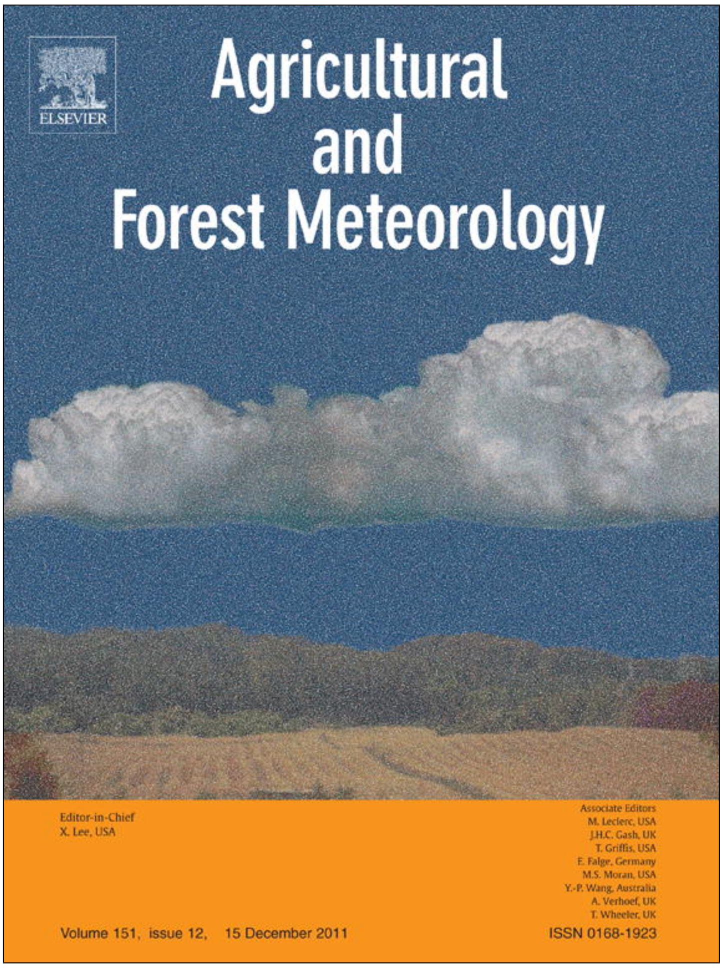
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Short communication

Adjustment of annual NEE and ET for the open-path IRGA self-heating correction: Magnitude and approximation over a range of climate

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The self-heating correction is known to modify open-path eddy covariance estimates of net ecosystem CO_2 exchange, typically towards reduced uptake or enhanced emissions, but with a magnitude heretofore not generally documented. We assess the magnitude of this correction to be of order 1 μmol m^{-2} s^{-1} (daytime) for half-hourly fluxes and consistently over 100 g C m^{-2} for annual integrations, across a tower network (CARBORED-ES) spanning climate zones from Mediterranean temperate to cool alpine. We furthermore examine the sensitivity of the correction to its determining factors. Due to significant diurnal variation, the means of discriminating day versus night can lead to differences of up to several tens of g C m^{-2} year^{-1}. Since its principal determinants – temperature and wind speed – do not include gas flux data, the annual correction can be estimated using only meteorological data so as to avoid uncertainties introduced when filling gaps in flux data. For fast retro-correction of annual integrations published prior to the recognition of this instrument surface heating effect, the annual impact can be roughly approximated to within 12 g C m^{-2} year^{-1} by a linear function of mean annual temperature. These determinations highlight the need for the flux community to reach a consensus regarding the need for and the specific form of this correction.

1. Introduction

In the last two decades infrared gas analyzers (IRGA) of open- and closed-path design have become fundamental for tracking greenhouse gases, providing datasets with worldwide coverage that are very useful for global change assessments. Initial comparisons of the two instrument types found similar results when appropriate corrections were applied (Haslwanter et al., 2009; Yasuda and Watanabe, 2001). However, further comparisons have revealed substantial differences between them, especially in cold environments (Clement et al., 2009; Hirata et al., 2005; Hirata et al., 2007), causing concern in the flux research community.

Specifically, carbon dioxide and water vapor density measurements from an open-path IRGA may be biased when the instrument significantly heats the air that it measures, particularly in cold environments (Burba et al., 2008). Burba et al. (2008) proposed corrections requiring no complementary closed-path measurements (Method 4), introducing new sensible heat flux terms estimated theoretically and verified experimentally (Burba et al., 2008; Grelle and Burba, 2007).

While use of this self-heating correction is increasing (Alberti et al., 2010; Delpierre et al., 2009; Domec et al., 2010; Noormets et al., 2010; Reverter et al., 2010; Sun et al., 2010) it is not yet applied systematically (Pingintha et al., 2010; Zeeman et al., 2010; Zona et al., 2010), perhaps because recent direct comparisons of flux measurements between open- and closed-path analyzers have lead to its rejection in some (Bowling et al., 2010; Haslwanter et al., 2009; Wohlfahrt et al., 2008), but not all cases (Clement et al., 2009; Järvi et al., 2009).

