Experimental Test of Density and Energy-Balance Corrections on Carbon Dioxide Flux as Measured Using Open-Path Eddy Covariance

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ABSTRACT

Eddy covariance is the most direct technique for measuring water, C, and energy fluxes above crops and managed ecosystems. When using open-path gas analyzers, corrections for air density fluctuations due to heat and water vapor flux must be applied, and these corrections are often larger in magnitude than the CO2 fluxes. Lack of energy balance closure, a common problem when using eddy covariance, implies that CO2 fluxes often are underestimated. Research was conducted to evaluate performance of the density corrections by making eddy covariance measurements above a large parking lot where CO2 and water vapor fluxes were almost zero. Uncorrected and corrected flux measurements were compared to the "known" values to determine accuracy. Data also were collected from a tallgrass prairie and a cedar forest to examine how density corrections and adjustments for energy balance closure affected daily C balances. Raw measurements from the parking lot showed apparent, density-induced, downward CO2 fluxes (i.e., apparent photosynthesis) of approximately -0.4 mg m\(^{-2}\) s\(^{-1}\) that were correlated with sensible heat. On average, the daily uncorrected CO2 flux was -12.7 mg m\(^{-2}\) d\(^{-1}\), but the density correction reduced and changed the direction of the flux to 1.8 mg m\(^{-2}\) d\(^{-1}\), which was very close to independent chamber measurements of 2.8 mg m\(^{-2}\) d\(^{-1}\). Density corrections in the forest and prairie changed average daily CO2 fluxes by 20 to 80%. Energy balance closure averaged 80 and 95% in the prairie and forest, respectively. Corrections based on energy balance closure changed daily C balances by 16 to 35%. A plethora of post-measurement corrections, coupled with lack of energy balance closure, signals the need for additional research before eddy covariance can be routinely applied in agronomic research.

The movement of energy, water, and C between the field surface and the atmosphere is one of the most fundamental processes in the soil–plant–atmosphere continuum. Crop production, in essence, is the act of mining C from the atmosphere and refining and packaging CO2 molecules into a valuable commodity (i.e., grain or forage). As pointed out by Campbell and Norman (1998), turbulent mixing and transport of air is essential for replenishing the supply of C and removing water vapor surrounding the crop canopy. Turbulent transport in the surface boundary layer also affects sensible (H) and latent (LE) heat fluxes, which along with the radiation balance, govern evapotranspiration and canopy temperature. Measuring the movement of energy and mass in the surface boundary layer is one of the most essential tasks associated with micrometeorology. Unfortunately, there are gaps and unresolved issues surrounding these most fundamental of measurements. In this paper, we examine the performance of open-path eddy covariance, a flux measurement technique that was first used in the 1970s (e.g., Desjardins and Lemon, 1974). It saw limited use at first because of technical problems—Desjardins and Lemon used a propeller anemometer to sense vertical wind speed. However, as new sonic anemometers and improved gas analyzers became available, the popularity of the technique increased rapidly. However, like many measurements, eddy covariance can be fraught with pitfalls, and data often require extensive postprocessing to remove sources of error. In this paper, we examine some of the most important corrections that must be applied to flux data obtained using eddy covariance.

Eddy covariance is the most direct technique for measuring heat and mass fluxes between the surface and the atmosphere (Baldocchi et al., 1988). Historically, the complexity and cost of eddy covariance instrumentation has limited its use. However, as sonic anemometers and open-path gas analyzers become less expensive and more reliable, it is probable that researchers from a wide range of disciplines will use this technique. Eddy covariance instruments are well suited for continuous long-term monitoring of field-scale processes. Agronomists, range scientists, and others conducting research on managed systems may select the technique to evaluate how management decisions and interannual variations in climate affect field-scale water and C balances. Furthermore, as new types of gas analyzers are developed, it will be possible to estimate the flux of many different trace gases (e.g., N\(_2\)O), isotopes, aerosols, and organic compounds. Thus, eddy covariance could become a useful tool in examining agriculture’s impact on air and water quality.

