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CONSEQUENCES OF INCOMPLETE SURFACE ENERGY BALANCE CLOSURE FOR CO_2 FLUXES FROM OPEN-PATH CO_2/H_2O INFRARED GAS ANALYSERS

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Abstract. We present an approach for assessing the impact of systematic biases in measured energy fluxes on CO_2 flux estimates obtained from open-path eddy-covariance systems. In our analysis, we present equations to analyse the propagation of errors through the Webb, Pearman, and Leuning (WPL) algorithm [*Quart. J. Roy. Meteorol. Soc.* **106**, 85–100, 1980] that is widely used to account for density fluctuations on CO_2 flux measurements. Our results suggest that incomplete energy balance closure does not necessarily lead to an underestimation of CO_2 fluxes despite the existence of surface energy imbalance; either an overestimation or underestimation of CO_2 fluxes is possible depending on local atmospheric conditions and measurement errors in the sensible heat, latent heat, and CO_2 fluxes. We use open-path eddy-covariance fluxes measured over a black spruce forest in interior Alaska to explore several energy imbalance scenarios and their consequences for CO_2 fluxes.

Keywords: Carbon dioxide flux, Eddy covariance, Error analysis, Open-path CO_2/H_2O infrared gas analysers (IRGA), Surface energy imbalance, WPL algorithm.

1. Introduction

The eddy-covariance technique has been widely used to directly measure energy, water vapour, and carbon exchange between terrestrial ecosystems

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and the atmosphere (Aubinet et al., 2000; Baldocchi et al., 2001). A critical issue with this approach is to quantify the uncertainties related to long-term eddy-covariance measurements of carbon exchange so that reliable assessments of carbon sources or sinks can be made over time scales ranging from hours to years (Goulden et al., 1996; Massman and Lee, 2002; Baldocchi, 2003). In the micrometeorological community, the evaluation of surface energy balance closure is accepted as an important procedure in assessing data quality (Aubinet et al., 2000; Wilson et al., 2002). However, direct measurements of sensible (H) and latent (LE) heat fluxes, net radiation (Rn), soil heat flux, and storage almost always indicate an incomplete energy balance closure (Aubinet et al., 2000; Oncley et al., 2002; Wilson et al., 2002; Culf et al., 2004). Experimental evidence has also shown that the energy imbalance (typically ranging from about 5 to 30%) and its causes are site dependent (Aubinet et al., 2000; Twine et al., 2000; Oncley et al., 2002; Turnipseed et al., 2002; Wilson et al., 2002). It is generally accepted that methodological and instrumental problems exist that cause energy flux loss, especially over non-ideal surfaces (Foken and Oncley, 1995; Lee, 1998; Panin et al., 1998; Finnigan, 1999, 2004; Massman and Lee, 2002; Baldocchi, 2003; Finnigan et al., 2003). Considerable work has gone into seeking corrections for these flux losses (Webb et al., 1980 - WPL; Moore, 1986; Kramm et al., 1995; Massman, 2000; Paw U et al., 2000; Fuehrer and Friehe, 2002; Massman and Lee, 2002; Liebethal and Foken, 2003, 2004; Liu, 2005; Massman, 2004). Since CO_2 fluxes are also measured by the same system that often underestimates sensible and latent heat fluxes, several studies have addressed possible links between surface energy imbalance and uncertainties in estimates of CO_2 fluxes (Twine et al., 2000; Wilson et al., 2002). Twine et al. (2000) provide experimental evidence suggesting that the magnitude of CO_2 fluxes measured using closed-path H_2O/CO_2 infrared gas analysers (IRGA) may be underestimated by the same factor as latent heat fluxes. In contrast, other investigators argue that the magnitude of CO_2 fluxes using open-path IRGAs are largely overestimated because sensible heat flux, and thus the WPL algorithm associated with this flux, is underestimated (Anthoni et al., 2002b). Alternatively, using the data measured by both open-path and closed-path IRGAs at 22 sites in FLUXNET, Wilson et al. (2002) proposed that CO_2 fluxes are underestimated when turbulent fluxes are underestimated relative to available energy. As illustrated by these contrasting findings, uncertainties in our understanding of the links between surface energy imbalance and CO_2 fluxes still remain.

Despite the large differences in the types of measurement errors associated with open-path and closed-path IRGAs (Baldocchi, 2003), the relationship between incomplete energy balance closure and the uncertainties

of CO_2 fluxes has not been separately and quantitatively addressed in previous studies using open-path and closed-path systems.

There are two primary types of errors embedded in the measurements of CO_2 fluxes with an open-path IRGA. The first is the measurement error in raw CO_2 fluxes caused by multiple factors (Goulden et al., 1996; Wilson et al., 2002), which may be caused by the uncertainties in instrument calibration or errors resulting from methodological aspects such as loss of high and/or low frequency contributions to fluxes, or the neglect of horizontal advection, vertical divergence, or storage terms (Wilson et al., 2002). The second type of error arises from the propagation of systematic or random errors in raw sensible heat flux $(\overline{w'T'})$ $(\overline{w'T'}$ is actually the kinematic heat flux), latent heat flux $(\overline{w'\rho_v'})$ $(\overline{w'\rho_v'}$ is actually the kinematic moisture flux), and CO_2 flux $(\overline{w'\rho_c'})$ through the WPL algorithm. When open-path IRGAs are used in eddy-covariance systems to measure CO_2 flux (hereafter, raw CO_2 flux), the WPL algorithm (Webb et al., 1980) is usually applied to account for the density effects caused by heat and water vapour transfer to obtain corrected CO_2 fluxes (hereafter, final CO_2 flux). Since the WPL algorithm relates the final CO_2 fluxes to the raw eddy-covariance fluxes, any errors in the raw sensible and latent heat fluxes as well as raw CO_2 fluxes will be propagated through the WPL algorithm to generate final CO_2 fluxes. Hereafter, this type of error is referred to as a propagation error. Although this additional propagation error has potential impacts on CO_2 fluxes, it has received little attention (Anthoni et al., 2002b; Baldocchi, 2003). Instead, it is common that the raw measurement errors are used in discussing errors of final CO_2 fluxes or assessing uncertainties in long-term net ecosystem exchange (NEE) regardless of the difference in IRGA types (i.e. open-path and closed-path IRGAs).