At present the correction is generally used only at cold sites, where it has been deemed essential (Amiro, 2010); however, no objective criteria have been established to identify just when and where it must be applied, and its magnitude for temperate sites remains unreported. Determining whether the self-heating

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Table 1
Experimental sites from CARBORED-ES Spanish NEE monitoring network.

	Altitude (m)	Mean annual temperature (°C)	Biome	Reference
Balsablanca (BAL)	200	17	Mediterranean shrubland	Rey et al., 2011
Llano de los Juanes, Gador (GAD)	1600	12	Mediterranean shrubland	Serrano-Ortiz et al., 2007
Laguna Seca (LAS)	2300	6	Mediterranean alpine shrubland	Reverter et al., 2010
Las Majadas del Tiétar (MAJ)	258	17	Savanna	Casals et al., 2009
El Saler (SAL)	5	18	Coniferous evergreen forest	Sanz et al., 2004
Sueca (SUE)	10	18	Rice paddy	–
Vall d'Alinyà (VDA)	1770	6	Grassland	Gilmanov et al., 2007

correction improves estimation of the carbon balance is a topic of growing concern, as it may change conclusions regarding annual carbon balances, in some cases changing from sink to source (Amiro, 2010; Reverter et al., 2010; Wohlfahrt et al., 2008).

In this study we explore the magnitude of the self-heating correction and its sensitivity to drivers that determine revisions of carbon and water vapor fluxes. We assess the magnitudes of the correction over a broad range of climate, and propose a simple approximation to estimate its magnitude. We also caution that calculating the magnitude of the self-heating correction via gap-filled fluxes instead of meteorological data leads to increased uncertainty, and that the means of discriminating day and night are important for reducing discrepancies in calculating the correction worldwide.

2. Methods

2.1. Experimental sites

This study comprises data from seven eddy covariance stations over a 2300 m altitudinal gradient in Spain, within the national carbon flux monitoring network CARBORED-ES (Table 1). Every site operates with an open-path infrared gas analyzer LI-7500 (LI-COR Inc., Lincoln, NE, USA) IRGA, inclined *ca.* 15° from the vertical in accordance with the instrument manual.

2.2. Mathematical definition of the self-heating correction

The calculation of CO_2 and H_2O fluxes using open-path analyzers follows (Webb et al., 1980):

$$F = F_0 + \mu \frac{\rho_c}{\rho_d} E_0 + \frac{\rho_c}{\rho c_p T_a} \left(1 + \mu \frac{\rho_v}{\rho_d}\right) H \quad (1)$$

$$E = \left(1 + \mu \frac{\rho_v}{\rho_d}\right) \left(E_0 + \frac{\rho_v}{\rho c_p T_a} H\right) \quad (2)$$

where F_0 is the covariance between the vertical velocity and the CO_2 density and E_0 the covariance between the vertical velocity and water vapor density, μ the air to water vapor molecular mass ratio, c_p the specific heat at constant pressure, H and E the sensible heat and water vapor fluxes, T_a the air temperature and ρ, ρ_d, ρ_c and ρ_v the densities of air, dry air, CO_2 and water vapor.

Burba et al. (2008) proposed substituting the traditional sensible heat flux H with the 'measured' sensible heat flux (S) within the IRGA measurement path:

$$F_B = F_0 + \mu \frac{\rho_c}{\rho_d} E_0 + \frac{\rho_c}{\rho c_p T_a} \left(1 + \mu \frac{\rho_v}{\rho_d}\right) S \quad (3)$$

where S is the sum of the traditional sensible heat flux H plus the estimated new terms resulting from heating by the instrument bottom, top and spar (Burba et al., 2008):

$$S = H + S_{bot} + S_{top} + 0.15 S_{spar} \quad (4)$$

These new heating terms are defined by:

$$S_{bot} = k_{air} \frac{(T_{bot} - T_a)}{\delta_{bot}} \quad (5a)$$

$$S_{top} = k_{air} \frac{(r_{top} + \delta_{top})(T_{top} - T_a)}{r_{top}\delta_{top}} \quad (5b)$$

$$S_{spar} = k_{air} \frac{(T_{spar} - T_a)}{r_{spar} \ln\left(\frac{r_{spar}+\delta_{spar}}{r_{spar}}\right)} \quad (5c)$$

where δ_{bot}, δ_{top} and δ_{spar} are the average thickness of the boundary layer above the bottom and top window and spar given by:

$$\delta_{bot} = 0.004\sqrt{\frac{l_{bot}}{U}} + 0.004 \quad (6a)$$

$$\delta_{top} = 0.0028\sqrt{\frac{l_{top}}{U}} + \frac{0.00025}{U} + 0.0045 \quad (6b)$$

