A Meta-Analysis of Open-Path Eddy Covariance Observations of Apparent CO_2 Flux in Cold Conditions in FLUXNET

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ABSTRACT

Open-path eddy covariance systems are widely used for measuring the CO_2 flux between land and atmosphere. A common problem is that they often yield negative fluxes or physiologically unreasonable CO_2 uptake fluxes in the nongrowing season under cold conditions. In this study, a meta-analysis was performed on the eddy flux data from 64 FLUXNET sites and the relationship between the observed CO_2 flux and the sensible heat flux was analyzed. In theory, these two fluxes should be independent of each other in cold conditions (air temperature lower than 0°C) when photosynthesis is suppressed. However, the results show that a significant and negative linear relationship existed between these two fluxes at 37 of the sites. The mean linear slope value is -0.008 ± 0.001 μmol m^{-2} s^{-1} per W m^{-2} among the 64 sites analyzed. The slope value was not significantly different among the three gas analyzer models (LI-7500, LI-7500A, IRGASON/EC150) used at these sites, indicating that self-heating may not be the only reason for the apparent wintertime net CO_2 uptake. These results suggest a systematic bias toward larger carbon uptakes in the FLUXNET sites that deploy open-path eddy covariance systems.

1. Introduction

The eddy covariance (EC) technique is widely used for measuring exchanges of carbon dioxide between terrestrial ecosystems and the atmosphere. In the global EC network [Flux Network (FLUXNET)], about half of the sites located north of 40°N deploy open-path CO_2/H_2O analyzers for flux measurements. Compared to closed-path analyzers, open-path analyzers need less power and less maintenance, and thus are better suited for remote locations. However, a physiologically unreasonable CO_2 uptake phenomenon has been reported frequently for cold seasons when no photosynthetic activities exist (Hirata et al. 2005; Welp et al. 2007; Lafleur and Humphreys 2008; Järvi et al. 2009; Wang et al. 2016) or for environments where CO_2 uptake is not expected (Liu et al. 2012; Ma et al. 2014; Ono et al. 2008; Wohlfahrt et al. 2008). Specifically, for desert ecosystems, Schlesinger (2017) argued that abiotic CO_2 uptake mechanisms like atmospheric pressure pumping, carbonate dissolution, and percolation of soil water through the vadose zone cannot adequately explain the observation of EC systems. Following the micrometeorological sign convention, the uptake phenomenon is marked by a negative CO_2 flux or a flux directed toward the surface. According to Amiro et al. (2006) and other research groups (e.g., Burba et al. 2008; Helbig et al. 2016), the problem is not caused by software or hardware malfunction. Accurate CO_2 flux measurement is important for evaluating the global CO_2 cycle,

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terrestrial ecosystem responses to climate change, and modeling studies. Long-term integrated carbon flux will suffer a systematic bias if corrections are not made to the apparent flux in the cold season (Burba et al. 2008) or even in the whole year (Helbig et al. 2016).

Several explanations for the apparent negative flux are found in the published literature. Self-heating of an open-path instrument is considered a major reason for the negative flux (Burba et al. 2005, 2008; Grelle and Burba 2007). Because of the heat released by the instrument's electronics and solar radiation heating of the instrument's supporting frame, the air in the sensing volume of the analyzer may be warmer than the undisturbed air. Density corrections using the sensible heat flux measured outside the sensing volume cannot fully remove the effects of temperature fluctuations on CO_2 density fluctuations in the sensing volume. It is estimated that in mild temperatures (about 12°C), the sensible heat flux in ambient air is 14% lower than the flux involving the actual temperature fluctuations in the sensing volume, and this rate of underestimation should increase as temperature decreases (Burba et al. 2008). The apparent cold-season CO_2 uptake was first observed with an older analyzer model manufactured by LI-COR (model LI-7500, LI-COR Inc., Nebraska). To reduce the self-heating effect, the manufacturer has introduced an improved model (LI-7500A) with reduced power consumption during cold periods (Burba 2013, 78–79). However, using an LI-7500A analyzer in their open-path EC system, Wang et al. (2016) found that there is still an apparent CO_2 uptake in a desert ecosystem in low temperatures (mean air temperature: −6.7°C), implying that other sources of wintertime bias exist for LI-7500A, if this gas analyzer indeed avoids the self-heating effect according to its producer.

Another explanation for the uptake phenomenon is related to spectroscopic effects. Spectroscopic effects result from changes in the shape and the strength of CO_2 absorption lines; these changes are caused by changes in temperature, water vapor, and pressure. If these effects are not properly dealt with, the fluctuations can be interpreted as changes in the concentration of the gas (Welles and McDermitt 2005; Detto et al. 2011; McDermitt et al. 2011). These effects fall into two types: insufficient compensation due to high-frequency temperature fluctuations (Helbig et al. 2016) and spectroscopic cross sensitivity (Kondo et al. 2014). In a class of analyzers [models IRGASON (Integrated CO_2 and H_2O Open-Path Gas Analyzer and 3-D Sonic Anemometer) and EC150, Campbell Scientific Inc., Utah] that use EC operating software released before September 2016, the CO_2 density is determined by a scaling law (Jamieson et al. 1963) with temperature measured by a slow-responding thermometer mounted outside the analyzer's sensing volume. In an experiment that compared an open-path EC system using an IRGASON analyzer and a closed-path EC system, Bogoev et al. (2015) found that the CO_2 flux measured with the open-path EC is biased low and the low bias scales linearly with sensible heat flux. These authors and Helbig et al. (2015, 2016) showed that this spectroscopic effect can be corrected by using fast-response air temperature measurements to perform the absorption line calculation. After this correction, the linear relationship between the corrected CO_2 flux and the heat fluxes almost disappears. Unlike the self-heating effect, which is believed to be limited to only cold seasons, this spectroscopic error exists in all seasons. At low temperatures when the true CO_2 flux is very small, the flux measured with an IRGASON may appear negative (Wang et al. 2016). It is not known to what extent spectroscopic effects affect the CO_2 flux measured with other open-path analyzers.

Spectroscopic cross sensitivity can arise from a pressure broadening effect and from absorption line interference between CO_2 and H_2O. Generally, the absorption interference is much smaller than the pressure broadening effect (Kondo et al. 2014). These effects are corrected by using measurements of air pressure and H_2O mole fraction and manufacturer-determined correction coefficients. Kondo et al. (2014) found that for an LI-7200 gas analyzer with the same design as the LI-7500, the manufactured correction coefficient for spectroscopic cross sensitivities results in an overestimation of the CO_2 mixing ratio by about 0.9% at an H_2O mole fraction of 30.6 mmol mol^{-1}. Different from the effect associated with high-frequency temperature fluctuations, this spectroscopic cross sensitivity biases the CO_2 flux toward more positive values, and the biases increase with the H_2O mole fraction. Because this influence is much smaller than the other bias sources, in the following we will not examine this problem.