The interaction of measurement errors of raw CO_2 fluxes directly related to incomplete energy balance closure and propagation errors indirectly related to incomplete energy balance closure through the WPL algorithm presents a challenge to assessing the precision and accuracy of final CO_2 fluxes and the error sources. Understanding the role of propagation error is important because such errors could lead to large biases in the estimation of long-term NEE. Here we present an approach for assessing the influence of measurement errors in energy balance on CO_2 fluxes through the WPL algorithm when open-path IRGAs are used. We then illustrate the role of these propagation errors using eddy-covariance data measured from a flux tower in interior Alaska. We show, in a quantitative way, that errors (or biases) in the measurement of eddy-covariance fluxes do not necessarily lead to proportional errors in the CO_2 fluxes computed through the WPL algorithm; instead, the impact of these errors depends strongly on the magnitude of the sensible heat flux.

2. Theoretical Considerations

When an eddy-covariance system with an open-path IRGA is used for measuring water vapour and CO_2 fluxes, the WPL algorithm is usually applied to account for the density effects. We rewrite the WPL algorithm as follows (Webb et al., 1980),

$$E = \overline{w'\rho_v'}\,(1+\mu\sigma) + \frac{\bar{\rho}_v}{\bar{T}}\,(1+\mu\sigma)\,\overline{w'T'}, \tag{1}$$

$$F_c = \overline{w'\rho_c'} + \frac{\bar{\rho}_c}{\bar{\rho}_a}\mu\,\overline{w'\rho_v'} + \frac{\bar{\rho}_c}{\bar{T}}(1+\mu\sigma)\,\overline{w'T'}, \tag{2}$$

where $\overline{w'T'}$, $\overline{w'\rho_v'}$, and $\overline{w'\rho_c'}$ are the sensible heat flux, latent heat flux, and CO_2 flux measured by eddy-covariance systems, respectively. Although other corrections (e.g., a frequency response correction) may be made to these fluxes, we still refer them as the raw fluxes. E and F_c are the latent heat flux and the CO_2 flux after application of the WPL algorithm (hereafter, referred as to the final fluxes), respectively; $\bar{\rho}_c$, $\bar{\rho}_a$, and $\bar{\rho}_v$ are the densities of CO_2, dry air, and water vapour, respectively; $\mu = m_a/m_v$ and $\sigma = \bar{\rho}_v/\bar{\rho}_a$; m_a and m_v are the molecular mass of dry air and water vapour, respectively. T is the air temperature.

Differentiating Equations (1) and (2), we obtain

$$\frac{\delta E}{E} = \left[\frac{\overline{w'\rho_v'}}{\overline{w'T'}}\frac{\delta\overline{w'\rho_v'}}{\overline{w'\rho_v'}} + \frac{\bar{\rho}_v}{\bar{T}}\frac{\delta\overline{w'T'}}{\overline{w'T'}}\right] \bigg/ \left[\frac{\overline{w'\rho_v'}}{\overline{w'T'}} + \frac{\bar{\rho}_v}{\bar{T}}\right], \tag{3}$$

$$\frac{\delta F_c}{F_c} = \frac{\overline{w'\rho_c'}}{F_c}\frac{\delta\overline{w'\rho_c'}}{\overline{w'\rho_c'}} + \frac{\mu\overline{w'\rho_v'}}{F_c}\frac{\bar{\rho}_c}{\bar{\rho}_a}\frac{\delta\overline{w'\rho_v'}}{\overline{w'\rho_v'}} + \frac{\bar{\rho}_c\overline{w'T'}(1+\mu\sigma)}{\bar{T}F_c}\frac{\delta\overline{w'T'}}{\overline{w'T'}}. \tag{4}$$

Note from Equation (3) that a change in final latent heat flux ($\delta E/E$) is sensitive to changes in raw latent heat fluxes $\left(\omega_v = \delta\overline{w'\rho_v'}/\overline{w'\rho_v'}\right)$ and to changes in raw sensible heat fluxes $\left(\omega_T = \delta\overline{w'T'}/\overline{w'T'}\right)$. Equation (4) indicates that a change in the final CO_2 fluxes ($\delta F_c/F_c$) is related not only to a change in raw CO_2 fluxes ($\omega_c = \delta\overline{w'\rho_c'}/\overline{w'\rho_c'}$) but also to a change in raw sensible and latent heat fluxes (i.e. ω_T and ω_v).

These equations allow for an assessment of the impact of systematic and random errors incurred in measurements of raw sensible and latent heat fluxes and CO_2 fluxes on the final CO_2 fluxes (as propagated through the WPL algorithm).

We identify the potential magnitudes of raw systematic errors for our open-path eddy-covariance system (i.e. ω_T, ω_v and ω_c) through evaluation of energy balance closure and other techniques in Section 4.1. We then

make three case studies to further explore consequences of error propagation through the WPL algorithm for the CO_2, NEE, and latent heat flux estimates obtained from our site (Sections 4.2, 4.3, and 4.4). Finally, in Section 4.5, we explore how random errors may be amplified or damped through the WPL algorithm, specifically examining the effect of coordinate rotation.

3. Site Description and Instruments

Our experimental study was conducted at a black spruce forest near Delta Junction (63°54′N, 145°40′W) located about 100 km south-east of Fairbanks, Alaska. This site was dominated by relatively homogeneous old black spruce stands (*Picea mariana*) about 80 years old; the mean canopy height was approximately 4 m above the surface (Liu et al., 2005), and the canopy coverage was about 60%. The terrain was generally flat on glacial outwash in the Tanana River drainage of interior Alaska (Manies et al., 2004), and the fetch exceeded 1 km to the south, west, and north, and was approximately 200 m to the east. The dominant ground cover species were feathermoss (*Pleurozium schreberi* and *Rhytidium rugosum*) and lichens (*Cladonia* spp. and *Stereocaulon* spp.) that reached a depth of 0.1–0.15 m (Liu et al., 2005).