$$\delta_{spar} = 0.0058\sqrt{\frac{l_{spar}}{U}} \quad (6c)$$

and k_{air} is the thermal conductivity of air in W m^{-1} K^{-1}, r_{top}, r_{spar}, l_{bot}, l_{top} and l_{spar} are experimental coefficients addressed in Burba et al., 2008 (Table 2) and U is the wind speed. Surface temperatures (T_{bot}, T_{top} and T_{spar}) are assessed by experimental regressions (Table 2; Burba et al., 2008) which are different for day and night. Thus, by subtracting F from F_B to the self-heating correction for CO_2 fluxes is

$$C_{B,C} = \frac{\rho_c}{\rho c_p T_a} \left(1 + \mu \frac{\rho_v}{\rho_d}\right) (S_{top} + S_{bot} + 0.15 S_{spar}) \quad (7)$$

and likewise for water fluxes

$$C_{B,V} = \frac{\rho_v}{\rho c_p T_a} \left(1 + \mu \frac{\rho_v}{\rho_d}\right) (S_{top} + S_{bot} + 0.15 S_{spar}) \quad (8)$$

and simplifying Eqs. (7) and (8)

$$C_{B,V} = \frac{\rho_v}{\rho_c} C_{B,C} \quad (9)$$

From Eqs. (8) and (9) it is clear that the self-heating correction magnitude for carbon and water vapor can be estimated using only meteorological data (from the right-hand sides of Eqs. (7) and (8)), requiring no eddy covariance data. One of the main advantages of this for determining the annual magnitude of the correction is that

Table 2
Surface temperatures estimated from air temperature (T_a) regressions and experimental coefficients at the bottom, spar and top of the LI-7500 open-path IRGA addressed by Burba et al. (2008).

	Daytime surface temperatures T (°C)	Nighttime surface temperatures T (°C)	Radius, r (m)	Diameter, l (m)
Bottom	$0.944T_a + 2.57$	$0.883T_a + 2.17$	–	0.065
spar	$1.01T_a + 0.36$	$1.01T_a - 0.17$	0.0025	0.005
top	$1.005T_a + 0.24$	$1.008T_a - 0.41$	0.0225	0.0045

meteorological data usually present a much lower gap percentage if compared to gas flux data.

2.3. Applied method

The annual magnitude of the self-heating correction for CO_2 and water fluxes may be estimated by two different methods that do not always produce identical results. In the first method ($\langle C_{B1} \rangle$), Eqs. (7) and (8) (or (9)) are used to calculate individual, half-hourly contributions to the annual sum using only gap-filled meteorological data. In the second method ($\langle C_{B2} \rangle$), Eqs. (1) and (3) are used to calculate half-hourly contributions whose differences are integrated to form an annual sum. In contrast to the first method however, this approach requires gap-filled flux data, both with and without the self-heating correction applied ($F_B - F$).

Various studies have estimated $\langle C_{B2C} \rangle$ (Amiro, 2010; Reverter et al., 2010; Wohlfahrt et al., 2008), using this second methodology that introduced additional gap-filling uncertainty which could be avoided. Note that with the second approach errors (ΔC_{B2C}) increase because, since C_{B2C} is determined as the integrated difference between two gap-filled time series, its uncertainty (ΔC_{B2C}) is defined as the sum of the uncertainties ($\Delta F_B + \Delta F$). Since overall uncertainty of annual NEE is dominated by gap filling (Dragoni et al., 2007), differences in the importance of the self-heating correction across studies may derive from uncertainties in gap-filling, rather than on the self-heating correction *per se*.

The annual magnitude $\langle C_{B1} \rangle$ for the CARBORED-ES experimental sites was calculated based on the air temperature, the densities of air, CO_2 and water vapor, and the wind speed as required by Eqs. (7) and (9). For annual integrations, gaps in CO_2, water and air densities and wind speed were filled using annual average values. Gaps in air temperature, the incident flux of photosynthetically active radiation (PAR) and in carbon and water vapor fluxes were filled following (Reichstein et al., 2005) (http://gaia.agraria.unitus.it/database/eddyproc/index.html).

Sensitivity analyses were performed, applying an arbitrary positive and negative percent variation individually for each meteorological input (T_a, U, ρ, ρ_d, ρ_c, ρ_v) affecting the half-hour correction (Eqs. (7) and (8)). Half-hours were then summed to obtain the annual self-heating correction magnitude $\langle C_{B1} \rangle$.