Finally, a negative CO_2 flux in the cold season can result from errors propagated through the density correction procedure. The Webb–Pearman–Leuning (WPL) density correction requires that the CO_2 density ρ_c be measured precisely. But in field conditions, biases in ρ_c can be caused by thermal expansion and contraction of the analyzer's frame on which the transducers are mounted, by dirt contamination on the transducers and by aging of the optical components (Fratini et al. 2014). An underestimation of ρ_c will cause the CO_2 flux to be too negative (Serrano-Ortiz et al. 2008). The bias in the CO_2 flux scales linearly with the sensible heat flux if the CO_2 density is underestimated by a constant amount.

In this study we perform a meta-analysis of the eddy flux data from 64 sites located in North America, Europe, Asia, and Australia, and analyze the relationship between the apparent CO_2 flux and the sensible heat flux in cold conditions. We aim to 1) compare the negative bias problem among different open-path gas analyzers and 2) investigate the bias errors in relation to climatic conditions (temperature, humidity) and to biases in the CO_2 concentration.

2. Data and methods

a. Theoretical consideration

1) Self-heating

The CO_2 flux bias error arising from self-heating can be understood by examining the WPL algorithm (Webb et al. 1980),

$$F_{c,a} = \overline{w'\rho'}_c + \frac{\overline{\rho_c}}{\overline{T}C_p\overline{\rho_a}}\left(1 + \frac{\overline{\rho_v}M_a}{\overline{\rho_a}M_v}\right)H + \frac{\overline{\rho_c}M_a}{\overline{\rho_a}M_v}E_0, \tag{1}$$

where $F_{c,a}$ is the CO_2 flux after density correction ($kg\,m^{-2}\,s^{-1}$); w is the vertical wind velocity ($m\,s^{-1}$); ρ_c and ρ_a are the density of CO_2 ($kg\,m^{-3}$) and dry air ($kg\,m^{-3}$), respectively; T is the air temperature (K); M is the molecular mass ($g\,mol^{-1}$); C_P is the specific heat of air ($J\,kg^{-1}\,K^{-1}$); H is the sensible heat flux ($W\,m^{-2}$) measured in ambient air outside the analyzer's sensing volume; E_0 is the H_2O flux ($kg\,m^{-2}\,s^{-1}$); and subscripts a, v, and c represent dry air, water vapor, and CO_2, respectively. Let H_{real} be the real sensible heat inside the open path. To obtain the correct CO_2 flux F_c, Eq. (1) should be modified to

$$F_c = \overline{w'\rho'}_c + \frac{\overline{\rho_c}}{\overline{T}C_p\overline{\rho_a}}\left(1 + \frac{\overline{\rho_v}M_a}{\overline{\rho_a}M_v}\right)H_{real} + \frac{\overline{\rho_c}M_a}{\overline{\rho_a}M_v}E_0. \tag{2}$$

A comparison of Eqs. (1) and (2) yields

$$F_{c,a} = F_c + \frac{\overline{\rho_c}}{\overline{T}C_p\overline{\rho_a}}\left(1 + \frac{\overline{\rho_v}M_a}{\overline{\rho_a}M_v}\right)(H - H_{real}). \tag{3}$$

According to Burba et al. (2008), the sensible heat flux measured in the ambient air (H) is highly correlated with the sensible heat flux inside the open path measured with a fine-wire platinum resistor (H_{real}). Their linear relationship is defined as

$$H = b'H_{real} - a', \tag{4}$$

where $b' = 0.86$ and $a' = 2.67\,W\,m^{-2}$.

Equation (3) can be rewritten as

$$\begin{aligned} F_{c,a} &= F_c + \frac{\overline{\rho_c}}{\overline{T}C_p\overline{\rho_a}}\left(1 + \frac{\overline{\rho_v}M_a}{\overline{\rho_a}M_v}\right)\left[\left(1 - \frac{1}{b'}\right)H - \frac{a'}{b'}\right], \\ &= F_c + bH + a, \end{aligned} \tag{5}$$

where

$$b = \frac{\overline{\rho_c}}{\overline{T}C_p\overline{\rho_a}}\left(1 + \frac{\overline{\rho_v}M_a}{\overline{\rho_a}M_v}\right)\left(1 - \frac{1}{b'}\right), \quad \text{and} \tag{6}$$

$$a = \frac{\overline{\rho_c}}{\overline{T}C_p\overline{\rho_a}}\left(1 + \frac{\overline{\rho_v}M_a}{\overline{\rho_a}M_v}\right)\left(-\frac{a'}{b'}\right). \tag{7}$$

For $b' = 0.86$ and $a' = 2.67$, the slope parameter b in Eq. (6) is approximately $-0.008\,\mu mol\,m^{-2}\,s^{-1}$ per $W\,m^{-2}$ after unit conversion (from $kg\,m^{-2}\,s^{-1}$ per $W\,m^{-2}$ to $\mu mol\,m^{-2}\,s^{-1}$ per $W\,m^{-2}$, divided by CO_2 molar mass), and parameter a is approximately $-0.16\,\mu mol\,m^{-2}\,s^{-1}$.

Equation (5) predicts that negative $F_{c,a}$ is more likely to occur at times of high sensible heat flux. An implicit assumption is that sensor self-heating is dominated by solar radiation rather than heating caused by the sensor electronics. We also hypothesize that b is more negative for colder sites, since the self-heating effect is expected to be more severe.

2) Insufficient compensation for spectroscopic effects

Spectroscopic effects affect every instrument that measures absorption. For IRGASON/EC150 gas analyzers, which are subject to insufficient compensation for spectroscopic effects as a result of high-frequency temperature fluctuations, the observed flux $F_{c,a}$ and the true flux F_c also follows the linear relationship with the ambient sensible heat flux (Bogoev et al. 2015; Helbig et al. 2015, 2016), as given by Eq. (5). A theoretical slope value can be described as (Wang et al. 2016)

$$b = -\frac{1}{2}\frac{\overline{\rho_c}}{\overline{T}C_p\overline{\rho_a}}. \tag{8}$$

Under typical atmospheric conditions, the theoretical value for b is about $-0.025\,\mu mol\,m^{-2}\,s^{-1}$ per $W\,m^{-2}$. A comparison of an IRGASON open-path EC versus a closed-path EC reveals that the actual slope is about half of the theoretical value, at $-0.014\,\mu mol\,m^{-2}\,s^{-1}$ per $W\,m^{-2}$ (Bogoev et al. 2015). Subsequent experiments by Helbig et al. (2015, 2016) in boreal forest, grassland, and cropland sites showed that the slope value ranges from -0.014 to $-0.020\,\mu mol\,m^{-2}\,s^{-1}$ per $W\,m^{-2}$ and that the intercept value a ranges from -0.300 to $0.080\,\mu mol\,m^{-2}\,s^{-1}$.

