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Short communication

Energy budget closure observed in paired Eddy Covariance towers with increased and continuous daily turbulence

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ABSTRACT

The lack of energy closure has been a longstanding issue with Eddy Covariance (EC). Multiple mechanisms have been proposed to explain the discrepancies in energy balance including diurnal energy storage changes, advection of energy, and larger scale turbulent processes that cannot be resolved by field EC. To investigate the energy balance issue, we used a year of data from paired EC towers in irrigated sugarcane in Maui, Hawai'i, USA. The towers were in identical crops and cultivation practices and had similar climate with the notable exception of wind. One tower was in a location where nearby orographic features funneled Trade Winds, resulting in sustained, continuous turbulence. The other was in a leeward location with less turbulence, particularly at night (u^*). We found significantly improved closure (8.5–10%) at both sites using daily sums of Available Energy in closure regressions as opposed to 30 min data, illustrating the importance of storage terms. The energy budget closed for both fields when only days with continuous turbulence (all 30 min u^* > critical u^*) were considered, with significantly larger uncertainty in the leeward field (±13%) due to the small number of days ($n = 13$) with this condition. Significant energy imbalance appeared in both fields with even 30 min of subcritical turbulence in a day, and each field had different turbulence-closure patterns. Closure with continuous turbulence was sensitive to choice of critical u^*; an arbitrary u^* of 0.1 m s^{-1} resulted in non-closure. The results show the value of paired EC towers in contrasting turbulence conditions to assess energy budget closure.

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1. Introduction

Eddy Covariance (EC) is a well-established technique to measure mass and energy fluxes to and from the land surface because of its larger areal average and minimal environmental modification compared to other methods (Baldocchi, 2003). EC observations are used in multiple applications including parameterizing and validating prognostic environmental models (Trusilova et al., 2009), parameterizing and validating remote-sensing and mobile observation techniques (Anderson and Goulden, 2009; Jin et al., 2011; Mu et al., 2011), and determining environmental controls on local, regional, and global hydrology (Goulden et al., 2012; Jung et al., 2011; Wilson et al., 2001) and carbon balance (Baker and Griffis, 2005; Beer et al., 2010; Reichstein et al., 2007). The widespread use of EC data and networks of EC towers has generated considerable interest in the accuracy and uncertainty of these data (Massman and Lee, 2002; Richardson et al., 2012); a thorough understanding of errors and uncertainties in EC at varying spatial and temporal scales is crucial for correctly using EC data (Alfieri et al., 2012).

One long-standing methodological issue with the EC technique is the energy budget closure problem, as shown in Eq. (1):

$$R_n - G - Q_A - Q_B - Q_S - Q_M + R = H + \mathrm{LE} \qquad (1)$$

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where the sum of the EC observed turbulent sensible (H) and latent (LE) heat flux is systematically less than the sum of the observed net radiation (R_n), ground heat flux (G), and observed and/or parameterized energy storage terms in the atmosphere beneath the EC sensor (Q_A), canopy biomass (Q_B), soil above the soil heat flux observations (Q_S), and plant metabolic processes (Q_M), leaving a positive, unaccounted residual (R) (Foken, 2008; Leuning et al., 2012). The energy closure problem has long been recognized in EC towers across dissimilar ecosystems (Aubinet et al., 1999; Wilson et al., 2002). Many EC studies adjust measured turbulent fluxes by forcing energy budget closure. Most studies achieve forced energy budget closure by preserving the Bowen ratio (Barr et al., 2006; Twine et al., 2000), which has resulted in reconciliation between EC and other mass balance observational techniques (Chávez et al., 2009; Ding et al., 2010).