Eddy-covariance and microclimate measurements were made at this site during 2001–2004 (Liu et al., 2005), and the 2002 summer data were used here. The eddy-covariance system consisted of a three-dimensional sonic anemometer (model CSAT3; Campbell Scientific, Inc.) and an open-path CO_2/H_2O IRGA (model LI-7500; LI-COR, Inc.) that were mounted at a height of 9.5 m (more than twice the mean canopy height). The sonic anemometer was used to determine wind velocity and sonic temperature fluctuations, and the IRGA was used to measure the fluctuations of water vapour and CO_2 density. Water vapour calibration was made regularly using compressed air with a magnesium perchlorate desiccant as a zero gas and output from a dew point hygrometer (model LI-610, LI-COR, Inc.) as the water vapour span. CO_2 calibration was made by passing a standard CO_2 gas as a span and passing compressed air through desiccants and a scrubber (soda lime) as a zero reference. The distance between the IRGA and the sonic anemometer was about 0.25 m (Liu et al., 2005).

Signals from the sonic anemometer and the IRGA were sampled at 10 Hz, and fluxes of sensible heat (H), latent heat (LE), and CO_2 (F_c) were calculated using the 30-min covariances of vertical wind velocity with virtual temperature, water vapour density, and CO_2 concentration. The planar fit method was adopted for rotating the coordinate system to streamline (Wilczak et al., 2001), and the fluxes were computed using a block average

rather than a linear detrending method. Because the sonic temperature is used, and because the crosswind effect should be taken into account (Schotanus et al., 1983; Kaimal and Finnigan, 1994), we converted the buoyancy flux derived directly from the sonic temperature to sensible heat flux according to Liu et al. (2001). Latent heat and CO_2 fluxes obtained by the open-path IRGA were calculated following Webb et al. (1980). Data were rejected when winds were blowing through the tower or from the east, or when the data did not pass a quality check (Foken and Wichura, 1996; Foken et al., 2004).

We also measured microclimate variables as 30-min averages of 1-s readings. These variables included net radiation (Rn; model Q-7.1, Radiation and Energy Balance Systems (REBS), Inc.), incoming and reflected shortwave radiation (model Precision Spectral Pyranometer, Eppley Laboratories), and photosynthetic photon flux density (model LI-190SB, LI-COR, Inc.). Air temperature and relative humidity were measured at 10, 6 and 2 m with temperature/humidity probes (model HMP45C, Vaisala, Inc.). We estimate the heat storage in the canopy air space (S_a) using the air temperature measurements (HMP45C) at 2 m and a mean canopy height of 4 m. A 3-cup anemometer and wind vane (model 03001, RM Young, Inc.) was mounted at 12 m to measure wind speed and wind direction, and an additional wind speed sensor (Model 03101, RM Young, Inc.) was mounted at 6 m to measure wind speed. Additionally, thermocouples and soil moisture probes (model CS615, Campbell Scientific, Inc.) were buried at 0–0.34 m below the surface and soil heat flux (S) plates (model HFT3, REBS, Inc.) were buried at 0.1 m below the surface in three microenvironments near the tower, including one in an open patch and another under a shrub. The 30-min heat storage (S) in the soil above the soil heat flux plates was estimated using the combination method (Oke, 1987), using volume fractions of moss/lichen community mineral, organic and water content of the surface soil for calculating surface heat capacity (Beringer et al., 2001; Chambers and Chapin, 2002).

4. Results and Discussion

4.1. Eddy-covariance fluxes and closure of the surface energy budget

Closure of the surface energy budget is commonly accepted as an important factor in assessing the quality of eddy-covariance data. We used a straight-line regression with errors in both coordinates (i.e. $H + LE$ vs. $Rn - G - S - S_a$) where H: sensible heat flux, LE: latent heat flux, Rn: net radiation, G: soil heat flux at 0.1 m below the surface, S: soil heat storage
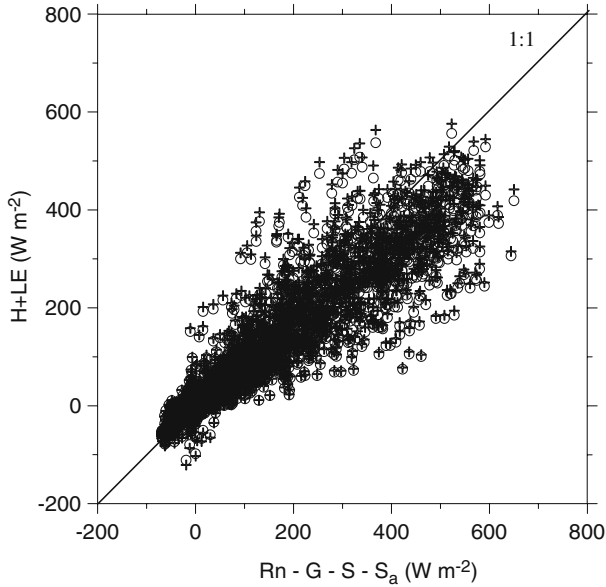
Figure 1. Surface energy balance closure in a black spruce forest in interior Alaska from June 15 to August 15, 2002. Eddy-covariance fluxes of sensible heat (H) and latent heat (LE) are plotted against available energy at the surface. Available energy consists of net radiation (Rn), soil heat flux (G; soil heat flux at 0.1 m), and soil heat storage (S; soil heat storage above 0.1 m), and heat flux storage in the canopy air space (S_a). This site has a slope of 0.85 and a zero offset of 2.8 W m^{-2} ($r^2 = 0.87$, $n = 3302$) before application of the frequency response corrections (denoted with circles). The slope increased to 0.89 and the offset changed to 3.6 W m^{-2} ($r^2 = 0.88$, $n = 3302$) after application of the frequency response corrections (denoted with crosses).

above the soil heat flux plates, S_a: heat storage at the canopy air space) to estimate the slope and intercept of the regression line (Press et al., 1992). Using the data from the 2002 summer season from June 15 to August 15, the slope and intercept between $H + LE$ and $Rn - G - S - S_a$ were 0.85 and 2.8 W m^{-2} respectively for our boreal forest site ($r^2 = 0.87$) (Figure 1). Generally, the closure of the energy budget was higher during the day (0.86) and lower during the night (0.70). The ratio of the sum of $H + LE$ and the sum of $Rn - G - S - S_a$ over the whole period is considered as an alternative method to evaluate closure (Wilson et al., 2002). This ratio for our site was 0.83.