3) Biases in CO_2 density

Bias errors in the CO_2 density ρ_c can also be examined in the framework of WPL theory. Let $\overline{\rho_c}$ be the true mean CO_2 density and $\delta\overline{\rho_c}$ be the measurement bias. The measured flux $F_{c,a}$ after the WPL correction is

$$F_{c,a} = \overline{w'\rho'}_c + \frac{(\overline{\rho_c} + \delta\overline{\rho_c})}{\overline{T}C_p\overline{\rho_a}}\left(1 + \frac{\overline{\rho_v}M_a}{\overline{\rho_a}M_v}\right)H + \frac{(\overline{\rho_c} + \delta\overline{\rho_c})M_a}{\overline{\rho_a}M_v}\frac{\mathrm{LE}}{\lambda},$$
$$\approx F_c + bH, \tag{9}$$

with the slope parameter given by

$$b = \frac{\overline{\rho_c}}{\overline{T}C_p\overline{\rho_a}}\left(1 + \frac{\overline{\rho_v}M_a}{\overline{\rho_a}M_v}\right)\frac{\delta\overline{\rho_c}}{\overline{\rho_c}},$$
$$\approx 0.05[\mu\mathrm{mol\,m^{-2}s^{-1}\ per\ W\ m^{-2}}]\frac{\delta\overline{\rho_c}}{\overline{\rho_c}}. \tag{10}$$

In Eq. (9), LE is the latent heat flux and λ is the latent heat of vaporization. The magnitude of LE is comparable with H, and the term before LE is equal to 0.004 (μmol m^{-2} s^{-1} per W m^{-2}) $\delta\overline{\rho_c}/\overline{\rho_c}$, which is one order of magnitude smaller than 0.05 (μmol m^{-2} s^{-1} per W m^{-2}) $\delta\overline{\rho_c}/\overline{\rho_c}$ in Eq. (10). Thus, we ignored this term to simplify the analysis.

In the situation where $\overline{\rho_c}$ is underestimated by 10% [$(\delta\overline{\rho_c}/\overline{\rho_c} = -10\%)$; Serrano-Ortiz et al. 2008], the slope b is approximately $-0.005\,\mu$mol m^{-2} s^{-1} per W m^{-2}.

b. *Data sources and data processing*

The eddy flux data analyzed in the present study were obtained from AmeriFlux, FLUXNET, the Chinese Terrestrial Ecosystem Flux Research Network (ChinaFlux), and the Chinese Heihe databases (Agarwal et al. 2016; Wolf 2016; Yu 2016; Liu 2016). The majority of the sites are located north of 40°N (Fig. 1; Tables S1 and S2). These sites have continuous eddy flux records for at least 5 days when the air temperature is below the freezing point in the winter. There are a total of 64 sites, including 57 sites using LI-7500, 6 sites using LI-7500A, and one site using IRGASON. The eddy flux data at 28 sites were obtained from the FLUXNET. These data have been gap filled and through a Ustar-threshold filtering following the FLUXNET data processing pipeline. The other eddy flux data, obtained from AmeriFlux (20 sites), ChinaFlux (7 sites), and the Heihe databases (9 sites), were not gap filled and are without the Ustar-threshold filtering.

When the air temperature is below 0°C in the winter (January–December in the Northern Hemisphere; June–August in Australia), the true carbon flux F_c should be slightly positive because of ecosystem respiration, but it should be very small and independent of the sensible heat flux H due to suppression of photosynthesis. We assume that any correlation between the measured flux $F_{c,a}$ and H is evidence of measurement errors. For each site, we used only winter data when the half-hourly or hourly air temperature was below 0°C, and applied the ordinary linear regression to the observed CO_2 flux and sensible heat flux, using the sensible heat flux as the independent variable. The regression yields b and a. We then tried to discern patterns of the slope parameter among the 64 sites. Half-hourly or hourly data influenced by precipitation were excluded from the regression analysis. We also restricted the sensible heat flux to the range of -100 to 400 W m^{-2} and the latent heat flux to the range of -200 to 700 W m^{-2} to avoid extreme values due to unknown measurement errors. The CO_2 flux was limited to -10 to 10 μmol m^{-2} s^{-1}. Prior to the regression, the half-hourly or hourly data were averaged by every 20 W m^{-2} bin of sensible heat flux to reduce the effect of random measurement errors on the parameter estimation.

We used the CO_2 mole fraction data from CarbonTracker (version CT2016, global 3° × 2° grid, level 1) to calculate the bias in ρ_c measured by the EC open-path analyzers. CarbonTracker is a data inversion system that aims to calculate global CO_2 fluxes from high-precision atmospheric CO_2 measurements. Peters et al. (2007) compared the optimized three-dimensional CO_2 mole fraction fields produced by CarbonTracker with 13 000 independent CO_2 flask samples taken in the free troposphere, and found that the mean and standard deviation of the residuals are 0.07 and 1.91 ppm, respectively.

To determine the bias error in the CO_2 density, we first selected a CarbonTracker grid cell that is closest to the measurement site. We then chose the CarbonTracker surface CO_2 mole fraction for those days when the actual flux data were used for our analysis. The mean CarbonTracker CO_2 mole fraction of those measurement days is regarded as the true CO_2 mole fraction. Finally, the bias ratio in CO_2 mass density $(\delta\overline{\rho_c}/\overline{\rho_c})$ is represented by the bias ratio of the CO_2 mole fraction (CO_2 concentration is given by the mole fraction in FLUXNET), since the pressure and temperature effects are canceled out.

3. Results and discussion

a. *Relationship between observed $F_{c,a}$ and H*

A significant ($p < 0.05$) and negative correlation exists between the observed $F_{c,a}$ and H at 37 of the 64 sites, and only 4 sites have a significant and positive correlation. The mean coefficient of determination (R^2) is 0.63 for all the sites. The regression statistics are shown in the supplemental material; see Table S1, and the scatterplots for individual sites are given in Fig. S1. Among the sites analyzed, 45 sites have an R^2 value larger than 0.5.

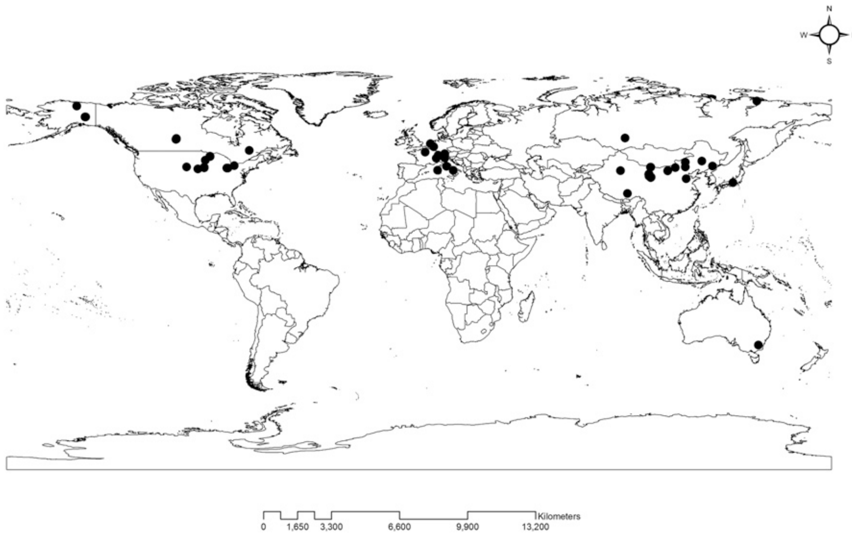

FIG. 1. Locations of the 64 eddy flux sites used in this study.