Eddy covariance is often touted as the best available method for flux measurement because it does not require simplifying assumptions about the physics of the boundary layer, unlike flux profile or Bowen ratio (B) approaches. Unfortunately, raw eddy covariance measurements must be corrected to account for a host of factors, many of which result from limitations in the instruments or non-ideal boundary-layer conditions (i.e., advection, non-simple terrain). Corrections include adjustment for density variations caused by fluxes of heat and water vapor (Webb et al., 1980), adjustment to account for the separation distance between the anemometer and gas analyzer (Moore, 1986), adjustments to account for frequency response of the sensors (e.g., Horst, 1999; Massman, 2000; Massman and Lee, 2002), coordinate rotation to account for the slope of the ter-

Abbreviations: B, Bowen ratio(s); DOY, day of year; G, soil heat flux; H, sensible heat flux; Rn, net radiation; LE, latent heat flux.
rain or transducer misalignment (Wilczak et al., 2001), corrections for advection (Paw U et al., 2000), and the removal of long-term trends. When an open-path gas analyzer is used on relatively flat, uniform terrain, the adjustment for density fluctuations is the largest of these corrections and can change the estimate of flux by 20 to 80% (Leuning and Judd, 1996).

Webb et al. (1980) described the principles underlying the density effects and demonstrated how raw CO₂ and water vapor flux measurements can be adjusted. The corrections originate because open-path gas analyzers do not measure CO₂ and water vapor concentrations as mixing ratios (kg kg⁻¹) but instead measure density (kg m⁻³). For the typical daytime case of upward H and λE, the air density of the up-moving eddies is less than that of those moving down because up-moving eddies are warmer and contain more water vapor. If one assumes there is no mean vertical flow of dry air (i.e., no source or sink of air at the surface and no terrain effects), there must be a small net upward wind speed to maintain conservation of mass. Webb et al. (1980) argue that the contribution from this small upward velocity component is missed when flux is computed solely from the covariances. Thus, a correction must be added to covariance estimates of CO₂ flux that has the same sign as the water vapor and sensible heat flux. Leuning et al. (1982) evaluated the density correction over a plowed field where CO₂ flux was assumed to be negligible. Kramm et al. (1995) describe a variation of the density correction that uses a weighting method while Paw U et al. (2000) propose corrections that consider the simultaneous effect of both density and advection.

Lack of energy balance closure is another issue that can reduce confidence in eddy covariance measurements. The conservation of energy, represented by the surface energy balance, is the theoretical linchpin meteorologists use to test the accuracy of flux measurements and is expressed as

$$\text{Rn} - \text{G} = \text{H} + \lambda \text{E}$$  \[1\]

where Rn is net radiation and G is soil heat flux and the rate change in canopy heat storage, all in W m⁻². In agricultural systems, canopy storage is small, and G is equated to soil heat flux. Available energy (Rn - G), measured by radiometers and soil instruments, must equal H + λE measured by eddy covariance; \((\text{H} + \lambda \text{E})/(\text{Rn} - \text{G})\) should equal unity. Eddy flux measurements across a wide range of vegetation types have shown that energy balance closure typically ranges from 0.7 to near perfect closure, with overall averages near 0.82 (Aubinet et al., 2000; Twine et al., 2000). These results suggest that eddy covariance may be underestimating H and λE and imply that CO₂ flux might be underestimated as well. Some have proposed methods to adjust λE and CO₂ fluxes based on forced closure of the energy balance (e.g., Twine et al., 2000). However, energy balance closure methods have legitimate weaknesses and are forced to make assumptions that could result in errors as large as those they are attempting to amend.

The objective of this study was to examine the accuracy of the density corrections and energy balance closure adjustments on the measurement of CO₂ and water vapor flux when using open-path eddy covariance. Data were collected above a large parking lot where actual CO₂ and water vapor fluxes were essentially zero, but large H from the dry surface created apparent fluxes of CO₂ and water vapor. The density correction was evaluated by quantifying how well the Webb et al. (1980) correction re-zeroed the CO₂ and water vapor fluxes. Flux deviation from zero (i.e., measurement error) also gave an indication of the overall noise in the eddy flux instrumentation. Additional measurements from tallgrass prairie and ced-ear forest were used to evaluate the effect of the density correction and energy balance closure on calculations of the daily ecosystem C balance.