All eddy-covariance systems encounter attenuation of turbulent fluxes at high and/or low frequencies (Moore, 1986; Massman and Lee, 2002). Based on the theoretical approach described by Moore (1986), Eugster and Senn (1995), and Horst (1997, 2000), we calculated the diurnal variation in the correction factors for sensible heat flux, latent heat flux, and CO_2 flux to account for flux losses due to sensor separation, line average, and time
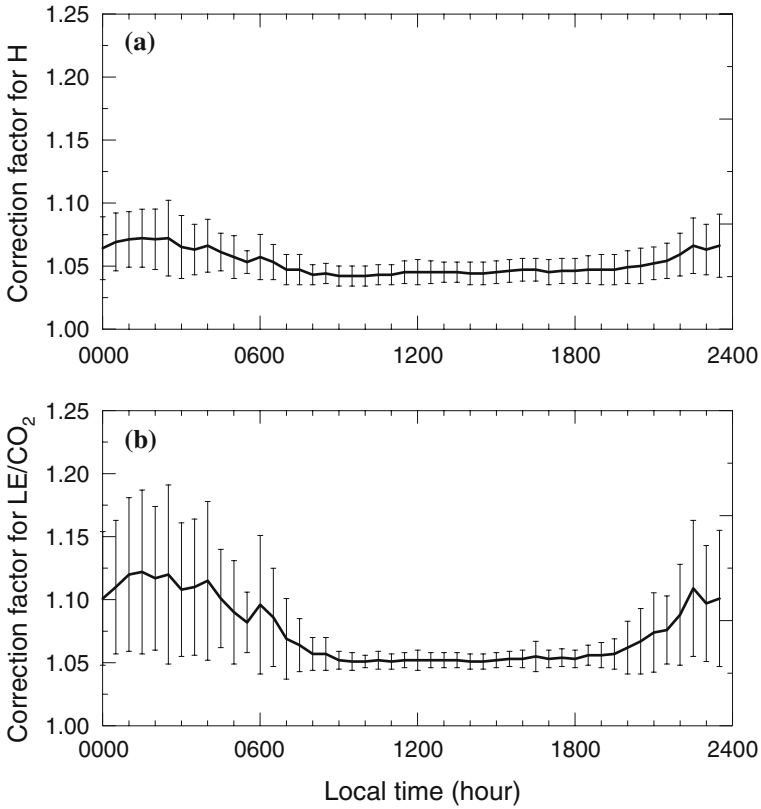
Figure 2. Correction factors for sensible heat flux (a) and latent heat flux/CO_2 flux (b) due to frequency response loss. Data were measured in a black spruce forest in interior Alaska from June 15 to August 15, 2002.

response (Figure 2). In general, the spectral correction factor for latent heat and CO_2 fluxes was slightly greater than that for sensible heat fluxes. During the day, spectral response loss decreased latent heat and CO_2 fluxes by about 5% while it decreased sensible heat fluxes by about 4%. The magnitudes of these correction factors are comparable to the estimates by Leuning and Judd (1996) and Chambers and Chapin (2002), who used closed-path IRGAs that encountered high-frequency losses due to tube attenuation of turbulent fluctuations. The dominant part of the turbulent spectrum shifted from a low frequency range (about 0.005–0.05 Hz) during the day to a higher frequency range (about 0.01–0.5 Hz) during the night when the atmosphere was stable. This led to larger spectral correction factors at night (about 12% for latent heat and CO_2 fluxes and about 7% for sensible heat fluxes) due to high frequency loss (Figure 2).

After frequency response corrections of the raw flux data, we obtained a slope and intercept of the regression line between corrected $H + LE$ and

$Rn - G - S - S_a$ of 0.89 and $3.6\,\mathrm{W\,m^{-2}}$ respectively ($r^2 = 0.88$) (Figure 1). We did not measure the canopy heat storage (in boles and other components of the above ground vegetation) although we believe this term to be small because of the relatively low height and sparse nature of the canopy (with a mean height of 4 m and mean surface coverage of 60%). Taking account of heat storage in the canopy air space (S_a) accounted for a small increase in the slope. Combining the frequency response losses and heat storage in the canopy air appeared to account for some, but not all, of the energy loss identified in our analysis of the energy budget closure. Other unidentified error sources must contribute to the remainder of the imbalance.

A lack of closure of the surface energy budget by 10% or more is not uncommon at eddy flux sites that are used to study ecosystem processes in remote areas under conditions that are not perfectly ideal. The causes for this remaining imbalance in the surface energy budget (after application of all appropriate corrections) still remain unclear (Wilson et al., 2002).

One possibility is that these heterogeneities introduce both horizontal and vertical advective flow terms that are not resolvable with our single point vertical flux tower. If these advective terms contribute to vertical fluxes at our site, non-closure of the surface energy balance would be inevitable even though we made the appropriate adjustments for high/low frequency losses and storage. Another possibility could be the effect of the roughness sublayer on the flux measurements. For our site with the mean canopy height of 4 m (Liu et al., 2005), the roughness sublayer with its height of about one to two times the mean canopy height (Garratt, 1994) might have a small impact on our measurements at 9.8 m.

The intercomparison experiment with different eddy-covariance systems from six groups in the Energy Balance Experiment (EBEX) indicates that the uncertainties for the sensible and latent fluxes could be reduced to around 5% when the eddy-covariance systems are well calibrated and maintained, as well as the measurement field being well selected to meet the requirements of the similarity theory (Mauder et al., submitted to B.L.M.). Using the same dataset, but with different post-field data processing methods from the EBEX participants, gives the sensible and latent heat fluxes with their uncertainties of 10 – 15% as a result of the difference in correction methods and physical parameters used (Mauder et al., ibid). Although all terms of the energy budget are taken into consideration in the EBEX, including net radiation, sensible and latent heat fluxes, heat storage by plant and air mass within the canopy, heat flux at the top of the soil canopy heat storage, and vertical flux divergence/horizontal advection from multi-layer measurements, the EBEX dataset still contained an imbalance in the surface energy budget of around 10% that the EBEX community is unable to explain (Oncley et al., submitted to B.L.M.). Both

instrumental and methodological problems are believed to be responsible for these uncertainties since both the performance of instruments and flux correction methods are not perfect.