3. Results and discussion

Fig. 1 shows, for El Saler in 2007 (Table 1), the sensitivity of the estimated annual magnitude of the self-heating correction for NEE to its means of calculation. The top frame shows cumulative gap-filled NEE both with and without the correction applied; in the bottom frame, the difference between these two signals (C_{B2C}) is seen to diverge from C_{B1C} calculated directly from Eq. (7). We therefore emphasize that, while the data in Fig. 1a do permit an examination of the effect of applying the correction for a particular site/year of data, it includes unnecessary uncertainty due to the influence of two gap-filling procedures. Furthermore, it is important to note that the annual magnitude of the self-heating correction, if applicable at this temperate Mediterranean site, would be 140 g m^{-2}. By contrast, for the annual evapotranspiration estimate, at no site does the effect of applying this correction reach 11 mm, and so it might be considered negligible (Table 3).

Sensitivity analysis of the magnitude of C_{B1C} reveals that it depends mostly on T_a, and to some extent U (via the additional sensible heat flux terms, S_x). Just a 1% variation in T_a (*ca.* 3 K) and a 10% variation in U values would result in changes of 15 and 4 g C m^{-2} year^{-1} respectively. The influence of the remaining variables in Eq. (7) is far less important. Changes in the ratio ρ_v/ρ_d in Eq. (7) hardly affect the annual carbon budget, since this term is very small compared to unity. For the terms outside the brackets in Eq. (7), variations in gas densities dissociated from temperature, such as altitudinal differences, are offsetting since variations in CO_2 density are proportional to those in air density. Thus, air density is not a major determinant of the self-heating correction as was wrongly stated by Reverter et al. (2010).

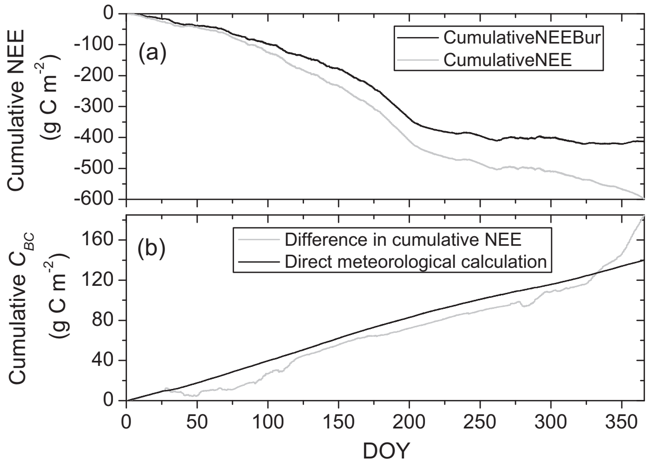

Fig. 1. (a). Cumulative NEE with and without the Burba correction applied. b). Cumulative Burba correction magnitude for carbon estimated both directly from meteorological data (C_{B1C}; Eq. (7)) and as the difference between gap-filled fluxes (C_{B2C}; $F_B - F$) at SAL2007. The two series diverge as a consequence of uncertainties introduced by gap filling: the first month was relatively gap-free, but during the last days of the year (after DOY 323) the flux gap percentage was 83%.

Discriminating between day and night also influences C_{B1C} strongly, as regressions of the temperature at the bottom (T_{bot}), at the top (T_{top}), and on the spars (T_{spar}) of the LI-7500 housing obtained by Burba et al., 2008 produce different results during day and night time (see Burba et al., 2008 for further details). In fact, the calculated correction is very near zero during nighttime, jumping to *ca.* 1 µmol m^{-2} s^{-1} at sunrise and exhibiting a square wave behavior that might be avoided by smoothing during the transitional hours to soften such a step-change. Differences between day and night corrections are so great that discriminating between them is crucial when summing to obtain an annual carbon budget. For instance, choosing $R_n > 0$ W m^{-2} as a night-day discriminator instead of an arbitrary PAR > 10 µmol m^{-2} s^{-1} may result in up to 30 g C m^{-2} year^{-1} of additional emissions. Net radiation might seem to be an appropriate discrimination variable, but it can be affected by the state of the ground. We therefore think it more appropriate to use those PAR values corresponding to $R_n = 0$ obtained from site-specific annual regressions of PAR versus R_n, excluding snow cover and flooded soils.

However relevant, the calculated annual correction varies among Spanish sites from 129 g C m^{-2} year^{-1} at Mediterranean sites to 190 g C m^{-2} year^{-1} at cold, alpine sites (Table 3). Even at warmer sites like BAL and MAJ, with a mean annual temperature near 17 °C (Table 2), the correction is above 140 g C m^{-2} year^{-1}. Generally, the importance of the self-heating correction has been stressed at cold sites (Amiro, 2010), and it may be unnecessary except for determining “wintertime fluxes” (Brown et al., 2010). Overall, no universal, objective criterion has yet been established to distinguish between “warm” and “cold” conditions or sites, but is clearly needed in order to avoid the application of a large and maybe inappropriate “corrections”.