The causes of the energy balance problem are an area of ongoing micrometeorological research (Leuning et al., 2012; Stoy et al., 2013), with crucial and differing implications for interpreting and correcting EC observations for applications. Four potential causes are reviewed here. One is unobserved energy storage that is not included in the energy balance equation. Energy storage terms have often been neglected or assumed to be negligible. In theory, most of the storage terms neglected at 30 min timescales, with the exception of metabolic storage, should nearly cancel out on a daily basis. In an analysis of the FLUXNET database, Leuning et al. (2012) found significant improvement in energy closure at a substantial fraction of sites when energy closure regressions were applied to daily fluxes as opposed to half-hourly or hourly fluxes. A second cause of energy imbalance is advection of energy beneath the EC sensors, resulting in an imbalance of radiometric and turbulent observations of land-atmosphere energy exchange. Advection has been commonly associated with near surface gravimetric drainage of mass and energy during stable nighttime periods with minimal turbulence (Goulden et al., 2006; Yi et al., 2008). A third potential cause of energy budget non-closure is meso-scale eddies driven by local and landscape-level heterogeneity (Foken, 2008; Thomas, 2011), which are not fully captured by EC processing. Fourth, there may be a under measurement of turbulent fluxes due to design and observational issues with three dimensional sonic anemometers (Frank et al., 2013; Kochendorfer et al., 2012; Nakai et al., 2006). These appear to be larger in areas where sloped terrain results in larger angles of attack or where wind direction creates shielding issues with the design of the anemometer.

Corrections for energy closure issues are challenging. Parameterizations of storage terms can have significantly uncertainty (>20%), sub-canopy variability (Thomas, 2011), and can require extensive modeling in their own right (Haverd et al., 2007). Studies of advection require extensive and large instrumentation suites without necessarily resolving advective fluxes (Aubinet et al., 2010; Leuning et al., 2008). Underestimation of vertical wind velocity may require highly specific corrections depending upon the wind direction, the angle of attack, and the sonic anemometer model (Kochendorfer et al., 2012).

EC observations from unique turbulence environments may help assess energy budget closure. In this study, we present data from paired EC towers, established in agricultural fields in relatively close proximity to each other, and with identical crops and management practices. The climate was similar between the two fields with the notable exception of different wind regimes at the two sites. One site had adequate daytime turbulence with substantial periods of intermittent nighttime turbulence. The other site had vigorous, sustained turbulence due to orographic enhancement of the predominant trade flow patterns. This climatological control enables us to examine the relationship between sustained turbulence and energy closure.

Table 1
EC tower and site information for Windy and Lee along with average wind speed (u) and daily friction velocity (u^*) values during the Study Period (1 August 2011–31 July 2012).

Field	Lee	Windy
Latitude (°N)	20.784664	20.824633
Longitude (°W)	156.403869	156.491278
Elevation (m)	203	44
Date field planted	28 March 2011	11 May 2011
Date tower established	21 July 2011	23 July 2011
Mean meteorological observations for Study Period		
Mean daily u (m s^{-1})	2.04	4.58
Mean minimum daily u^* (m s^{-1})	0.06	0.32
Mean daily u^* (m s^{-1})	0.28	0.58
Mean maximum daily u^* (m s^{-1})	0.68	0.88

2. Methods

We installed EC towers in two highly productive, irrigated sugarcane (*Sacccharum officinarum* L.) fields (Evensen et al., 1997) separated by 10 km in a contiguous plantation in Maui, Hawai'i, USA. One field (hereafter referred to as "Windy") has sustained, high wind speed, whereas the other field ("Lee") is in a more leeward location with lower, more variable, wind speed (Table 1). Winds at the plantation are dominated by trade winds that can be orographically enhanced by the plantation's location between the West and East Maui mountains. Mean precipitation for both fields is under 350 mm year^{-1} (Giambelluca et al., 2013). The EC tower consists of an integrated open path infrared gas analyzer and sonic anemometer with a 10 Hz observation rate (EC150, Campbell Scientific, Logan, Utah, USA[2]). We measured net radiation with a net radiometer (NR-Lite2, Kipp and Zonen, Delft, Netherlands), ground heat flux with four heat flux plates installed uniformly across a sugarcane row at 5 cm depth (HFP01-SC, Huseflux, Delft, Netherlands), and air temperature/relative humidity with an integrated probe (HMP45C, Vaisala, Vantaa, Finland). All instruments were factory calibrated prior to deployment. All meteorological instruments were mounted at the same height on the tower; sonic anemometers were oriented into the predominant wind direction. The tower was raised periodically to maintain a height of ~3 m above the zero plane displacement of the sugarcane, calculated as 67% of canopy height (Arya, 2001). Both fields have a fetch >200 m during the predominant trade winds. We used data for one year (1 August 2011–31 July 2012 – hereafter referred to as the "Study Period") with continuous sugarcane cultivation. Infrared gas analyzers were user calibrated during the middle (January 2012) and near the end (July 2012) of the Study Period.