**METHODS**

A portion of the research was conducted in July 2002 on a parking lot located adjacent to the Kansas State University football stadium in Manhattan, KS. The parking lot provided a uniform, dry surface with little or no latent heat flux and very low CO₂ fluxes. A sonic anemometer (CSAT3, Campbell Sci., Logan, UT) and an open-path gas analyzer (LI-7500, LI-COR, Lincoln, NE) were deployed 3 m above the surface near the north edge of the lot. Sensor separation was 0.12 m, and the LI-7500 was tipped 15 degrees to the north to minimize any radiation effects on the gas analyzer. During a portion of the study, a 0.013-mm-diam. fine-wire thermocouple was positioned next to the sonic anemometer. Fetch to the south, the prevailing wind direction, was in excess of 400 m. A net radiometer (Q7.1, Radiation Energy Balance Syst., Seattle, WA) was positioned 1.75 m above the surface. Surface temperature was measured with 0.127-mm-diam. thermocouples that had been mounted to the surface using a thin layer of epoxy.

Temperature of the asphalt was measured at 0.042 m using two additional thermocouples. Soil heat flux was calculated using the combination method after assuming a linear temperature gradient between the surface and 4.2 cm. The thermal conductivity and heat capacity of the pavement were approximated as 2.1 W m⁻¹ K⁻¹ and 1.95 MJ m⁻³ K⁻¹, respectively (Incropera and DeWitt, 1990). Signals from the gas analyzer, anemometer, and fine-wire thermocouple were sampled at 10 Hz using a Campbell Scientific CR23X data logger. All other sensors were sampled every 10 s. Raw fluxes (covariances) and scalar averages were computed and stored every 30 min using the CR23X data logger.

Postprocessing of the eddy covariance data included coordinate rotation, correction of sonic-derived H estimate (Schotanus et al., 1983), and density corrections on the raw CO₂ and water vapor fluxes (Webb et al., 1980). Theoretically, some of these corrections were not needed on the parking lot because it was almost level and latent heat flux (λE) was zero. However, because the precision of the entire system was in question (measurements and processing), the postprocessing algorithms were identical to those used above vegetated surfaces. Coordinate rotation was performed using the traditional micrometeorological approach by rotating the data about two axes such that the mean vertical wind speed was zero (Paw U et al., 2000). Rotation had minimal effect on the covariances because the parking lot had minimal slope. The Schotanus et al. (1983, Eq. [8]) humidity correction on the sonic-derived H and the Webb et al. (1980) correction on λE were computed by iteration because they are interdependent. That is, the raw value of H from the sonic was used to make the initial density correction on λE, and then the new λE was used to make the humidity correction on H. This processing loop (Eq. [2], [3], [4], and [5]) continued until changes in H and λE were negligible. After corrected values of H and λE were available, the density correction was applied to CO₂ flux (Eq. [6]). Formulas used for the postprocessing sequence were

$$E = (1 + \mu \sigma) \left[ \rho \beta \right] + [2]$$
(\frac{\rho}{\rho_e} T_T) w w' \Gamma

H = \rho C_p T_T \epsilon - 0.51 T \rho C_p \lambda E \quad [3]

w w' \Gamma = \frac{H}{\rho C_p} \quad [4]

T = T_e + 1 + 0.51 q \quad [5]

F_c = w w' \rho' + \mu (\bar{w}/\bar{\rho}) w w' \rho' + \mu \sigma (\bar{w}/\bar{T}) w w' T' \quad [6]

where

E = evaporation (kg m\(^{-2}\) s\(^{-1}\))

\(\rho, \rho_e, \) and \(\rho_c\) = densities of air, water vapor

and CO\(_2\), respectively

C\(_p\) = specific heat of air (J kg\(^{-1}\) K\(^{-1}\))

\(\lambda\) = latent heat of vaporization (J m\(^{-2}\) s\(^{-1}\))

\(T_e\) = temperature reported by the sonic anemometer (K)

T = actual air temperature (K)

q = specific humidity (kg kg\(^{-1}\))

\(\mu\) = the ratio of the molecular masses

of dry air and water vapor

\(\sigma\) = the ratio of vapor and dry air

densities

w = vertical wind speed where prime denotes instantaneous fluctuations

about the mean and the overbar denotes a time average

\(F_c\) = CO\(_2\) flux (kg m\(^{-2}\) s\(^{-1}\))

The last term on the right hand side of Eq. [3] was replaced with \(-0.072 \lambda E\) for the calculations after assuming typical values for \(\lambda\), \(\rho\), and \(C_p\). As defined here, downward fluxes are negative, and upward fluxes are positive. Equations [2] and [6] are those derived by Webb et al. (1980). Details on the theory underlying eddy covariance are available elsewhere; a good review for the nonspecialist is provided by Baldocchi (2003).