Table 3 also shows a clear correlation of the self-heating correction with mean annual temperature ($\langle T_a \rangle$ °C). In fact, a simple linear model (Fig. 2) predicts the annual correction as:

$$\left\langle C_{B1C} \right\rangle = 202 - 3.4 \left\langle T_a \right\rangle \tag{10}$$

Table 3
Annual carbon and water vapor flux correction magnitudes (⟨C_{B1C}⟩ and ⟨C_{B1V}⟩) calculated by summing half-hour contributions (C_{B1C} and C_{B1V}) assessed from meteorological data (⟨T_a⟩: Mean Annual Air Temperature, ⟨U⟩: Mean Annual Wind Speed). The abbreviations for the sites are: BAL (Balsablanca, Mediterranean shrubland), GAD (Llano de los Juanes, Sierra de Gádor, Mediterranean shrubland), LAS (Laguna Seca, Mediterranean alpine shrubland), MAJ (Las Majadas del Tiétar, broad evergreen forest), SAL (El Saler, coniferous evergreen forest), SUE (Sueca, rice paddy), VDA (Vall d'alinyà, grassland). Uncorrected annual sums of CO_2 ⟨F⟩ and water vapor fluxes ⟨E⟩ are included. Percentages of gaps in the variables upon which the self-heating correction depends are also included in the last column. The instrument tilt was no more than 15 °C for every experimental site/year.

	⟨T_a⟩ (°C)	⟨U⟩ (m s^{-1})	⟨C_{B1C}⟩ (g C m^{-2} year^{-1})	⟨C_{B1V}⟩ (mm H_2O year^{-1})	⟨F⟩ (g C m^{-2} year^{-1})	⟨E⟩ (mm H_2O year^{-1})	Gaps in PAR, ρ, ρ_d, ρ_c, ρ_v, T_a or U (%)
BAL 2007	17.3	2.87	149	7.8	118	200	4.2
BAL 2008	17.1	3.09	150	7.9	131	172	19.4
GAD 2007	11.6	1.96	152	5.8	−11	201	33.8
GAD 2008	12.0	2.33	155	5.8	−9	339	22.5
LAS 2007	5.8	2.49	182	5.7	−135	346	16.1
LAS 2008	5.8	2.63	178	6.3	−100	380	28.2
MAJ 2006	16.5	2.55	151	6.8	−105	554	31.7
MAJ 2007	15.1	2.45	159	7.0	−159	650	28.8
SAL 2007	17.4	2.67	140	10.8	−598	749	46.1
SAL 2008	17.8	2.41	129	10.4	−544	564	61.7
SUE 2005	17.0	2.87	141	10.6	−710	886	6.2
SUE 2006	17.6	2.95	141	9.6	−548	822	15.6
VDA 2007	6.1	2.69	184	7.0	−188	501	74.3
VDA 2008	5.1	2.41	190	8.0	−102	370	51.2

Table 4
Examples of annual NEE values computed from open-path flux measurements, and published in Agricultural and Forest Meteorology since 2008, restricted to the CARBORED-ES range of mean annual temperatures, and hypothetical effects of the heating correction when applied to these data. Errors of the published annual NEE were not taken into account.

Reference	Ecosystem type	Annual T_a (°C)	Year	Published annual NEE (g C m^{-2})	Revised annual NEE (g C m^{-2})
Kochendorfer et al., 2011	Riparian forest	15.8	2004	−310	−162
Rodrigues et al., 2011	Eucalypt plantation	15.3	2002	−866	−716
Rodrigues et al., 2011	Eucalypt plantation	16.1	2003	−791	−644
Peichl et al., 2010	18-year old Pinus Strobus forest	7.8	2007	*c.a.* −800	*c.a.* −625
Zeeman et al., 2010	Grassland at 1000 m	7.2	2006	−222	−44
Zeeman et al., 2010	Grassland at 400 m	9.5	2006	−59	111
Zeeman et al., 2010	Grassland at 1000 m	7.7	2007	−417	−241
Zeeman et al., 2010	Grassland at 400 m	10.0	2007	−69	99
Béziat et al., 2009	Cropland (maize)	12.9	2006	−186	−28
Béziat et al., 2009	Cropland (sunflower)	13.3	2007	28	185
Béziat et al., 2009	Cropland (rapeseed)	12.8	2005	−286	−128
Béziat et al., 2009	Cropland (triticale)	12.5	2005	−335	−176
Béziat et al., 2009	Cropland (winter weat)	13.0	2006	−324	−166
Béziat et al., 2009	Cropland (winter weat)	13.1	2007	−369	−212
Dusek et al., 2009	Temperate herbaceous wetland	7.9	2006	−199	−24
Dusek et al., 2009	Temperate herbaceous wetland	9.1	2007	−220	−49
Holst et al., 2008	Pine forest	10.3 (period 1978–2001)	2005	−600	−433
Holst et al., 2008	Pine forest	10.3 (period 1978–2001)	2006	−380	−213