We also analyzed the relationship between the apparent CO_2 flux and the incoming solar radiation. The mean R^2 is 0.48 for the 39 sites that have the radiation data. Among these sites, 17 sites have R^2 values larger than 0.5. The results show that H is a better independent variable than solar radiation to do this analysis.

We analyzed the relationship between the CO_2 flux and the sensible heat measured by a closed-path analyzer at site AT-Neu (Neustift, Austria) in the cold season, and we found that this relationship is insignificant ($p = 0.13$, $R^2 = 0.26$). The result supports our hypothesis that F_c should be independent of H. On the other hand, the relationship for the open-path measurement at this site is significant ($p = 0.017$, $R^2 = 0.71$).

Figure 2 shows two examples. In a shrubland ecosystem in the Kubuqi Desert in China [site identification (ID): CN-Kub_s; analyzer type: LI-7500; Fig. 2a], the linear relationship can be described as

$$F_{c,a} = -0.014(\pm 0.001)H - 0.28(\pm 0.064), \quad (11)$$

where $F_{c,a}$ is the observed carbon flux ($\mu mol\,m^{-2}\,s^{-1}$) and H is sensible heat ($W\,m^{-2}$). The error bounds on the regression parameters are ± 1 standard error. In this case, the negative correlation between $F_{c,a}$ and H is very strong, with an R^2 value of 0.99 and a p value smaller than 0.0001.

Not all the sites have such a nearly perfect linear relationship between $F_{c,a}$ and H as shown in Fig. 2a. For example, the relationship is much weaker for the Brooks cropland site in the United States [site ID: US-Br3 (Brooks field site 11, Ames, Iowa); analyzer type: LI-7500; Fig. 2b]. The linear equation for this site is given as

$$F_{c,a} = -0.004(\pm 0.001)H + 0.068(\pm 0.127) \quad (12)$$

with $R^2 = 0.38$ and a p value of 0.79. US-Br3 is one of the 15 sites that show a large scatter around $H = 0$. Nine of them belong to the cold climate zone and the other 6 sites belong to the mild temperature zone. None of the scatter is found in the arid zone and the polar region. Perhaps the scatter was caused by moisture interferences (dew formation or rain). Significant negative correlation exists between the site mean CO_2 flux and the site mean sensible heat flux (Fig. S2).

The regression slope b ranges from -0.051 to $0.013\,\mu mol\,m^{-2}\,s^{-1}$ per $W\,m^{-2}$ with an average value of $-0.008\,\mu mol\,m^{-2}\,s^{-1}$ per $W\,m^{-2}$ among the 64 sites analyzed. For the sites listed in Table S1, 84% have a negative slope and 16% have a positive slope. The frequency histogram shows that 38% of them range from -0.015 to $-0.007\,\mu mol\,m^{-2}\,s^{-1}$ per $W\,m^{-2}$, and 67% of them range from -0.015 to $0.00\,\mu mol\,m^{-2}\,s^{-1}$ per $W\,m^{-2}$ (Fig. 3). The mean slope of the 28 FLUXNET sites, whose data have been gap filled and through a Ustar-threshold filtering, is $-0.009 \pm 0.0004\,\mu mol\,m^{-2}\,s^{-1}$ per $W\,m^{-2}$, and is not significantly different from the mean slope of other sites ($-0.007 \pm 0.0003\,\mu mol\,m^{-2}\,s^{-1}$ per $W\,m^{-2}$; $p = 0.45$). Here and hereafter, the variation range on b is expressed as ± 1 standard error. The difference between vegetation types considered is not statistically significant ($p = 0.70$, Fig. S3).

We compared the slope of the sites that deployed the CSAT3 anemometer to measure the turbulent velocity

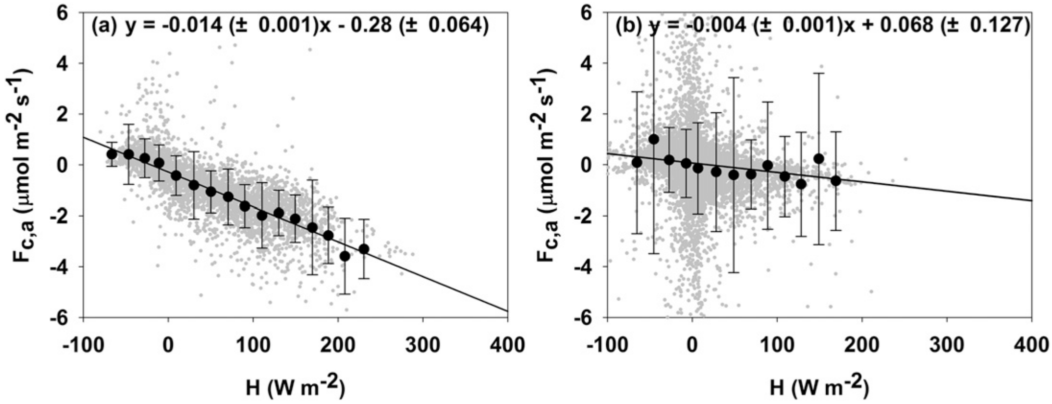

FIG. 2. Relationship between wintertime $F_{c,a}$ and H (a) at a shrub land site in China (site ID: CN-Kub_s) and (b) at a cropland site in the United States (site ID: US-Br3). Shown are half-hourly data (gray dots), bin-average values (black dots), and standard deviations (error bars). Error bounds of the regression coefficients are ±1 standard error.

and those that deployed the Gill anemometer. The mean slope b is $-0.008 \pm 0.001\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ per $\mathrm{W\,m^{-2}}$ for the CSAT3 sites (number of sites $n = 46$) and $-0.008 \pm 0.002\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ per $\mathrm{W\,m^{-2}}$ for the Gill sites ($n = 17$). The difference between these two groups is statistically insignificant ($p = 0.92$). For the site [site ID: JP-SMF (Seto mixed forest site, Japan)] that deployed the DAT-540 anemometer (Kaijo, Japan), the slope b is $-0.010\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ per $\mathrm{W\,m^{-2}}$. It should be mentioned that biases in H can be also caused by sonic anemometer measurement errors, such as the angle of attack errors with Gill anemometers (Nakai et al. 2006;