The accuracy of the eddy covariance system and the correction procedures were evaluated by comparing the raw and corrected fluxes of \(\lambda E\) and CO\(_2\) to known fluxes from the parking lot. Latent heat flux was assumed to be zero because the surface was dry. Surface CO\(_2\) flux was measured in the source area of the tower using a portable gas analyzer (LI6200, LI-COR, Lincoln, NE) and hand-held chamber (Norman et al., 1992). Data were collected along a transect in the source area of the tower for 3 d during the study. The average surface CO\(_2\) fluxes were 0.03, 0.05, and 0.02 mg m\(^{-2}\) s\(^{-1}\), with an average standard deviation of ±0.02 mg m\(^{-2}\) s\(^{-1}\). Apparently, there were very small amounts of CO\(_2\) diffusing through the pavement at an almost constant rate. For analyses purposes, it was assumed that CO\(_2\) flux was constant at 0.032 mg m\(^{-2}\) s\(^{-1}\) during the entire study.

Two additional eddy covariance systems were operated on tallgrass prairie and an 80-yr-old cedar forest. Data collected in June and July were used to examine how the density corrections on the CO\(_2\) flux measurements would affect the calculation of the daily C balance. The eddy flux instrumentation used at these locations was identical to that used at the parking lot. Net radiation also was measured with a Q7.1 radiometer, but G was measured using heat flux plates (HFT-3, Radiation Energy Balance Syst., Seattle, WA) at 0.05 m and dual-probe heat capacity sensors at 0.025 m (Campbell et al., 1991). The prairie site was located on the Konza Prairie Natural Research Area approximately 15 km south of Manhattan, KS. The vegetation at the site was dominated by C4 grasses, including big bluestem (Andropogon gerardii Vitman) and indian grass (Sorghastrum nutans (L.) Nash). Leaf area index of the grassland was approximately 2.5 m\(^2\) m\(^{-2}\) during the study. Eddy flux instrumentation was positioned 3 m above the soil surface. The forest site was an 80-yr-old stand of eastern red cedar (Juniperus virginiana L.) located 32 km north of Manhattan, KS. The average tree height was 9 m, and the eddy flux instruments were positioned at 14 m. Measurements of the within-canopy CO\(_2\) concentration profile were used to estimate the rate change in C storage in the 0- to 14-m layer. The storage term was added to the eddy covariance estimates of \(F_c\). At the time of the study, the region around Manhattan was experiencing an extreme drought; there had not been any measurable rainfall at either site in the 5 wk before the measurements.

For a brief period, a fine-wire thermocouple (0.013 mm diam.) was added to the prairie site and positioned near the open-path gas analyzer, approximately 15 cm from the sonic anemometer. The difference in \(H\) estimated using the sonic temperature was compared to \(H\) derived from the thermocouple to estimate the effect of sensor separation on the calculation of water vapor and CO\(_2\) fluxes (Villalobos, 1997; Laubach and McNaughton, 1999).

In addition to the density corrections, the effect of forced energy balance closure also was evaluated using two closure techniques described by Twine et al. (2000). In the first method, it was assumed that the eddy covariance systems measured the B correctly after the water vapor and density corrections had been applied to \(H\) and \(\lambda E\) (Eq. [2]–[5]). New values for latent heat flux (\(\lambda E_{RS}\)) then were computed from \(B\) and \(Rn - G\) in the traditional manner. It was then assumed that errors in \(F_c\) were in the same proportion as those for water vapor. Thus, new values for CO\(_2\) flux (\(F_{c,RS}\)) were obtained as the product of \(F_c\) (from Eq. [6]) and the ratio between \(\lambda E_{RS}\) and \(\lambda E\). The second technique was similar to the first approach except that latent heat flux was estimated as the residual of the energy balance (\(\lambda E_{RS} = Rn - G - H\)). New estimates of CO\(_2\) flux (\(F_{c,RS}\)) were estimated as the product of \(F_c\) (from Eq. [6]) and the ratio between \(\lambda E_{RS}\) and \(\lambda E\).