Raw EC (10 Hz.) data were post-processed using commercial software (Eddy Pro Advanced V 3.0 and 4.0 – LI-COR, Lincoln, NE, USA). We used the software's default settings for time-series checks (Vickers and Mahrt, 1997), low and high pass filtering (Moncrieff et al., 1997, 2004), density fluctuations (Webb et al., 1980), sonic anemometer tilt correction with double rotation (Wilczak et al., 2001), lag minimization using maximum covariance with default lag of 0, and calculation of u^* using both along and cross wind shear. Footprint lengths were calculated following Kljun et al. (2004) and quality flags determined following Mauder and Foken (2004). All raw data were processed to 30 min averages. 30-min periods where the 90% flux footprint extended beyond the edge of the field were flagged and removed. We gap-filled missing or unsuitable EC and meteorological data (Reichstein et al., 2005) using an

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[2] Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

automated online tool (Max Planck Institute for Biogeochemistry – http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/). We selected air temperature for gap-filling/partitioning and used the online tool to calculate a friction velocity threshold for each field (hereafter referred to as "critical u^*"). We considered a day to have continuous turbulence if every 30 min flux period in that day had friction velocity greater than critical u^*. We corrected the net radiometer for wind effects (Cobos and Baker, 2003) and excluded periods with rain.

We calculated radiometric Available Energy (AE_{rad}) as net radiation (R_n) minus ground heat flux averaged from the heat flux plates (G) and metabolic (Q_m) storage ($AE_{rad} = R_n - G - Q_m$). Q_m was determined from EC observations of net carbon flux (Meyers and Hollinger, 2004). Q_m was included because it is not removed by daily averaging and because it is relatively large in highly productive sugarcane fields (peak carbon flux of ~70 μmol m^2 s^{-1}, corresponding to Q_m of 28 W m^{-2}). Other storage terms were not measured and were assumed to be negligible on a daily basis. We calculated EC Available Energy (AE_{EC}) as the sum of latent (LE) and sensible (H) heat ($AE_{EC} = LE + H$). Four closure regression analyses were conducted; all of which were ordinary least squares regression with the intercept forced through the origin. Two regressions were with 30 min flux data; one for days with continuous turbulence, the other for all days. For the 30 min flux regression, we only used suitable original flux data (no gap-filled fluxes). The other two regressions used daily sums of AE_{rad} and AE_{EC} with continuous turbulence days and the entire Study Period. Since these regressions relied on sums of 30 min data, we included gap-filled data to ensure complete days. Days with AE_{rad} lower than 5 MJ m^{-2} day^{-1} were excluded since the few days with this condition were associated with significant rain events that result in a negative bias in NR-Lite2 R_n observations.

3. Results

Mean wind speed was 2.5 m s^{-1} and friction velocities were 0.2–0.3 m s^{-1} higher in Windy than Lee (Table 1). As expected, the difference between 30 min fluxes of AE_{rad} and AE_{EC} in Windy and Lee showed similar temporal patterns but significantly different (Fig. 1). AE_{rad}–AE_{EC} in Windy ranged from −325 to 427 W m^{-2} with a mean (standard deviation) of 2 (52) W m^{-2}. AE_{rad}–AE_{EC} in Windy ranged from −454 to 392 W m^{-2} with a mean (s. d.) of 30 (84) W m^{-2}. Minimum daily friction velocity (min u^*) showed larger differences between Windy and Lee (Fig. 2). In Windy, min u^* ranged from 0 to 0.87 m s^{-1}, with a mean min u^* of 0.32 (Table 1) and 65% of days in the Study Period having a min u^* with a higher value than the critical friction velocity (critical u^*) of 0.23 m s^{-1}. In Lee, min u^* ranged from 0.01 to 0.65 m s^{-1} with a mean min u^* of 0.06 m s^{-1} and only 4% of days having min u^* higher than the critical u^* of 0.13 m s^{-1}. Windy also had multiple periods with continuous turbulence ($u^* >$ critical u^*) lasting longer than a week. Examinations of diurnal patterns of u^* further illustrate the enhanced nighttime turbulence at Windy (Fig. 3). Windy also had a smaller mean diurnal range of u^* (0.27 m s^{-1}) than Lee (0.38 m s^{-1}). Turbulence and atmospheric stability parameters differed considerably between days with continuous turbulence and those with at least some subcritical turbulence (Table 2). In particular, the standard deviation of vertical and along stream wind velocities for the example day in Lee was less than 50% of the fields with continuous turbulence. Atmospheric stability also exhibited a much wider diurnal variation with subcritical turbulence.