Although the question of the surface energy imbalance is well known, the implications for CO_2 flux measurements are not yet fully understood (Wilson et al., 2002; Baldocchi, 2003). In this context, it is useful to understand how (even small) losses of turbulent energy fluxes influence CO_2 fluxes derived from open-path analysers via application of the WPL algorithm. In the following sections, we generate three cases to quantitatively illustrate how it is important to apply simultaneously all corrections for high and low frequency losses to sensible and latent heat fluxes and CO_2 fluxes prior to application of the WPL algorithm. In particular, we stress that applying corrections solely to CO_2 fluxes, but not to sensible and latent heat fluxes, is not a good strategy for obtaining high-quality CO_2 flux data. Instead, large biases in the final CO_2 fluxes may be introduced in this scenario.

4.2. Impact of incomplete energy closure on CO_2 fluxes

4.2.1. *Case 1: Raw Sensible Heat and Moisture Fluxes and CO_2 Fluxes Without Correction*

We use the information from the energy balance closure (Section 4.1) construct the first case for analysis to illustrate the effects of the imbalance on CO_2 fluxes in the case where no corrections are made. The objective of this paper is not to show how well we can achieve energy balance closure for our site, but rather, to show that non-closure, even if quite small, may have negatively large impacts on the accuracy of CO_2 fluxes through the WPL algorithm.

Starting with our assumption that sensible and latent heat fluxes were underestimated by about 15% for daytime periods and by about 30% at nighttime according to the above energy balance closure, we assumed that raw CO_2 fluxes were also underestimated by this same amount. Specifically, to correct the fluxes for these losses, we obtain $\omega_c = -15\%$, $\omega_v = -15\%$, and $\omega_T = -15\%$ for the daytime measurements (Table I, Case 1), and $\omega_c = -30\%$, $\omega_v = -30\%$, and $\omega_T = -30\%$ for the nighttime measurements (Table II, Case 1).

It was expected that the errors of final CO_2 fluxes would vary with time, depending on the relative contributions from the individual error sources (i.e. ω_T, ω_v and ω_c) and their corresponding coefficients (i.e. $C_1 = \overline{w'\rho_c'}/F_c$, $C_2 = (\mu \overline{w'\rho_v'}/F_c)(\bar{\rho}_c/\bar{\rho}_a)$ and $C_3 = \overline{\rho_c}\,\overline{w'T'}(1+\mu\sigma)/\overline{T}F_c)$ in Equation (4) under different atmospheric conditions. Using the data obtained over the black spruce stands during the 2002 summer season, we obtained the variation of the coefficients C_1, C_2, and C_3 with sensible heat fluxes

TABLE I

Error estimates of daytime CO_2 fluxes.

Sensible heat flux ($W\,m^{-2}$)	Coefficients in Equation (4)			$\delta F_c/F_c$ in Equation (4) (%)		
	C_1	C_2	C_3	Case 1*	Case 2**	Case 3***
50	1.76	−0.15	−0.77	−12.8	−8.5	−4.0
100	2.15	−0.19	−1.20	−11.5	−7.6	−0.7
150	2.64	−0.23	−1.88	−8.0	−5.4	+5.2
200	3.23	−0.27	−2.80	−2.3	−1.6	+13.8
250	3.91	−0.30	−3.99	+5.5	+3.7	+25.1
300	4.71	−0.33	−5.42	+15.6	+10.4	+39.1
350	5.60	−0.35	−7.10	+27.7	+18.5	+55.7

* $\frac{\delta \overline{w'\rho_c'}}{\overline{w'\rho_c'}} = -15\%$, $\frac{\delta \overline{w'\rho_v'}}{\overline{w'\rho_v'}} = -15\%$, $\frac{\delta \overline{w'T'}}{\overline{w'T'}} = -15\%$.

** $\frac{\delta \overline{w'\rho_c'}}{\overline{w'\rho_c'}} = -10\%$, $\frac{\delta \overline{w'\rho_v'}}{\overline{w'\rho_v'}} = -10\%$, $\frac{\delta \overline{w'T'}}{\overline{w'T'}} = -10\%$.

*** $\frac{\delta \overline{w'\rho_c'}}{\overline{w'\rho_c'}} = -10\%$, $\frac{\delta \overline{w'\rho_v'}}{\overline{w'\rho_v'}} = -15\%$, $\frac{\delta \overline{w'T'}}{\overline{w'T'}} = -15\%$.

TABLE II

Error estimates of nighttime CO_2 fluxes.

Sensible heat flux ($W\,m^{-2}$)	Coefficients in Equation (4)			$\delta F_c/F_c$ in Equation (4) (%)		
	C_1	C_2	C_3	Case 1*	Case 2**	Case 3***
−25	1.45	0.04	−0.97	−15.9	−4.7	1.5
−50	1.75	0.06	−1.17	−19.0	−5.5	1.9
−75	2.12	0.08	−1.46	−22.2	−5.9	3.3
−100	2.59	0.09	−1.83	−25.5	−6.1	5.6

* $\frac{\delta \overline{w'\rho_c'}}{\overline{w'\rho_c'}} = -30\%$, $\frac{\delta \overline{w'\rho_v'}}{\overline{w'\rho_v'}} = -30\%$, $\frac{\delta \overline{w'T'}}{\overline{w'T'}} = -30\%$

** $\frac{\delta \overline{w'\rho_c'}}{\overline{w'\rho_c'}} = -18\%$, $\frac{\delta \overline{w'\rho_v'}}{\overline{w'\rho_v'}} = -18\%$, $\frac{\delta \overline{w'T'}}{\overline{w'T'}} = -23\%$

*** $\frac{\delta \overline{w'\rho_c'}}{\overline{w'\rho_c'}} = -18\%$, $\frac{\delta \overline{w'\rho_v'}}{\overline{w'\rho_v'}} = -30\%$, $\frac{\delta \overline{w'T'}}{\overline{w'T'}} = -30\%$

(Figure 3). Except for the large scattering when the sensible heat fluxes were close to zero, which was normal when F_c and other fluxes approached zero during the morning and evening transition periods, there were strong relationships between the coefficients (i.e. C_1, C_2 and C_3) and sensible heat fluxes. We made second-order polynomial regressions for the data in Figure 3 and then obtained the magnitudes of the coefficients from the relationship between the fit curves and the sensible heat fluxes. On average, during the day coefficient C_1 ranged from 1.7 to 5.6, C_2 from −0.15 to

-0.35, and C_3 from -0.77 to -7.1, while during the night, coefficient C_1 ranged from 1.45 to 2.6, C_2 from 0.04 to 0.09, and C_3 from -0.9 to -1.8.