RESULTS AND DISCUSSION

Parking Lot Test

Data from the parking lot test were evaluated over a 5-d period from 5 July to 10 July 2002 [day of year (DOY) 186–191] and between 15 and 17 July (DOY 196–198). Approximately 15% of the data collected during these periods were discarded because of wind direction. Typical summer conditions prevailed with mostly clear skies, \(Rn\) of 15 MJ m\(^{-2}\) d\(^{-1}\), maximum daily air temperatures between 35 and 40°C, and wind speeds between 1 and 5 m s\(^{-1}\). A large portion of the daytime \(Rn\) was conducted into the pavement (Fig. 1). Soil heat flux, shown as a residual in Fig. 1 (\(G = Rn - H\)), was
Fig. 1. Net radiation \( (Rn) \), sensible heat flux \( (H) \), and soil heat flux \( (G) \) at the parking lot used to test the open-path eddy covariance instrumentation. Soil heat flux was calculated as a residual after assuming latent heat flux was negligible, \( G = -(Rn - H) \).

near 400 W m\(^{-2}\) at midday. The values of \( G \) calculated using temperature gradient measurements were similar in magnitude. However, there was large uncertainty in these calculations because the thermal conductivity and heat capacity of the pavement was unknown. When tabulated values for pavement thermal properties were used to calculate \( G \), and \( \lambda E \) was assumed negligible, energy balance closure for the experiment was \( (Rn - G) = 0.72(H + \lambda E) - 6.5 \) W m\(^{-2}\). The difficulty in measuring \( G \) from this surface decreased the utility of the energy balance closure to test. Variation in wind speeds over time was larger than observed at flux towers on nearby prairie ecosystems. Surface temperatures were between 55 and 65°C at midday, which were 20 to 25°C greater than air temperature. The surface boundary layer was unstable during the entire test, with an average daytime Obukhov stability parameter \( (z/L) \) of \(-0.018\). Sensible heat fluxes were about 250 W m\(^{-2}\) at midday, which seemed low for a surface with no latent heat flux. However, the smooth surface had a low aerodynamic conductance, and the asphalt surface was a large energy sink.

Sonic estimates of air temperature, when corrected for humidity, were in excellent agreement with the results from the fine-wire thermocouple (Fig. 2). The 30-min averages of the sonic- and thermocouple-derived temperatures were within 0.3°C throughout the test. When differences between the two sensors were computed as \( T_{\text{sonic}} - T_{\text{fine-wire}} \), the average difference (i.e., bias) was \(-0.09\)°C. Similar comparisons made above the prairie showed slightly more disagreement (not shown), but the sonic and fine wires always agreed to within ±0.5°C. Likewise, \( H \) computed using sonic- and thermocouple-derived covariances were in excellent agreement with no signs of bias (Fig. 3). Again, when differences between the two fluxes were computed as \( H_{\text{sonic}} - H_{\text{fine-wire}} \), the bias was less than 2 W m\(^{-2}\). These data confirm that sonic-derived air temperature measurements are more than adequate to replace fragile fine-wire thermocouples. Data presented hereafter will use only sonic-derived estimates of \( H \).
The raw flux measurements showed an apparent downward flux of CO$_2$ having a marked diurnal pattern—as would be observed from canopy photosynthesis (Fig. 4). These apparent fluxes exceeded $-0.4$ mg m$^{-2}$ s$^{-1}$ (9 µmol m$^{-2}$ s$^{-1}$) at midday. Clearly, Fig. 4 provides a graphic example of the error caused by the density effect; an error correlated with diurnal fluctuations in $H$. After the density correction was applied, the adjusted values of $F_C$ were very close to the chamber measurements (0.032 mg m$^{-2}$ s$^{-1}$), especially during DOY 189, 190, and 196 (Fig. 4 and Table 1). There were periods during the first 3 d of the study when the corrected $F_C$ was more variable and remained negative, indicating that factors other than density were affecting results. Wind speeds and direction were highly variable between DOY 186 and 188, which may have violated some of the underlying assumptions of eddy covariance. There was no correlation between wind direction and error. Lack of stationarity may have been the most probable cause (i.e., statistical properties of transport may not have been constant over each 30-min period). Nevertheless, on average, the corrected values of $F_C$ were very close to 0.032 mg m$^{-2}$ s$^{-1}$ (Table 1). When all data were pooled, the average corrected flux was 0.024, resulting in an overall error of $-0.008$ mg m$^{-2}$ s$^{-1}$. This error rate for the 30-min fluxes would produce a daily (24-h) error of 1.0 g m$^{-2}$ d$^{-1}$. Again, this is a small error rate when one considers that daily CO$_2$ fluxes from crops and native systems often range between 20 and 40 g m$^{-2}$ d$^{-1}$ during the growing season.