Daily AE_{rad} and AE_{EC} showed good agreement for days with continuous turbulence (Fig. 4a) with both Windy and Lee showing energy budget closure on a daily basis (regression slope not significantly different from 1). Lee had a larger uncertainty in closure (±13% of regression slope) due to the small number of days with continuous turbulence ($n = 13$), while Windy had less uncertainty for both continuous turbulence days and the entire Study Period (≤1.5% of slope). For all days during the Study Period, Lee had a significant lack of energy balance closure with ~24% less AE_{EC}

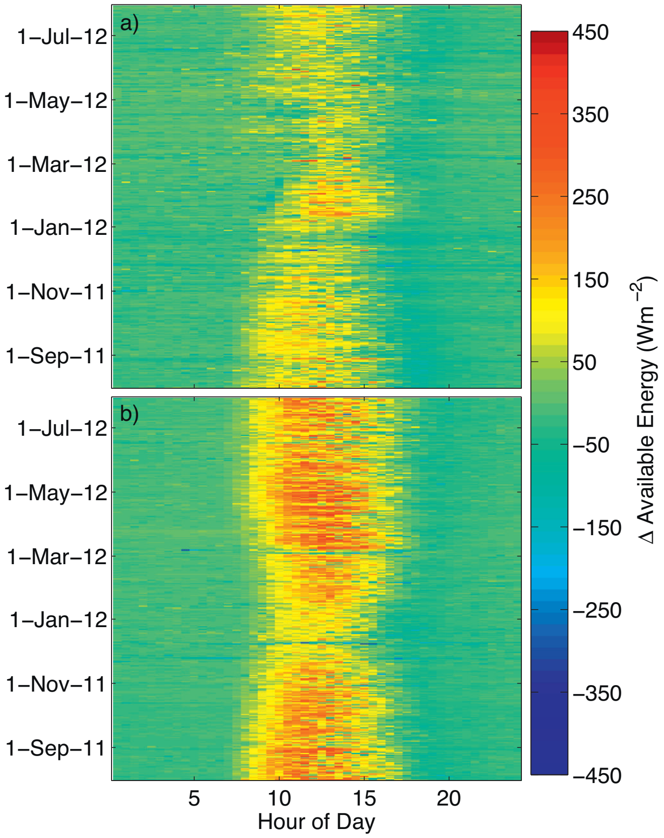

Fig. 1. Fingerprint plot of difference between radiometric and turbulent 30-min Available Energy (the energy balance residual) during the Study Period including gap-filled periods (AE_{rad}–AE_{EC}): (a) AE_{rad}–AE_{EC} in Windy field. (b) AE_{rad}–AE_{EC} in Lee field.

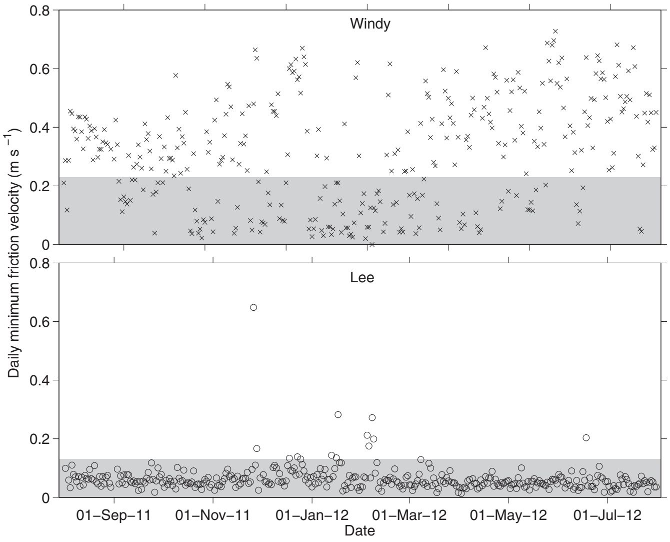

Fig. 2. Minimum daily friction velocity (u^*) for the two EC fields during the Study Period. Shaded area indicates region less than the critical u^* value for each field (critical u^* is 0.23 m s^{-1} in Windy and 0.13 m s^{-1} in Lee).