The variation in the coefficients listed in Table I suggests that the day-time errors of final CO_2 fluxes were mainly controlled by the measurement errors in raw CO_2 fluxes and raw sensible heat fluxes. For Case 1 during the day, even though we assumed the raw flux error was -15%, the final CO_2 flux errors $(\delta F_c/F_c)$ varied from -13% to $+28\%$.

For Case 1 during the night, the final nighttime CO_2 flux errors $(\delta F_c/F_c)$ varied from -16% to -26% (Table II). It was likely that the combination of the different error sources on the right-hand terms of Equation (4) reduced the errors for the final nighttime CO_2 fluxes through the WPL algorithm.

4.2.2. *Case 2: Raw H, LE, and CO₂ Fluxes After Frequency Response Corrections*

After frequency response corrections for raw data, the underestimation of turbulent fluxes and CO_2 fluxes was reduced to about 10% during the day (i.e. we take $\omega_c = -10\%$, $\omega_v = -10\%$, and $\omega_T = -10\%$; Table I, Case 2), and to about 18% for nighttime latent heat fluxes and CO_2 fluxes and to about 23% for nighttime sensible heat fluxes (i.e. we take $\omega_c = -18\%$, $\omega_v = -18\%$, and $\omega_T = -23\%$; Table II, Case 2).

For Case 2, the biases of the daytime final CO_2 fluxes $(\delta F_c/F_c)$ varied from -8.5% to $+18.5\%$ (Table I), again with the application of Equation (4) always leading to a smaller inferred carbon uptake rate by the ecosystem as compared with the initial guess at the raw CO_2 error of -10%. Similarly, the nighttime final CO_2 fluxes were always underestimated (about -5.5%; Table II). Clearly, the errors of the final CO_2 fluxes were substantially reduced due to the simultaneous corrections on the sensible and latent heat fluxes and CO_2 fluxes before the WPL algorithm was applied. Obviously, increasing the CO_2 fluxes by the same fractional percentage as required to bring the H and LE into agreement with the observed available energy fluxes is also flawed. Rather, uncertainties in the final CO_2 fluxes are the combination of uncertainties in raw CO_2, H, and LE, invariant with changes in atmospheric conditions.

4.2.3. *Case 3: Frequency Response Corrections for Raw CO₂ Flux (but not for H or LE)*

We also analysed a third case that describes the situation where accurate measurements or careful corrections are made for one individual quantity (e.g., CO_2 fluxes), but not for other fluxes (e.g., sensible and latent heat fluxes). This situation may occasionally arise in studies that focus solely on carbon fluxes with the accuracy of the energy fluxes being inadvertently ignored. In this scenario, we improved our estimate of CO_2 fluxes from
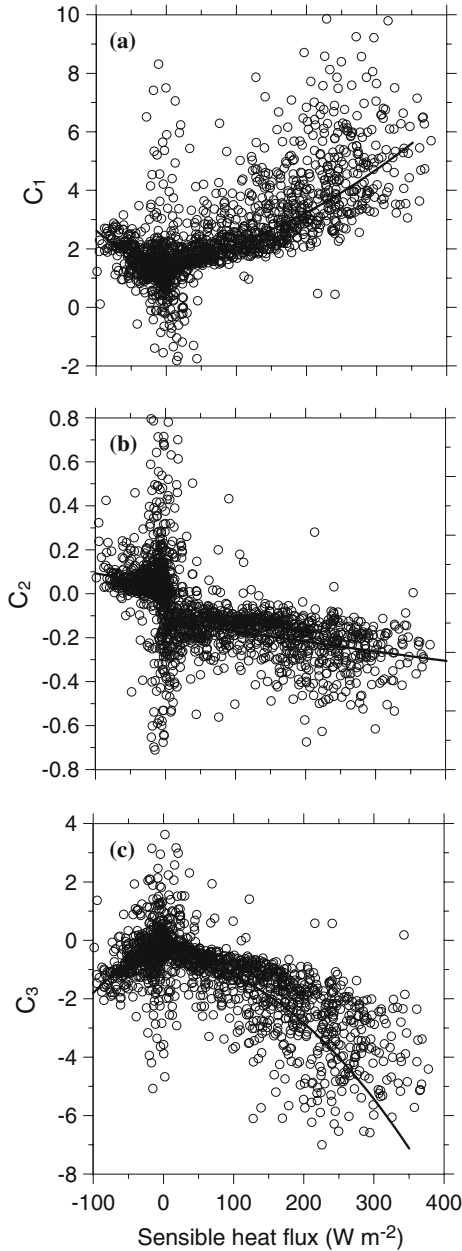
Figure 3. Relationship between the coefficients C_1(a), C_2 (b), and C_3 (c) in Equation (4) and sensible heat flux (H) using the data measured in a black spruce forest in interior Alaska from June 15 to August 15, 2002. The solid lines in the plots denote second-order polynomial regressions. When $H > 0.0$, $C_1 = 2 \times 10^{-5} H^2 + 0.0048 H + 1.4687$, $C_2 = 10^{-6} H^2 - 0.0011 H - 0.0888$, $C_3 = -5 \times 10^{-5} H^2 - 0.0011 H - 0.5859$; when $H < 0.0$, $C_1 = 7 \times 10^{-5} H^2 - 0.0064 H + 1.2478$, $C_2 = -2 \times 10^{-6} H^2 - 0.0009 H + 0.0231$, $C_3 = -0.0001 H^2 + 0.0049 H - 0.2927$.

Case 1 by applying frequency response correction for both day and night periods, but left the errors in sensible and latent heat fluxes at the same values. Specifically, in this case, $\omega_c = -10\%$ (-18%), $\omega_v = -15\%$ (-30%), and $\omega_T = -15\%$ (-30%) for the day (and night) measurements.