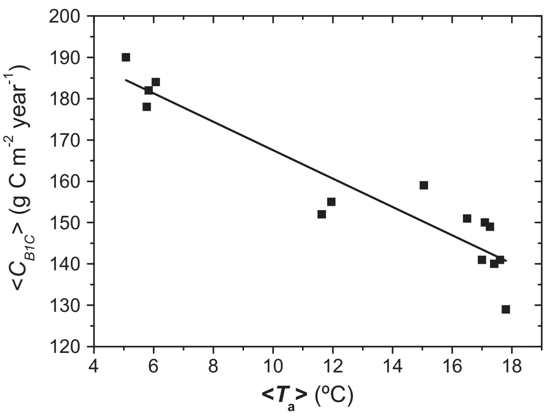

Fig. 2. Linear relationship (R^2 = 0.9, N = 14) between the annual magnitude of the Burba correction for carbon estimated directly from meteorological data (⟨C_{B1C}⟩; Eq. (7)) and annual air temperature (⟨T_a⟩) for two years of every site of CARBORED-ES.

with a maximum residual of 12 g C m^{-2} year^{-1} (R^2 = 0.9; N = 14) over all sites. Such a relationship might be very useful for correcting previous flux estimates with little error. An analogous equation was not found for the water vapor magnitude because the water vapor density (Eq. (8)) does not follow a linear relationship with altitude/air density.

Many published annual carbon balances estimated from measurements using the LI-7500 open-path systems without applying the self-heating correction may be biased. Table 4 displays annual carbon budgets from 2008 to 2011 as published in Agricultural and Forest Meteorology, together with corrected values obtained using Eq. (10). As expected, applying the self-heating correction would push estimates towards carbon loss everywhere, with greater magnitude at colder sites. Some of these sites could change from sink to source if application of this rough correction were necessary.

In the face of impending global climate change related to CO_2 and other greenhouse gases, eddy covariance data are being used in conjunction with models to quantify local, regional and global carbon exchange (Beer et al., 2010; Luyssaert et al., 2008) as well as their environmental drivers (Mercado et al., 2009). In this study, we have examined the magnitude and determinants of the correction to eddy covariance fluxes as proposed by Burba et al. (2008), the application of which is nonetheless far from resolved as definitive. There is an urgent need to revise the Burba et al., 2008 correction, both to establish when and where it must be applied (warm versus cold) and also to account for the inclination of the LI-7500, since the original formulation assumes a vertical $\pm 15^{\circ}$ mounting of the LI-7500, whereas much steeper mounting angles are sometimes used (Sottocornola and Kiely, 2010). Wind direction may play an important role in determining the degree of heating within the measurement path when the LI-7500 is inclined beyond about 15°. Additional studies in wind tunnels (similar to Burba et al., 2008 and Grelle and Burba, 2007) would provide insight into the most appropriate means of correcting for instrument heating of measured air. In any case, additional comparisons of open-path versus closed-path instruments should be conducted at contrasting sites in order to compare eddy fluxes with and without the correction.

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References

Alberti, G., Vedove, G.D., Zuliani, M., Perossotti, A., Castaldi, S., Giuseppe, Z., 2010. Changes in CO_2 emissions after crop conversion from continuous maize to alfalfa. Agriculture, Ecosystems and Environment 136, 139–147.

Amiro, B., 2010. Estimating annual carbon dioxide eddy fluxes using open-path analysers for cold forest sites. Agricultural and Forest Meteorology 150, 1366–1372.

Beer, C, Reichstein, M., Tomelleri, E., Ciais, P., Jung, M., Carvalhais, N., Rödenbeck, C., Altaf, A.M., Baldocchi, D., Bonan, G.B., Bondeau, A., Cescatti, A., Lasslop, G., Lindroth, A., Lomas, M.L., Sebastiaan, Margolis, H., Oleson, K.W., Roupsard, O., Veenendaal, E., Viovy, N., Williams, C., Woodward, F.I., Papale, D., 2010. Terrestrial gross carbon dioxide uptake: global distribution and covariation with climate. Science 329, 834–838.

Béziat, P., Ceschia, E., Dedieu, G., 2009. Carbon balance of a three crop succession over two cropland sites in South West France. Agricultural and Forest Meteorology 149, 1628–1645.

Bowling, D.R., Bethers-Marchetti, S., Lunch, C.K., Grote, E.E., Belnap, J., 2010. Carbon, water, and energy fluxes in a semiarid cold desert grassland during and following multiyear drought. Journal of Geophysical Research 115, G04026, doi:10.1029/2010JG001322.

Brown, M, Black, T.A., Nesic, Z., Foord, V.N., Spittlehouse, D.L., Fredeen, A.L., Grant, N.J., Burton, P.J., Trofymow, J.A., 2010. Impact of mountain pine beetle on the net ecosystem production of lodgepole pine stands in British Columbia. Agricultural and Forest Meteorology 150, 254–264.