Inspection of Eq. [6] shows that the correction on $F_C$ increases as $H$ and $\Delta E$ increase, and the affect of $H$ is approximately five times greater than that of $\Delta E$ (Monteith and Unsworth, 1990). Figure 5 shows the relationship between errors in the 30-min corrected flux measurements and the actual CO$_2$ flux during the parking lot study. Again, it was assumed the actual $F_C$ was 0.032 mg m$^{-2}$ s$^{-1}$ as determined with the hand-held chamber. Results show that errors were small and increased slightly with $H$. Errors appeared random around the zero axis, reflecting a very low degree of bias (Table 1).

Raw measurements of $\Delta E$ during the parking lot test, like the CO$_2$ fluxes, show an apparent downward flux (i.e., condensation) (Fig. 6). After the density correction was applied, the fluxes were upward and showed a somewhat noisy diurnal pattern. Nevertheless, more than 85% of the corrected $\Delta E$ values were between $\pm 15$ W m$^{-2}$, which was very close to the expected value of 0 W m$^{-2}$. When data from all 6 d were pooled, the overall average $\Delta E$ was 3.9 W m$^{-2}$, which would be equivalent to an evaporation rate of only 0.14 mm d$^{-1}$. Again, this is a small error considering that evaporation from many crops is often between 3 and 7 mm d$^{-1}$ during the growing season. Although we assumed that actual $\Delta E$ was zero, there may have been trace amounts of water vapor diffusing through the parking lot surface. Thus, the slight diurnal pattern of evaporation shown in Fig. 4 may be accurate. The noise in the $\Delta E$ time series, albeit quite small, provides additional evidence that factors other than density corrections are affecting the results (e.g., instrument errors, failed assumptions, etc.).

In attempt to explain some of the noise in the CO$_2$ flux

<table>
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<tr>
<th>DOY‡</th>
<th>Raw</th>
<th>Corrected</th>
<th>Actual</th>
<th>Bias</th>
<th>RMSE</th>
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</thead>
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<tr>
<td>186</td>
<td>-0.190</td>
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<td>0.032</td>
<td>-0.019</td>
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<tr>
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<td>0.032</td>
<td>0.008</td>
<td>0.030</td>
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<tr>
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<td>0.056</td>
<td>0.032</td>
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</tr>
<tr>
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<td>0.023</td>
<td>0.032</td>
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</tr>
<tr>
<td>Avg.</td>
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<td>0.021</td>
<td>0.032</td>
<td>-0.011</td>
<td>0.036</td>
</tr>
</tbody>
</table>

‡ DOY, day of year.
measurements, the more generalized correction of Paw U et al. (2000) was evaluated. This method accounts for non-zero mean advection caused by horizontal divergence and spatial variation in sources or sinks. The non-zero mean vertical velocities for each 30-min period were estimated using planer fit methods. Because the parking lot was very level, both the vertical rotations and the vertical velocities were small. The non-zero vertical velocities were then used to approximate the advection term (Paw U et al., 2000, Eq. [A2]), which was then added to the Webb et al. (1980) correction. Estimating the advection term required an estimate of the vertical CO$_2$ gradient. The gradient was not measured, so it was approximated using Monin–Obukhov theory after assuming a constant CO$_2$ flux of 0.032 mg m$^{-2}$ s$^{-1}$ (from the chamber results). Adding the advection correction increased noise in the CO$_2$ flux measurements instead of reducing it. Also, no correlations were found between the CO$_2$ flux residuals in Fig. 5 and the ratio of the vertical velocity and the friction velocity ($w$). One would expected some correlation if advection was responsible for the difference between actual and measured values. However, this was a difficult scenario to investigate because vertical velocities, concentration gradients, and the fluxes themselves were all close to zero. Also, numerous assumptions were made to estimate the CO$_2$ gradient. Finally, actual CO$_2$ fluxes may have varied slightly with time.