Corrections applied solely to CO_2 fluxes (Case 3) had the highest daytime sensitivity to sensible heat fluxes (Table I). Specifically, the daytime CO_2 fluxes were either underestimated or largely overestimated. At night, the propagation of errors through the WPL algorithm always led to positive errors in the final CO_2 fluxes (Table II). This case strongly suggests that special attention should be paid not only to the accuracy of raw CO_2 flux measurements but also to the accuracy of raw energy flux measurements (especially the sensible heat fluxes). Additionally, the accuracy of the raw sensible heat fluxes is even more important than the accuracy of the raw CO_2 fluxes under some circumstances when the correction magnitudes through the WPL algorithm are small as indicated in Equation (4).

4.3. Influence of incomplete energy closure on NEE estimates

The adjustments to the final CO_2 fluxes as measured by the open-path systems varied widely after variations in C_1, C_2 and C_3 were taken into consideration. In terms of the influence of energy imbalance on CO_2 fluxes, comprehensive evaluation of the uncertainties for long-term NEE should be made using the estimates from Equation (4) on a half-hour basis. Although we do not advocate adjusting CO_2 fluxes based on remaining surface energy imbalances (after all appropriate corrections have been applied), it is interesting to consider how these adjustments would propagate through the WPL algorithms. For example, during the summer period of our measurements we obtained a daily NEE of $-1.27 \, \text{gC m}^{-2} \, \text{day}^{-1}$ after application of the WPL algorithm. If we correct this value for the lack of energy balance closure during day and night (losses of 15% and 30% as described by case 1) we obtain a value of $-1.38 \, \text{gC m}^{-2} \, \text{day}^{-1}$. A more complete treatment for the lack of energy balance closure that accounted for propagation error through the WPL algorithm (Equation (4)) yields a daily integral of $-1.33 \, \text{gC m}^{-2} \, \text{day}^{-1}$. Thus, consideration of Equation (4) decreases the size of the inferred summer carbon sink in calculations that attempt to correct for energy losses. In other ecosystems with larger sensible heat fluxes we would expect differences in NEE inferred for the two approaches to be even greater.

NEE bias errors depend on the accuracy of daytime and nighttime eddy-covariance measurements that diurnally vary due to different daytime and nighttime error sources. Recently there has been considerable progress in the analysis and correction of nighttime CO_2 flux measurements (Goulden et al., 1996; Aubinet et al., 2000; Anthoni et al., 2002b). In con-

trast, the correction of daytime CO_2 flux measurements has received little attention although the influences of vertical advection, low and high frequency filtering and other factors on flux losses are known to be important (Lee, 1998; Massman and Lee, 2002; Wilson et al., 2002). As a result, applying an empirical correction for underestimated nighttime CO_2 fluxes, while ignoring the correction for the daytime bias of raw CO_2 flux measurements, could potentially enhance uncertainties of long-term NEE integrals obtained using open-path systems. Our analysis suggests that flux corrections should be made simultaneously and carefully for all raw flux components (i.e. sensible heat, latent heat and CO_2 fluxes) before applying the WPL algorithm. Any selective corrections for individual components of these raw fluxes may induce additional systemic errors and thus may enhance the uncertainties in the final fluxes.

Current extensive comparisons between open-path and closed-path IRGAs in the flux community have illustrated consistently higher daytime NEE and lower nighttime NEE by open-path IRGAs compared to close-path IRGAs (e.g., Anthoni et al., 2002a; Liang et al., 2004) except for some special cases with small differences between two systems (e.g., Ham and Heilman, 2003). Anthoni et al. (2002a) compared the response of a closed-path IRGA (i.e. LI-6262) and an open-path IRGA (i.e. LI-7500) over Pondersoa pine sites in Oregon, U.S.A. Concentrations measured by the open-path IRGA and the closed-path IRGA generally fell on a 1:1 line, but NEE estimated using the closed-path IRGA was about 20% higher than that using the open-path IRGA at night. In contrast, NEE estimated using the closed-path IRGA was about 20% less negative than that using the open path IRGA during the daytime. But NEE estimates from the closed-path IRGA remained about 35% more positive when integrating daily totals of NEE during summer periods with long day lengths (Anthoni et al., 2002a). Liang et al. (2004) found that the total integral of NEE over a larix forest was −2.1 to −2.4 t C ha^{-1} year^{-1} as measured using a closed-path IRGA (LI-6262) and −4.7 to −5.4 t C ha^{-1} year^{-1} as measured using an open-path IRGA (LI-7500) due to 20% more negative daytime NEE and 15% lower nighttime NEE as measured using the open-path IRGA. Our analysis suggests that more negative daytime NEE and lower nighttime NEE measured using open-path IRGAs relative to closed-path IRGAs may be partly caused by inappropriately accounting for the energy losses (especially underestimated sensible heat fluxes) through the WPL algorithm.

It is obvious that if these additional errors were corrected for in the final CO_2 fluxes obtained by the open-path system, the agreement between the final daytime CO_2 fluxes of the two systems could be greatly improved.

4.4. Influence of incomplete energy balance closure on latent heat fluxes

Since the latent heat fluxes were positive both during the day and at night for our site, the effect of the WPL algorithm (Equation (1)) was to increase the magnitudes of the raw latent heat fluxes during daytime and to reduce the magnitudes of the raw latent heat fluxes at night. Using the biases from Case 1 in Equation (3) (i.e. $\omega_v = -15\%$, and $\omega_T = -15\%$ for daytime measurements), we obtained an average $\delta E/E$ of -23% (ranging from -13 to -28%), indicating an additional reduction in latent heat flux obtained through use of the WPL algorithm.

4.5. Impact of random errors in raw fluxes on final CO_2 fluxes

Random errors in sensible heat fluxes and CO_2 fluxes may also affect the final CO_2 fluxes through the WPL algorithm. As an example, we investigated the influence of the coordinate rotation on the fluxes. Instead of using double rotation (DR) that is thought to induce large errors due to the sampling uncertainties of the mean vertical velocity (Wilczak et al., 2001) or possible low frequency loss, the planar fit (PF) technique was used in our study to rotate the sonic anemometer's coordinate system to make its vertical axis perpendicular to the mean air flow. We found no systematic errors in sensible heat, latent heat and CO_2 fluxes when comparing the PF coordinate system with the DR coordinate system (Figure 4). Instead, large scattering of fluxes was observed (about $\pm 5\%$ for sensible heat flux and about $\pm 10\%$ for latent heat flux) especially when wind speeds were small, which was demonstrated by the large scatter in friction velocity (u_*; m s^{-1}) (about $\pm 40\%$) when wind speeds were low ($u_* < 0.4$ m s^{-1}) (Wilczak et al., 2001; Foken et al., 2004). In particular, it was likely that the DR method induced much large random errors in CO_2 fluxes (up to about $\pm 30\%$) (Finnigan et al., 2003) when we compared the standard deviation for CO_2 fluxes of 2.93 for the DR coordinate and 2.84 for the PF technique. Additionally, large random errors in sensible and latent heat fluxes, as well as raw CO_2 fluxes, resulting from the double rotation of the coordinate system were amplified as a result of propagation through the WPL algorithm. In this case, uncertainties increased in the estimate of long-term NEE. Our study supports the use of the planar fit method (Wilczak et al., 2001) in flux calculations.