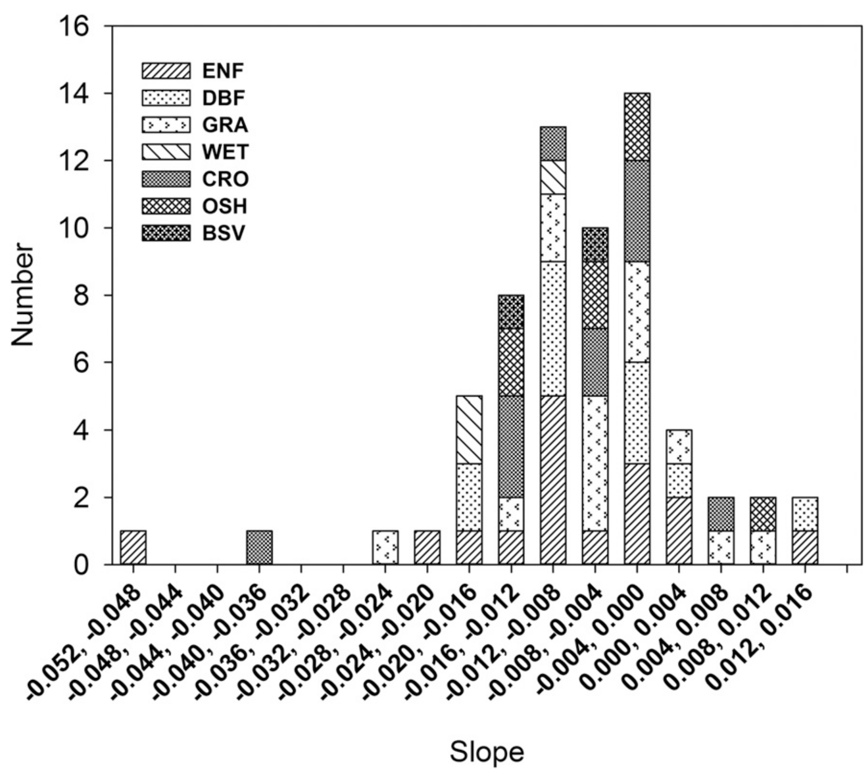

FIG. 3. Distribution of slope b ($\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ per $\mathrm{W\,m^{-2}}$) according to vegetation type: ENF, evergreen needleleaf forest; DBF, deciduous broadleaf forests; GRA, grasslands; WET, permanent wetlands; CRO, croplands; OSH, open shrub lands; and BSV, barren sparse vegetation.

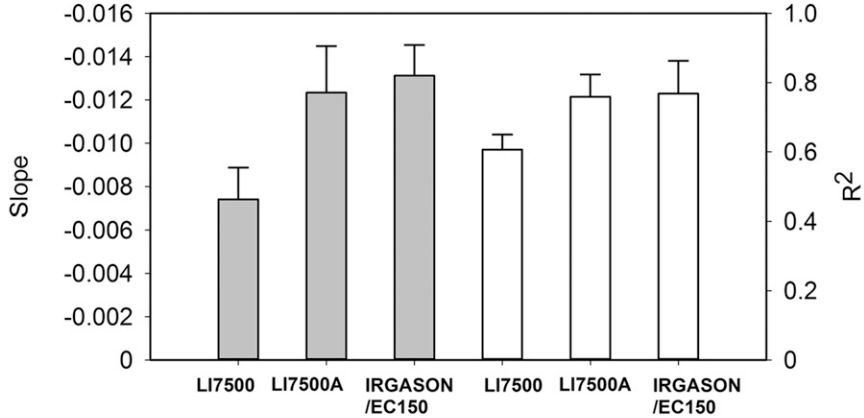

FIG. 4. Comparison among three gas analyzer types of slope b (μmol m^{-2} s^{-1} per W m^{-2}; gray bars) and the R^2 value (white bars) of the linear regression between wintertime CO_2 flux and sensible heat flux. Error bars are $\pm$1 standard error.

Nakai and Shimoyama 2012) and transducer shadowing effects on CSAT3 (Horst et al. 2015) and IRGASON (Horst et al. 2016).

The comparison among the three models of gas analyzer is given in Fig. 4. The mean slope value for the sites that deployed LI-7500 is -0.007 ± 0.001 μmol m^{-2} s^{-1} per W m^{-2} ($n = 54$), excluding three sites [site ID: US-ICh (Imnavait Creek Watershed Heath Tundra, Alaska), US-ICs (Imnavait Creek Watershed Wet Sedge Tundra, Alaska), and FR-Fon (Fontainebleau-Barbeau, France), with slope values of 0.011, -0.008, and -0.009, respectively] that are suspected to have archived the flux data after self-heating correction (Euskirchen et al. 2012; Delpierre et al. 2016). As for the LI-7500A sites, the average slope value is -0.012 ± 0.002 μmol m^{-2} s^{-1} per W m^{-2} ($n = 6$). The problem did not go away with LI-7500A despite hardware improvement over the older version, LI-7500. Besides the result of the Tarim site [site ID: CN-Tarim2 (Tarim basin, China); Wang et al. 2016], we also acquired the slope values published for three other sites using IRGASON analyzers and one site using an EC150 analyzer (Helbig et al. 2016). In that paper, the slopes were calculated for F_c and the kinematic temperature flux, and we used air density and specific heat capacities under typical atmospheric conditions to convert these values to slope values for the F_c and H. The mean slope is -0.013 ± 0.001 μmol m^{-2} s^{-1} per W m^{-2} for these sites ($n = 5$). The mean (and standard error) R^2 of the LI-7500, the LI-7500A, and the IRGASON/EC150 site group is 0.61 ($\pm$0.04), 0.76 ($\pm$0.06), and 0.77 ($\pm$0.10), respectively (Fig. 4). The differences in the regression slope or R^2 among the three analyzer types are not statistically significant ($p > 0.30$).

The mean slope value and its standard error are compared among different climate zones according to Köppen climate classification (Fig. 5). The sites in the temperate zone have the most negative mean slope value (-0.012 ± 0.003 μmol m^{-2} s^{-1} per W m^{-2}, $n = 17$), those in the polar zone have the least negative mean value (-0.001 ± 0.003 μmol m^{-2} s^{-1} per W m^{-2}, $n = 6$), and sites in the arid zone (-0.009 ± 0.002 μmol m^{-2} s^{-1} per W m^{-2}, $n = 16$) and the cold zone (-0.006 ± 0.002 μmol m^{-2} s^{-1} per W m^{-2}, $n = 25$) fall between these two mean values. The differences in the slope value may potentially reflect CO_2 flux measurement biases in different background air temperature, humidity, and CO_2 density in different climate zones.

b. Self-heating effect

According to our analysis in section 2a, if self-heating is the main reason for explaining the linear relationship between the apparent CO_2 flux and H and if the linear relationship between H and H_{real} reported by Burba et al. (2008) holds, the slope b should be -0.008 μmol m^{-2} s^{-1} per W m^{-2}. This expected value is very close to the mean value of -0.007 ± 0.001 μmol m^{-2} s^{-1} per W m^{-2} for the 54 sites that deployed the LI-7500 analyzer (Fig. 4).