**Carbon Dioxide Fluxes from Tallgrass Prairie and Cedar Forest**

Figure 7 shows raw and corrected $F_C$ as measured at the prairie and cedar forest sites during the same period used for the parking lot study. The region was experiencing drought, so canopy photosynthesis was less than normal and the $B$ was comparatively large. Sensible heat fluxes at midday were 200 and 500 W m$^{-2}$ on the prairie and forest, respectively. Because $H$ was large and $F_C$ was small, the density correction had a dramatic effect on the diurnal measured pattern and daily total CO$_2$ fluxes. Midday CO$_2$ fluxes were reduced from...
the magnitude of the correction plateaus as $H$ increases. As expected, open-path eddy covariance measurements at the forest site, which had mostly clear skies when $B$ is 2.0 or larger. Data from corrections reflect the failure in closing the energy balance. The same corrections at the forest site (not shown) had virtually no effect on fluxes because closure was already perfect. Adjustments to CO$_2$ flux using the residual energy balance closure method ($F_{C,R}$) resulted in large increases in $F_C$ (28 to 35%). Differences in the $B$-based and residual-based corrections may have been caused by errors in $B$ because $\lambda E$ was affected by sensor separation while $H$ was not. Laubach and McNaughton (1999) showed that sensor separation (0.25 m) between the sonic anemometer and the open-path analyzer could cause a 10% underestimation of $\lambda E$. The acoustic estimate of $H$ is immune from this error because both temperature and vertical wind speed are measured by the sonic anemometer (i.e., same sample volume).

**Energy Balance Closure**

A tendency to underestimate energy and mass fluxes has been a pervasive problem with the eddy covariance technique (e.g., Twine et al., 2000). As an example, Fig. 8 shows the degree of energy balance closure at the prairie and forest sites between DOY 174 and 182. If perfect closure had been achieved, all data would fall on a 1:1 line; however, closure was 0.79 and 0.96 for the prairie and forest locations, respectively. The forest site, which had an average daytime $B$ of 2.4, always had better energy balance closure than the prairie site, which had a $B$ of 0.24. This suggests that $H$ may have been measured more accurately than $\lambda E$. Also, the length scale of the eddies responsible for transport was larger at the forest; thus, the frequency response and sensor separation errors may have been smaller. In both cases, there was a slight tendency for $H + \lambda E$ to be less than $Rn - G$ when fluxes were less than 300 W m$^{-2}$. The validity of these comparisons depends on the accuracy of the $Rn$ and $G$ measurements; thus, lack of closure cannot be isolated to the eddy covariance equipment alone. Errors in $Rn - G$ are often 5 to 10%. Nevertheless, the size of the energy balance discrepancy in the prairie site was disconcerting; it suggested the fluxes of $\lambda E$ may have been underestimated. If the covariance measurements for CO$_2$ were subject to the same errors as those affecting water vapor, then $F_C$ was probably underestimated as well.

Three weeks of data from the prairie site were used to examine the impact of coordinate rotation, density correction, and energy balance corrections on daytime (sunrise/sunset) CO$_2$ flux when applied sequentially (Table 2). No precipitation was recorded during the period, and $B$ steadily increased from 0.26 during Week 1 to 0.94 during Week 3. Energy balance closure also increased as $B$ increased, improving from 78% during Week 1 to 88% in Week 3. Others have found improved energy balance closure as $B$ increases (Twine et al., 2000). However, additional analysis during periods with higher $B$ (August, 2002) showed that daily closure was never greater than 90%. During the first 7-d period, DOY 168 to 174, coordinate rotation (2.4 degrees) caused a 27% increase in $F_C$ when winds were southeasterly (Table 2). During the other two measurement periods, winds were from the southwest, and the effect of rotation was negligible. This demonstrates the importance of coordinate rotation even when the surface is relatively flat. The density corrections became more important as the system dried, reducing $F_C$ by 20 and 45% during Weeks 1 and 3, respectively.