Burba, G.G., Mcdermitt, D.K., Grelle, A., Anderson, D.J., Xu, L., 2008. Addressing the influence of instrument surface heat exchange on the measurements of CO_2 flux from open-path gas analyzers. Global Change Biology 14, 1854–1876.

Casals, P., Gimeno, C., Carrara, A., López-Sangil, L., Sanz, M.J., 2009. Soil CO_2 efflux and extractable organic carbon fractions under simulated precipitation events in a Mediterranean Dehesa. Soil Biology & Biochemistry 41, 1915–1922.

Clement, R.J., Burba, G.G., Grelle, A., Anderson, D.J., Moncrieff, J.B., 2009. Improved trace gas flux estimation through IRGA sampling optimization. Agricultural and Forest Meteorology 149, 623–638.

Delpierre, N, Soudani, K., François, C., Köstner, B., Pontailler, J. -Y., Nikinmaa, E., Misson, L., Aubinet, M., Bernhofer, C., Granier, A., Grünwald, T., Heinesch, B., Longdoz, B., Ourcival, J. -M., Rambal, S., Vesala, T., Dufrêne, E., 2009. Exceptional carbon uptake in European forest during warm spring of 2007: a data-model analysis. Global Change Biology 15, 1455–1474.

Domec, J.-C., King, J.S., Noormets, A., Treasure, E., Gavazzi, M.J., Sun, G., McNulty, S.G., 2010. Hydraulic redistribution of soil water by roots affects whole-stand evapotranspiration and net ecosystem carbon exchange. New Phytologist 187, 171–183.

Dragoni, D., Schmid, H.P., Grimmond, C.S.B., Loescher, H.W., 2007. Uncertainty of annual net ecosystem productivity estimated using eddy covariance flux measurements. Journal of Geophysical Research 112, D17102, doi:10.1029/2006JD008149.

Dusek, J., Cízková, H., Czerný, R., Taufarová, K., Smídová, M., Janous, D., 2009. Influence of summer flood on the net ecosystem exchange of CO_2 in a temperate sedge-grass marsh. Agricultural and Forest Meteorology 149, 1524–1530.

Gilmanov, T.G., Soussana, J.F., Aires, L., Allard, V., Ammann, C., Balzarolo, M., Barcza, Z., Bernhofer, C., Campbell, C.L., Cernusca, A., Cescatti, A., Clifton-Brown, J., Dirks, B.O.M., Dore, S., Eugster, W., Fuhrer, J., Gimeno, C., Gruenwald, T., Haszpra, L., Hensen, A., Ibrom, A., Jacobs, A.F.G., Jones, M.B., Lanigan, G., Laurila, T., Lohila, A., Manca, G., Marcolla, B., Nagy, Z., Pilegaard, K., Pinter, K., Pio, C., Raschi, A., Rogiers, N., Sanz, M.J., Stefani, P., Sutton, M., Tuba, Z., Valentini, R., Williams, M.L., Wohlfahrt, G., 2007. Partitioning European grassland net ecosystem CO_2 exchange into gross primary productivity and ecosystem respiration using light response function analysis. Agriculture, Ecosystems and Environment 121, 93–120.

Grelle, A., Burba, G.G., 2007. Fine-wire thermometer to correct CO_2 fluxes by open-path analyzers for artificial density fluctuations. Agricultural and Forest Meteorology 147, 48–57.

Haslwanter, A., Hammerle, A., Wohlfahrt, G., 2009. Open-path vs. close-path eddy covariance measurements of the net ecosystem carbon dioxide and water vapor exchange: a long-term perspective. Agricultural and Forest Meteorology 149, 291–302.

Hirata, R, Hirano, T., Mogami, J., Fujinuma, Y., Inukai, K., Saigusa, N., Yamamoto, S., 2005. CO_2 flux measured by an open-path system over a larch forest during the snow-covered season. Phyton 45, 347–351.

Hirata, R., Hirano, T., Saigusa, N., Fujinuma, Y., Inukai, K., Kitamori, Y., Takahashi, Y., Yamamato, S., 2007. Seasonal and interannual variations in carbon dioxide exchange of a temperate larch forest. Agricultural and Forest Meteorology 147, 110–124.

Holst, J, Barnard, R., Brandes, E., Buchmann, N., Gessler, A., Jaeger, L., 2008. Impacts of summer water limitation on the carbon balance of a Scots pine forest in the southern upper Rhine plain. Agricultural and Forest Meteorology 148, 1815–1826.

Järvi, L., Mammarella, I., Eugster, W., Ibrom, A., Siivola, E., Dellwik, E., Keronen, P., Burba, G., Vesala, T., 2009. Comparison of net CO_2 fluxes measured with open- and closed-path infrared gas analyzers in urban complex environment. Boreal Environment Research 14, 499–514.