Table 2

Selected turbulence (standard deviation of vertical (σ_w) and along stream (σ_u) wind velocity, standard deviation cross wind normalized by along stream wind (σ_w/u^*), and standard deviation of vertical wind velocity normalized by friction velocity) and atmospheric stability (Monin–Obukhov stability parameter (ζ (z/L))) statistics for Windy and Lee for two days. 18 June 2012 had continuous turbulence (CT day) in both Windy and Lee. 1 July 2012 had continuous turbulence in Windy and some periods with subcritical turbulence (SCT day) in Lee. Statistics are daily averages ($n = 48$) of half hourly flux data.

Field and wind condition	σ_w (m s^{-1})	σ_u (m s^{-1})	σ_v/u (–)	σ_w/u^* (–)	ζ (z/L)		
					Min	Mean	Max
Windy – CT day	1.11	2.07	0.37	1.23	-5.69×10^{-3}	1.01×10^{-3}	8.65×10^{-3}
Windy – SCT day	0.85	1.51	0.35	1.32	-1.98×10^{-2}	3.07×10^{-4}	2.95×10^{-2}
Lee – CT day	1.07	2.08	0.48	1.21	-7.22×10^{-2}	-8.87×10^{-3}	7.47×10^{-3}
Lee – SCT day	0.38	0.88	0.93	1.33	-2.13×10^{0}	-3.02×10^{-2}	2.58×10^{0}

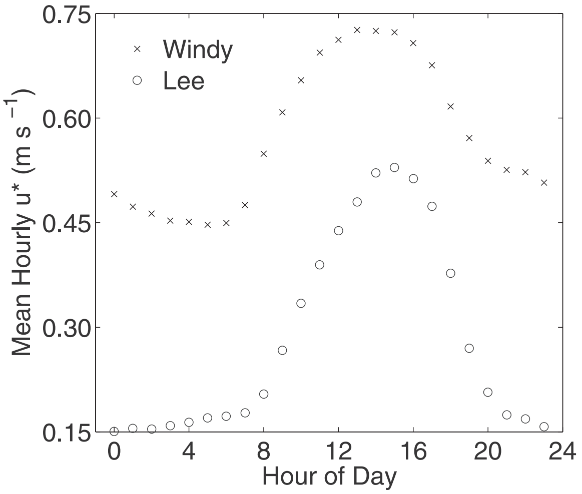

Fig. 3. Mean, hourly diurnal patterns of u^* for both Windy and Lee. Hourly data were calculated as an average of all valid sonic for that time during the Study Period.

compared to AE$_{rad}$ (Fig. 4b). Windy still showed significant closure for the entire period but regression slope decreased by 2% with inclusion of days with subcritical turbulence. RMSE for the daily energy closure regression in Lee decreased from 5.7 MJ day^{-1}, for the entire Study Period to 3.3 MJ day^{-1} for the continuously turbulent days; Windy showed a slight increase in RMSE from 2.5 to 2.7 MJ day^{-1} between the entire Study Period and continuously turbulent days. For the 30 min flux regressions, the slope for both fields was consistently lower. In Windy, the regression slope was 0.890 ± 0.002 for all valid 30 min periods and 0.907 ± 0.003 for continuously turbulent days. In Lee, the 30 min regression slope was 0.688 ± 0.003 for all valid periods and 0.799 ± 0.016 for continuously turbulent days (30 min regressions not shown). All of the 30 min regressions showed a hysteresis effect due to storage changes similar to the ones illustrated by Leuning et al. (2012).

To assess the impact of subcritical turbulence on energy closure, we plotted the length of subcritical turbulence against Energy Balance Ratio (daily AE$_{EC}$/daily AE$_{rad}$) and maximum Monin–Obukhov stability parameter (ζ) (Fig. 5). We binned days by the longest period of subcritical turbulence or maximum 30 min ζ for that day and calculated mean and standard error for each bin using daily data. Energy Balance Ratio (EBR) ranges from 1.05 and 0.97 for Windy and Lee, respectively, with no subcritical turbulence to 0.89 and 0.77 when subcritical turbulence exceeds 300 min in a day (Fig. 5a). EBR drops below 1 for Lee with any subcritical turbulence while EBR does not drop significantly below 1 in Windy until there is subcritical turbulence is 60 min or longer in length. With respect to maximum daily ζ, EBR ranges from 1.08 and 0.82 in Windy and Lee, respectively, when ζ is less 0.02 (Fig. 5b). When maximum daily ζ exceeds 0.02, EBR drops significantly below 1 in Windy, decreasing to a minimum of 0.88 when ζ is greater than 1.5. EBR shows no significant change in Lee above a maximum daily ζ of 0.02, while Windy's EBR decreases significantly for each ζ bin up to 0.25.