As demonstrated in our results, the uncertainties in the final CO_2 fluxes are related to both systematic and random errors in sensible heat fluxes. From the practical point of view, any effort that reduces the measurement errors in sensible heat fluxes can largely decrease the errors in final CO_2 fluxes. Even the conversion from buoyancy fluxes obtained from sonic
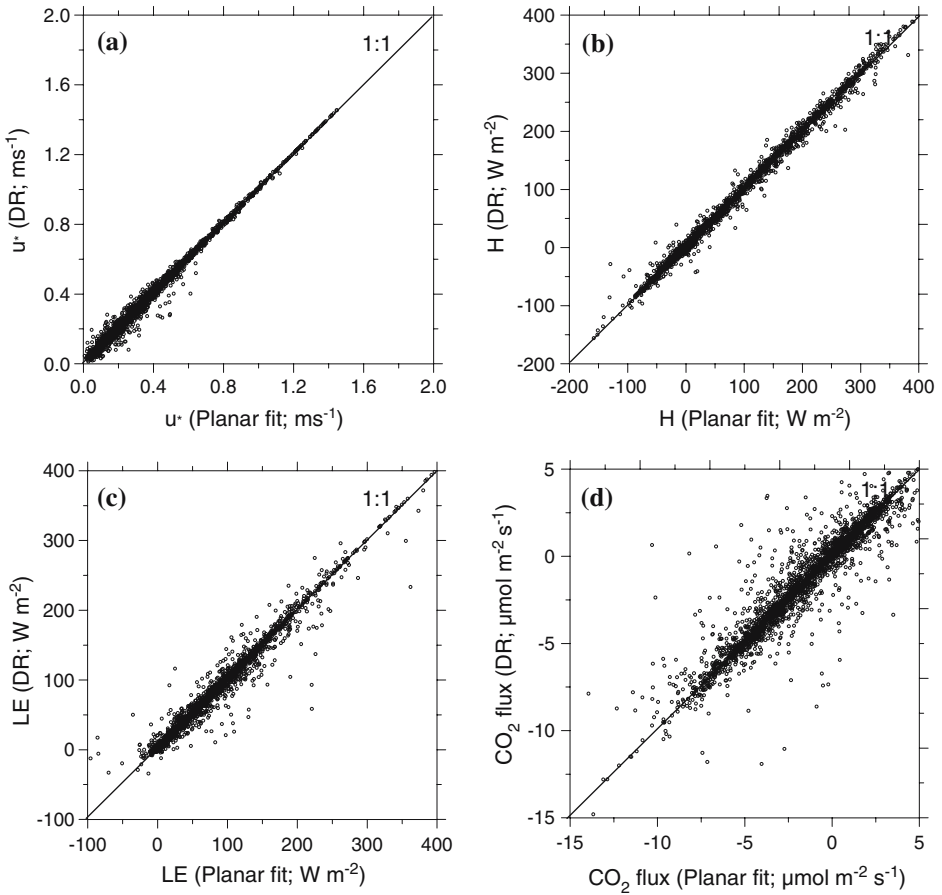
Figure 4. Comparison of friction velocity (u_*; m s^{-1}) (a), sensible heat flux (H; W m^{-2}) (b), latent heat flux (LE; W m^{-2}) (c), and CO$_2$ flux (μ mol m^{-2} s^{-1}) (d) between the double rotation method (DR) and the planar fit method (PF).

temperature could yield a 5–10% difference when compared with the sensible heat fluxes obtained directly from fine-wire thermocouples (Liu et al., 2001), one of the best options is still to use fast-response thermometers to directly measure sensible heat fluxes from this point of view.

5. Conclusions

The mechanisms responsible for incomplete energy balance closure, including the partitioning of loss terms across sensible and latent heat components, have important consequences for the calculation of CO$_2$ fluxes when open-path IRGAs are used. Although energy imbalance may lead to

underestimation of raw CO_2 fluxes, final CO_2 fluxes after application of the WPL algorithm may be either underestimated or overestimated. Some corrections (e.g., frequency response corrections) of all raw fluxes (i.e. CO_2 flux, sensible and latent heat fluxes) are quite effective in reducing the errors in the final CO_2 fluxes, and should be made simultaneously and diurnally for all raw fluxes before applying the WPL algorithm. Any selective corrections for individual raw fluxes (e.g., CO_2 fluxes only), while neglecting the accuracy of turbulent fluxes, could increase the uncertainties in the final CO_2 fluxes. However, since no correction method is perfect (Massman, 2004), therefore, uncertainties and biases in the raw sensible heat, latent heat, and CO_2 fluxes are inevitable. Consequently, the propagation error through the WPL algorithm is general, and may be amplified or dampened.

Since the errors in the final CO_2 fluxes are quite sensitive to the errors in sensible heat fluxes as well as raw CO_2 fluxes, it is necessary to consider the use of more robust fast-response thermometers, or the use of a careful conversion approach of the buoyant heat flux when sonic temperature is employed (e.g., Schotanus et al., 1986; Liu et al., 2001). Additionally, the methodology in calculating fluxes highlighted in this study supports the use of the planar fit algorithm for coordinate rotation to reduce random errors of CO_2 fluxes. Large run-to-run variations in CO_2 fluxes do not necessarily reflect variations in ecosystem functioning but may result from the combined effects of various random errors.

Although the adjustment of CO_2 fluxes based on a lack of energy closure remains controversial, it may be required for some applications. Here we show that the adjustment approach for open-path systems is fundamentally different from what is appropriate for closed-path systems, because of the consideration of the WPL algorithm.

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