Burba et al. (2008) also postulates that self-heating should be more severe in colder conditions, meaning that the slope should be more negative as the site temperature decreases, so a positive correlation is expected between the slope b and the site mean temperature. We plot the regression slope with the site mean air temperature (Fig. 6a) to test this postulation, and we find that the Pearson's correlation coefficient between the slope and temperature is slightly negative (-0.2) and that the correlation is not significant ($p = 0.13$). The correlation with site mean absolute humidity is not statistically significant either (Fig. 6b). This single-variable correlation can be confounded by bias errors in the

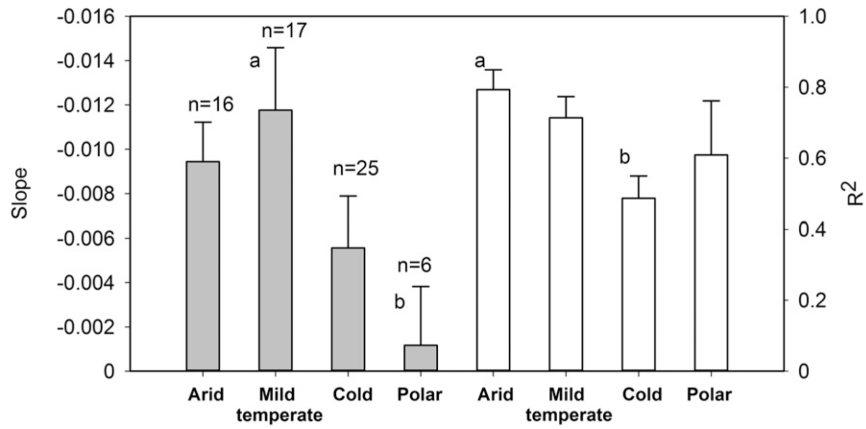

FIG. 5. As in Fig. 4, but for comparison among climate zones. Letters (a and b) mean statistical differences at $p < 0.05$.

CO_2 density. Thus, we first calculated b caused by $\delta\rho_c$ using Eq. (10) and then subtracted this value from the regression slope for each site. The resulting slope residual still does not show a positive linear relationship with air temperature (Fig. S4). In other words, our meta-analysis failed to uncover a climatic pattern regarding the self-heating effect.

c. Comparison among analyzer types

The slope among the sites that deployed either the IRGASON or the EC150 analyzer is all negative and varies in a narrow range from -0.019 to $-0.011\,\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$ per $\text{W}\,\text{m}^{-2}$, giving a mean value of $-0.013\,\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$ per $\text{W}\,\text{m}^{-2}$ (Fig. 4). This mean value is 86% greater in magnitude than the mean value obtained for the LI-7500 analyzers, but the difference is not statistically significant ($p = 0.14$). Because the IRGASON is an integrated system whose measurements of the CO_2 concentration and the temperature are made in the same sensing volume, any sensor self-heating would be automatically detected and be removed by the WPL correction procedure. Instead, the correlation between the CO_2 flux bias and the sensible heat flux is a result of the spectroscopic effect. The same spectroscopic effect also exists for the EC150 gas analyzer (Helbig et al. 2016).

As for LI-7500, Welles and McDermitt (2005), Fratini et al. (2014), and Helbig et al. (2016) believed that the air temperature only marginally affects the broadband measurements, so the spectroscopic effect can be ignored. Our results show that for LI-7500 the slope varies in a wider range from -0.051 to $0.013\,\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$ per $\text{W}\,\text{m}^{-2}$, with a mean value of $-0.007\,\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$ per $\text{W}\,\text{m}^{-2}$. The average slope value is less negative than the result of IRGASON/EC150. Thus, we infer that the spectroscopic effect, if there is any, should be weaker for LI-7500 than for IRGASON/EC150.

The slopes for the six sites that deployed the LI-7500A gas analyzer are all negative, ranging from -0.017

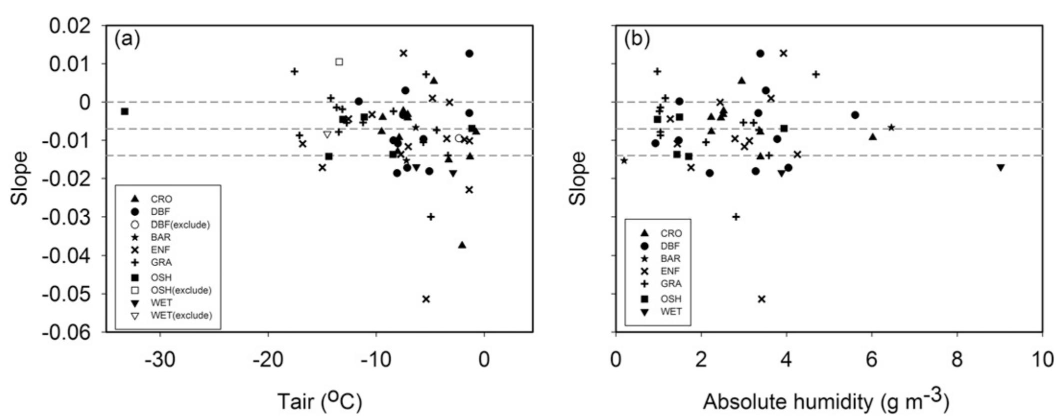

FIG. 6. Regression slope b ($\mu\text{mol}\,\text{m}^{-2}\,\text{s}^{-1}$ per $\text{W}\,\text{m}^{-2}$) vs (a) site mean air temperature and (b) absolute humidity. Different symbols represent different vegetation types. Dotted lines represent slope values as 0, -0.007, and -0.014.

to $-0.003\,\mu$mol m^{-2} s^{-1} per W m^{-2}, with a mean value of $-0.012\,\mu$mol m^{-2} s^{-1} per W m^{-2}. This mean value is 71% greater in magnitude than the mean value for LI-7500, but the difference is also not significant (p = 0.16). According to the manufacturer (Burba 2013, 78–79), LI-7500A has been improved over LI-7500 to reduce the self-heating effect. Our result suggests that the apparent uptake problem still exists for this type of analyzer, at least for the six sites we have analyzed (Fig. S1). This result suggests that surface heating may not be the only reason for the apparent wintertime net CO_2 uptake.