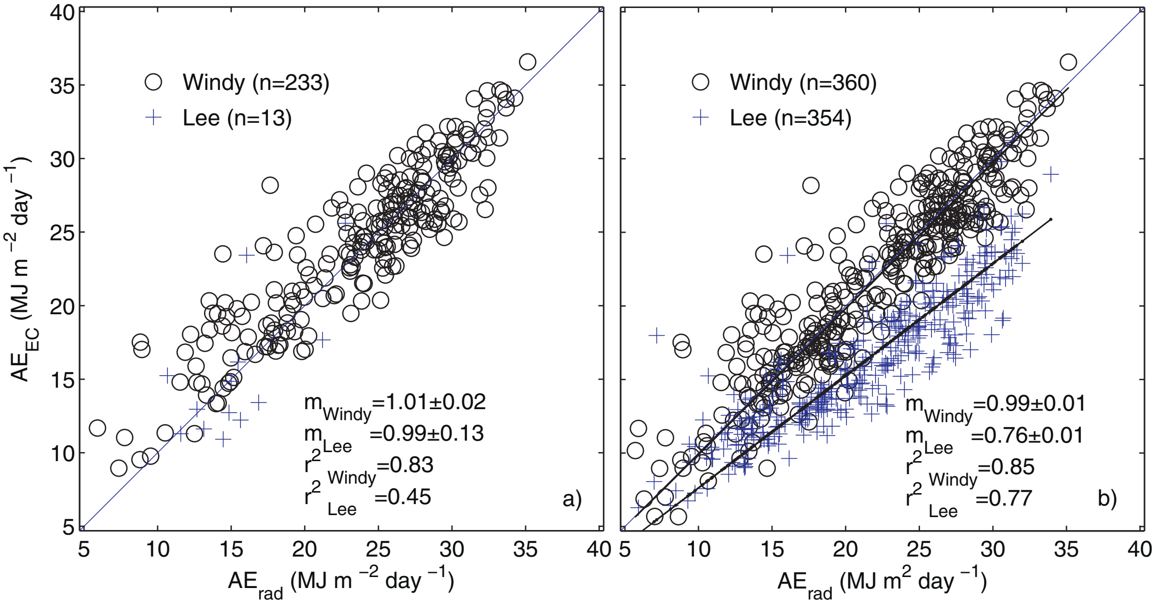

Fig. 4. Daily Energy budget closure for EC fields with slope (m) and coefficient of determination for regression (r^2) displayed. (a) Closure for days with continuous turbulence (no 30-min periods with u^* less than critical u^* for a given day). (b) Closure for all days in Study Period.