Kochendorfer, J., Castillo, E.G., Haas, E., Oechel, W.C., Paw, U.K.T., 2011. Net ecosystem exchange, evapotranspiration and canopy conductance in a riparian forest. Agricultural and Forest Meteorology 151, 544–553.

Luyssaert, S., Schulze, E.-D., Börner, A., Knohl, A., Hessenmöller, D., Law, B.E., Ciais, P., Grace, J., 2008. Old-growth forest as global carbon sinks. Nature 455, 213–215.

Mercado, L.M., Bellouin, N., Sitch, S., Boucher, O., Huntingford, C., Wild, M., Cox, P.M., 2009. Impact of changes in diffuse radiation on the global land carbon sink. Nature 458, 1014–1018.

Noormets, A., Gavazzi, M.J., McNulty, S.G., Domec, J.-C., Sun, G., King, J.S., Chen, J., 2010. Response of carbon fluxes to drought in a coastal plain loblolly pine forest. Global Change Biology 16, 272–287.

Peichl, M., Arain, M.A., Brodeur, J.J., 2010. Age effects on carbon fluxes in temperate pine forest. Agricultural and Forest Meteorology 150, 1090–1101.

Pingintha, N, Leclerc, M.Y., Beasley, J.P., Durden, D., Zhang, G., Senthong, C., Rowland, D.L., 2010. Hysteresis response of daytime net ecosystem exchange during drought. Biogeosciences 7, 1159–1170.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenger, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentini, R., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Global Change Biology 11, 1424–1439.

Reverter, B.R., Sánchez-Cañete, E.P., Resco, V., Serrano-Ortiz, P., Oyonarte, C., Kowalski, A.S., 2010. Analyzing the major drivers of NEE in a Mediterranean alpine shrubland. Biogeosciences 7, 2010–2601, 10. 5194/bg-7-2601-2611.

Rey, A., Pegoraro, E., Oyonarte, C., Were, A., Escribano, P., Raimundo, J., 2011. Impact of land degradation on soil respiration in a steppe (*Stipa tenacissima L.*) semiarid ecosystem in the SE of Spain. Soil Biology & Biochemistry 43 (2), 393–403.

Rodrigues, A., Pita, G., Mateus, J., Kurz-Besson, C., Casquilho, M., Cerasoli, S., Gomes, A., Pereira, J., 2011. Eight years of continuous carbon fluxes measurements in a Portuguese eucalypt stand under two main events: drought and felling. Agricultural and Forest Meteorology 151, 493–507.

Sanz, M.J., Carrara, A., Gimeno, C., Bucher, A.E., López, R., 2004. Effects of a dry and warm summer conditions on CO_2 and Energy fluxes from three Mediterranean ecosystems. Geophysical Research Abstracts 6, 3239.

Serrano-Ortiz, P., Kowalski, A.S., Domingo, F., Rey, A., Pegoraro, E., Villagarcía, L., Alados-Arboledas, L., 2007. Variations in daytime net carbon and water exchange in a montane shrubland ecosystem in southeast Spain. Photosynthetica 45 (1), 30–35.

Sottocornola, M., Kiely, G., 2010. Hydro-meteorological controls on the CO_2 exchange variation in an Irish blanket bog. Agricultural and Forest Meteorology 150, 287–297.

Sun, G, Noormets, A., Gavazzi, M.J., McNulty, S.G., Chen, J., Domec, J.C., King, J.S., Amatya, D.M., Skaggs, R.W., 2010. Energy and water balance of two contrasting loblolly pine plantations on the lower coastal plain of North Carolina. USA. Forest Ecology and Management 259, 1299–1310.

Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Quarterly Journal of the Royal Meteorological Society 106, 85–100.

Wohlfahrt, G., Fenstermaker, L.F., Arnone, J.A., 2008. Large annual net ecosystem CO_2 uptake of a Mojave Desert ecosystem. Global Change Biology 14, 1475–1487.

Yasuda, Y., Watanabe, T., 2001. Comparative measurements of CO_2 flux over a forest using closed-path and open-path CO_2 analysers. Boundary Layer Meteorology 100, 191–208.

Zeeman, M.J., Hiller, R., Gilgen, A.K., Michna, P., Plüss, P., Buchmann, N., Eugster, W., 2010. Management and climate impacts on net CO_2 fluxes and carbon budgets of three grasslands along an elevational gradient in Switzerland. Agricultural and Forest Meteorology 150, 519–530.

Zona, D, Oechel, W.C., Peterson, K.M., Clement, R.J., Paw U, K.T., Ustin, S.L., 2010. Characterization of the carbon fluxes of a vegetated drained lake basin chronosequence on the Alaskan Arctic Coastal Plain. Global Change Biology 16, 1870–1882.