Using an open-path EC system consisting of an LI-7500A analyzer and a Gill anemometer, Wang et al. (2016) observed a midday uptake flux of $-1.6\,\mu$mol m^{-2} s^{-1} at a desert ecosystem in the winter (mean air temperature: -6.7°C). They estimated that if self-heating were the cause, this negative flux would require an amount of self-heat equivalent to 31 W m^{-2}. However, the mean difference between the sensible heat fluxes derived from the two sonic anemometers is only about 0.4 W m^{-2}. In their study, the apparent uptake flux measured with the LI-7500A analyzer is nearly the same as that measured with an IRGASON EC system. It is interesting that the mean slope for LI-7500A is nearly the same as that for IRGASON/EC150 (Fig. 4). Similar to IRGASON/EC150, the open-path methane analyzer described by Burba et al. (2011) may need correction to account for the spectroscopic effect caused by temperature fluctuations. Our current understanding of the LI-7500A analyzers is inadequate to draw a firm conclusion as to whether they have the same type of errors.

d. Bias in gas concentration measurements

As explained in section 2a, errors in the CO_2 concentration measurements affect the CO_2 flux measurement. Underestimation of ρ_c will result in a negative slope value in the regression of the measured CO_2 flux versus the sensible heat flux. In the current study, the bias in the CO_2 concentration was calculated as the measured value minus the CarbonTracker result. To examine how well the surface CO_2 concentration produced by CarbonTracker represents the true CO_2 concentration, we compared the monthly CarbonTracker concentration in the winter (January–December) with the measurement made with closed-path analyzers in the United States and Canada [site ID: US-Ha1 (Harvard Forest EMS Tower, Petersham, Massachusetts) and site ID: CA-Oas (Old Aspen, Saskatchewan), respectively]. At these sites, the closed-path analyzers (model LI-6262) were calibrated periodically against CO_2 standard gases traceable to the World Meteorological Organization (WMO) standards (Bakwin et al. 2004;

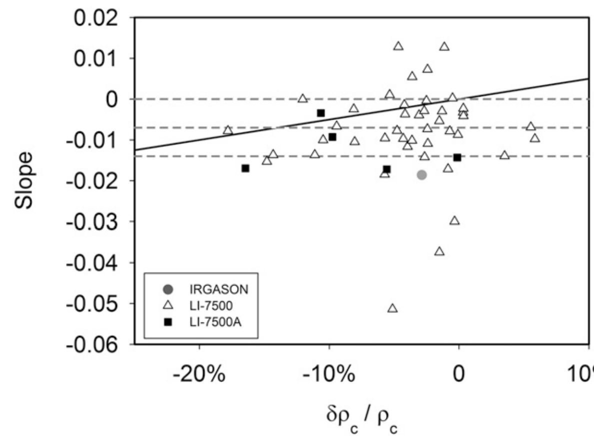

FIG. 7. Regression slope b (μmol m^{-2} s^{-1} per W m^{-2}) vs relative bias in the CO_2 concentration. Different symbols represent different analyzer types. Theoretical relationship $y = 0.05x$ is indicated (black line).

Krishnan et al. 2006), so the concentration measurements are of high quality. In a scatterplot, the results lie near the 1:1 line, with an R^2 equal to 0.77 and 0.89 for Harvard Forest and Old Aspen, respectively (Fig. S5). On average, the residual (CarbonTracker minus observation) is -1.9 ± 5.2 ppm (mean ± 1 SD) at Harvard Forest and -0.1 ± 2.6 ppm (mean ± 1 SD) at Old Aspen. This comparison supports the use of CarbonTracker CO_2 concentration as a benchmark to evaluate bias errors in ρ_c measured with open-path analyzers.

Among the 51 sites having CO_2 concentration measurement records, the bias ratio $\delta\rho_c/\rho_c$ ranges from -18% to 6%, with a mean value of -5%. Of these sites, 45 sites show a negative bias. The tendency to observe low biases with open-path analyzers in the cold season may be related to thermal contraction of the analyzer's optical path (Fratini et al. 2014) or a lack of frequent calibration. At these northern sites, it is common to perform instrument calibration in the warm season, when the sites are more accessible than in the cold season.

According to Eq. (10), under typical atmosphere conditions, the regression slope b should be approximately equal to 0.05(μmol m^{-2}s^{-1} per W m^{-2})($\delta\overline{\rho_c}/\overline{\rho_c}$). At the averaged CO_2 concentration bias ratio $\delta\rho_c/\rho_c$ of -0.05, the corresponding slope b is $-0.0025\,\mu$mol m^{-2} s^{-1} per W m^{-2}, or about 30% of the mean value of $-0.008 \pm 0.001\,\mu$mol m^{-2} s^{-1} per W m^{-2} of the sites we analyzed.

The Pearson's correlation coefficient between the slope parameter b derived from measurements and $\delta\rho_c/\rho_c$ is 0.04. There is no significant linear relationship between b and the bias in the CO_2 density (Fig. 7, p = 0.99). The three outliers in Fig. 7 are US-Wi5 (Wisconsin; $b = -0.051\,\mu$mol m^{-2} s^{-1} per W m^{-2}), DE-RuS (Selhausen

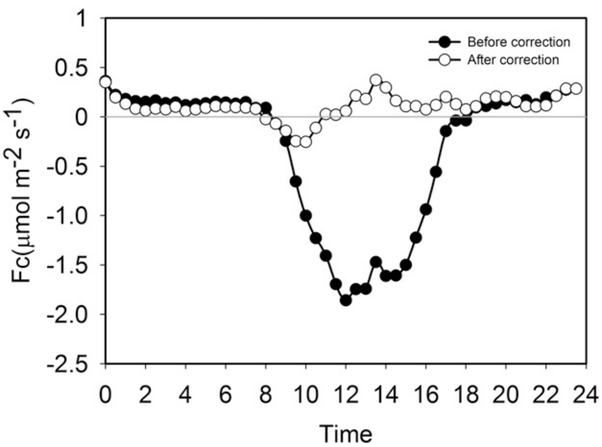

FIG. 8. Diurnal composite of the original uncorrected carbon flux (solid dots) and the corrected carbon flux (open dots) in December 2008 at CN-Kub_s.

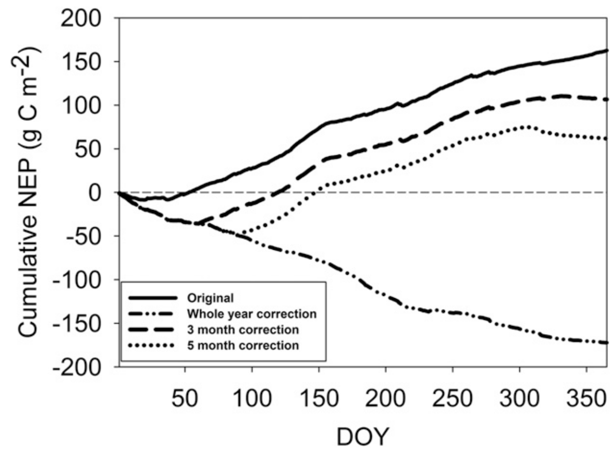

FIG. 9. Cumulated net ecosystem productivity at CN-Kub_s. A positive NEP indicates that the ecosystem is a sink for atmospheric CO_2 and vice versa.

