxes.

For data originators:

1.) Verify whether or not an affected sonic anemometer has been or is in use by checking the serial number and firmware version number (see Appendix).

2.) If an affected instrument is being used, contact the vendor to obtain a firmware patch and upgrade the instrument.

3.) If possible, re-process prior, affected data after applying the exact corrections to the high-frequency data.

4.) In all cases, discontinue application of the AoA correction until an updated algorithm is released.

5.) Re-submit the corrected data sets to any archives that currently hold them and update the instrument metadata.

We realize that these actions may not be possible or practical for all eddy covariance sites and data bases, but we encourage the scientific community to work towards removing this effect.

Acknowledgment

Funding for the AmeriFlux Management Project was provided by the U.S. Department of Energy's Office of Science under Contract No. DE-AC02-05CH11231.

Appendix A

The firmware issue discussed in this paper is described by a technical note from the manufacturer (Gill-Solent website, 2016 The firmware issue discussed in this paper is described by a technical note from the manufacturer (Gill-Solent website, 2016) and in a technical note for the EddyPro software by LI-COR (LI-COR website, 2016). In this appendix, we will summarize how to determine if a particular sonic anemometer is affected by this issue.

The only models directly affected are the Gill WindMaster and WindMaster Pro. The R2, R3, R3-50, HS, HS-50 and WindMaster-HS models are NOT affected. The issue is present in WindMaster and WindMaster Pro units that were manufactured between 2006 and October 2015. The problem is contained in all versions of the anemometer firmware (in this time period) up to version 2329v601. Instruments manufactured prior to 2006 are not affected. If the instrument is available, the firmware version may be determined by connecting a computer to the serial port of the anemometer in question and issuing the D2 command in interactive mode. Additionally, serial numbers of affected units will begin with the letter Y. If the serial number begins with the letter W, or the firmware version is 2329v700 or later, the issue has been corrected. It is not sufficient to rely on the serial number sticker on the instrument. If field-patches (available from the manufacturer or distributor) have been applied, this may not be updated. It is also recommended to review the instrument maintenance history as it is also not clear whether the field-patches update the internal serial number and firmware version stored in the instrument's EEPROM.

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