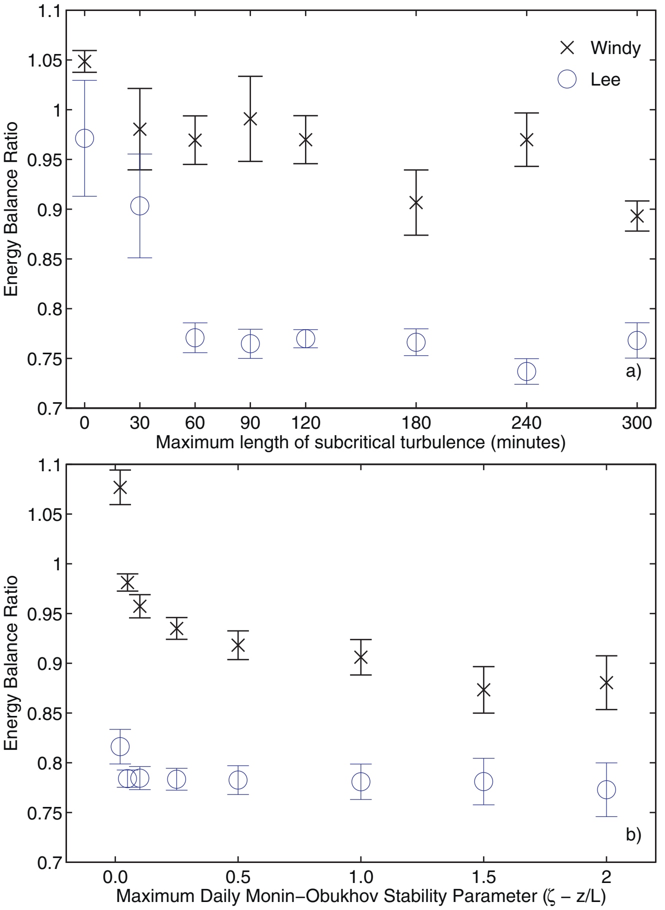

Fig. 5. Impact of length of subcritical turbulence (u^*) and daily maximum stability on daily energy balance ratio (AE_{EC}/AE_{rad}). Bars around mean indicate standard error. (a) Relationship between maximum length of subcritical turbulence and binned energy balance ratio. (b) Relationship between maximum daily ζ and binned energy balance ratio.

4. Discussion and conclusion

We presented data from two Eddy Covariance (EC) towers in almost identical agroecosystems with similar climate but uniquely dissimilar mean wind conditions. The windier tower site (Windy) showed significant closure without explicit inclusion of most energy storage terms while the other site (Lee) showed daily energy budget closure in line with many other EC sites. Both sites showed similar differences in energy closure regression slopes (0.085–0.101) between 30 min and daily Available Energy sums suggesting that storage fluxes have similar magnitudes at both Windy and Lee. The appearance of significant lack of closure with subcritical turbulence as short as 30 min indicates how quickly advective and larger scale processes can develop, which violate key meteorological requirements for EC and result in lack of closure.

Previous analysis of net radiation and vegetation cover at Windy did not show field heterogeneity that could account for closure; explicit, independent parameterizations of net radiation also showed no significant bias in our net radiation observations (R.G. Anderson et al., Divergence of reference evapotranspiration estimates under advective tropical conditions, submitted to *Agricultural Water Management*). Mean vegetation height in the near vicinity (<2 km) surrounding both sites is also relatively short (<10 m), thus flow separation is not likely an issue at these sites. While we did not explicitly investigate sonic anemometer errors, our site setup minimized the angle of attack and turbulent wake that contributes to anemometer error (Frank et al., 2013). For example, the sonic anemometer in Windy was oriented into the wind for >80% of the Study Period, while field slope was low (<3%).

The relationship between energy budget closure and friction velocity (u^*) has been observed in multiple studies (Barr et al., 2006; Sánchez et al., 2010; Turnipseed et al., 2002), with these studies showing little energy imbalance at the highest u^*, but significant energy imbalance remaining at moderate u^*, which are higher than the critical u^* used as a threshold to filter EC data but lower than the highest u^*. Our closure regressions demonstrated the importance of correctly determining critical u^*; if we had selected an arbitrary critical u^* of 0.1 m s^{-1} for determination of continuously turbulent days, there would still be statistically significant imbalance at Lee (regression slope $m = 0.898 \pm 0.072$) and slightly lower slope at Windy ($m = 0.999 \pm 0.013$). Improved, robust methods for determining critical u^* are warranted (Barr et al., 2013).

The presence of paired EC sites with dissimilar turbulence but ecological and climatological similarities provides novel experimental data that could enable a more thorough examination of the causes of the energy balance problem as well as potentially improved corrections for energy budget closure. Fortunately, increasing numbers of EC towers and mesonets (e.g. Goulden et al., 2012) are being established in regions with complex topography that can potentially enhance or suppress turbulence within a relatively short geographic distance. Having multiple towers in contrasting turbulent environments within close geographic proximity would also more easily enable modeling and observational techniques that have been suggested as research avenues to address the energy budget closure issue (Foken, 2008; Stoy et al., 2013). Further research activities in alternative EC processing techniques to improve closure (Barnhart et al., 2012), potential quality control metrics such as turbulent kinetic and potential energy (Zilitinkevich et al., 2007), and closure implications for use of EC data are needed. Improved empirical understanding of energy closure relationships and their corrections may help ensure proper processing and analysis of EC data; particularly by researchers who are non-specialists in boundary layer meteorology or lack the resources to fully quantify advective fluxes, storage terms and/or larger scale eddies that contribute to a lack of energy budget closure.

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