Juelich, Germany; $b = -0.037\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ per $\mathrm{W\,m^{-2}}$), and AT-Neu ($b = -0.030\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ per $\mathrm{W\,m^{-2}}$).

e. *Correcting wintertime CO_2 flux*

Our analysis suggests that a systematic bias exists at many open-path EC sites in FLUXNET. A natural question is how to best correct the bias error. According to Eqs. (5) and (9), F_c is related to the measured flux $F_{c,a}$ as

$$F_c = F_{c,a} - bH - a. \tag{13}$$

The mean value of a among the 64 sites is 0.02 ($\pm$0.10) $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$, which is higher than the value derived from self-heating theory (section 2a). In Bogoev et al. (2015), this interception term is 0.067 $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ for an IRGASON analyzer. We consider this term a bias source that is not scaled with H and is not site specific.

Figure 8 shows the diurnal composite of the flux for a shrubland site in northern China (site ID: CN-Kub_s) in December 2008 before and after correction using Eq. (13) (regression parameter values $b = -0.014\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ per $\mathrm{W\,m^{-2}}$ and $a = -0.28\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$). The mean air temperature during this month was $-9.2°$C. The analyzer model was LI-7500. The original flux $F_{c,a}$ is negative in the daytime, with the most negative value ($-2\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$) occurring at noon, when the sensible heat reaches the maximum value. The 24-h mean value is $-0.34\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$. After the correction, the flux F_c appears much more reasonable: it varies in a very narrow range between -0.25 and 0.37 $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ in the daytime, and the 24-h mean value is slightly positive (0.11 $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$).

The correction procedure has a large impact on the cumulative carbon flux at this site. Without the correction, the annual net ecosystem productivity (NEP) is 163 $\mathrm{g\,C\,m^{-2}}$ in 2008 (Fig. 9). Here, a positive NEP indicates that the ecosystem is a sink for atmospheric CO_2, and vice versa. If the correction is applied to the three winter months (December–February), then the annual NEP will change to 107 $\mathrm{g\,C\,m^{-2}}$. If the correction equation is applied to 5 months (November–March), the annual NEP will be 62 $\mathrm{g\,C\,m^{-2}}$ (Fig. 9). If the correction is extended to the whole year, the annual NEP will be negative ($-172\,\mathrm{g\,C\,m^{-2}}$), implying that the site is a carbon source. A similar sensitivity is documented by Amiro (2010), who showed that implementing the self-heating correction over varying time lengths results in contrasting annual NEP values at a burned boreal forest site.

At site AT-Neu (a grass land ecosystem in Austria), the annual NEP determined with an open-path gas analyzer (LI-7500) is $-72\,\mathrm{g\,C\,m^{-2}}$ in year 2003, while the result of a closed-path gas analyzer is $-119\,\mathrm{g\,C\,m^{-2}}$. If the correction is applied to the three winter months (December February; $b = -0.03\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ per $\mathrm{W\,m^{-2}}$ and $a = -0.39\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$), the annual NEP will change to $-84\,\mathrm{g\,C\,m^{-2}}$. When the correction is extended to the whole year, the annual NEP will be $-188\,\mathrm{g\,C\,m^{-2}}$ (Fig. 10). The result shows that some biases with the open-path flux may still exist in the warm season, but the regression parameters may be different from the values found for the cold season.

Our bias detection method assumes that the true CO_2 flux is independent of the sensible heat flux. Obviously, this assumption does not hold in the warm season, because a high rate of photosynthesis tends to occur at times of a high sensible heat flux, so we cannot use the same method to detect flux bias errors in the warm season. Intercomparisons of open-path and closed-path

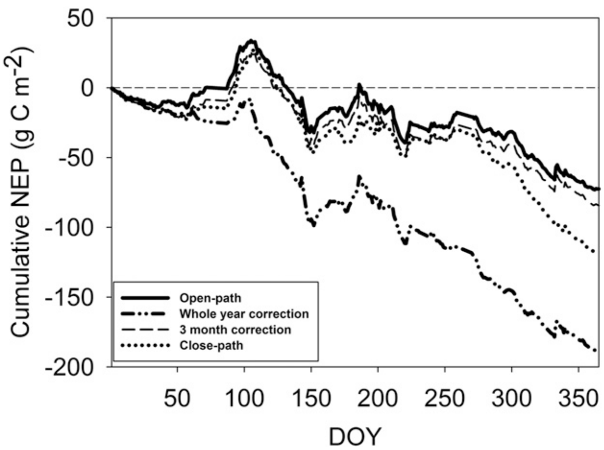

FIG. 10. Cumulated net ecosystem productivity at site AT-Neu. A positive NEP indicates that the ecosystem is a sink for atmospheric CO_2 and vice versa.

measurements are necessary in order to determine the relationship between the flux bias errors and sensible heat flux in the warm season. In the case of the IRGASON and EC150 analyzers, the correction equation [Eq. (13); Bogoev et al. 2015; Wang et al. 2016; Helbig et al. 2016] established in the cold season should also be applicable to other months because the spectroscopic effect is the same year-round.

4. Conclusions

In this study we analyzed the CO_2 and sensible heat flux data collected at 64 eddy flux sites in the cold season. A significant ($p < 0.05$) and negative linear relationship between the observed CO_2 flux $F_{c,a}$ and the sensible heat flux H was found for 37 of the sites, suggesting a systematic bias toward larger carbon uptakes in FLUXNET in the cold season. The mean regression slope was -0.007 ± 0.001, -0.012 ± 0.002, and $-0.013 \pm 0.001\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ per $\mathrm{W\,m^{-2}}$ for the LI-7500, LI7500A, and IRGASON/EC150 gas analyzers, respectively. The apparent uptake problem still exists for the LI-7500A analyzers, even though LI-7500A has been improved over LI-7500 to reduce the self-heating problem. This result suggests that self-heating may not be the only reason for the apparent wintertime net CO_2 uptake observed at many eddy flux sites. The slope value did not show statistically significant linear relationships with local temperature and humidity.

On average, the CO_2 concentration measured at these sites (with open-path analyzers) in the cold season is biased low by 5% in comparison to the CarbonTracker surface CO_2 concentration. The corresponding slope value is $-0.0025\,\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ per $\mathrm{W\,m^{-2}}$ and about 30% of the mean value of the 64 sites, but the slope value is only weakly correlated with the site mean concentration bias.

We have documented postfield corrections to the CO_2 flux measured with the LI-7500 and LI-7500A analyzers in the cold season. At present, we do not have evidence supporting the application of these corrections for the whole year. Intercomparisons of open-path and closed-path eddy covariance measurements are necessary to investigate whether similar bias errors exist in the warm season.

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