Bowen ratio–based adjustments to CO$_2$ flux ($F_{C,BR}$) increased estimates of daily CO$_2$ flux by 27% during Week 1 and 16% during Week 3 (Table 2). These large corrections reflect the failure in closing the energy balance. The same corrections at the forest site (not shown) had virtually no effect on fluxes because closure was almost perfect. Adjustments to CO$_2$ flux using the residual energy balance closure method ($F_{C,R}$) resulted in large increases in $F_C$ (28 to 35%). Differences in the $B$-based and residual-based corrections may have been caused by errors in $B$ because $\lambda E$ was affected by sensor separation while $H$ was not. Laubach and McNaughton (1999) showed that sensor separation (0.25 m) between the sonic anemometer and the open-path analyzer could cause a 10% underestimation of $\lambda E$. The acoustic estimate of $H$ is immune from this error because both temperature and vertical wind speed are measured by the sonic anemometer (i.e., same sample volume).
Lack of energy balance closure, in part, could be caused by underestimates of $\lambda E$ resulting from sensor separation and inadequate sensor response. These corrections were not applied to data in this study but are typically less than 10% and are often much smaller during the day (unstable conditions, higher wind speeds). To examine the potential errors caused by sensor separation, a 2-wk experiment was performed at the prairie site following the approach of Laubach and McNaughton (1999). Results showed that sensor separation of 0.15 m caused underestimates of flux between 0 and 3% under unstable conditions. One day of data were collected under stable conditions following an early morning rain shower. Between 0900 and 1500 h, the stability parameter $z/L$ averaged 0.028, and sensor separation caused a 15% underestimate of flux. These results are similar to those of Laubach and McNaughton (1999). While the magnitudes of the observed sensor separation errors were significant under stable conditions, they were not large enough to account for the lack of energy balance closure shown in Table 2 (i.e., predominantly unstable conditions). Nevertheless, a more complete analysis would include a correction for these effects. For example, this correction would be more important when working with an irrigated crop when stable conditions are common.

CONCLUSIONS

These experiments, like earlier studies, demonstrate how fluctuations in air density can cause a severe overestimate of downward CO$_2$ fluxes when using open-path eddy covariance. The Webb et al. (1980) corrections removed this effect almost completely during the parking lot experiments, and the corrected CO$_2$ flux measurements were within 1 g m$^{-2}$ d$^{-1}$ of independent estimates from chamber measurements. However, the noise in flux measurements, which appeared random for $F_C$ and slightly systematic for $\lambda E$, was approximately $\pm 0.1$ mg m$^{-2}$ s$^{-1}$ and $\pm 20$ W m$^{-2}$, respectively (Fig. 4).
Fig. 7. Eddy covariance measurements of CO$_2$ fluxes from (a) tallgrass prairie and (b) cedar forest, both located near Manhattan, KS. Shown are uncorrected raw measurements and the same data after density corrections have been applied. Downward fluxes are negative; upward fluxes are positive.
This indicates that other factors, such as instrumentation errors, inadequate sampling, or failed assumptions regarding the state of the boundary layer, were affecting the measurements. Data from prairie and forest ecosystems showed that removing density effects changed estimates of CO₂ flux by 20 to 80% and in some cases changed the estimate of daily CO₂ flux at the surface from negative (sink) to positive (source).

Energy balance closure at the prairie site was about 80%, which was very similar to other reports (Aubinet et al., 2000; Twine et al., 2000). Adjustment to CO₂ flux based on forced energy balance closure greatly increased the estimates of downward CO₂ flux by 16 to 35%. However, energy balance approaches for adjusting eddy covariance data are limited because they depend on the accuracy of Rn and G, must assume that errors in CO₂ are proportional to E, must assume that advection is negligible (assume horizontal uniformity), and in the case of the B-based correction, must assume errors in H and AE are proportional. Furthermore, all energy balance-based corrections in CO₂ flux will perform poorly at night when Rn − G is small.

Table 2. Daytime CO₂ fluxes (0800–1800 h) from the tallgrass prairie between 18 June and 8 July 2002. Shown are total CO₂ fluxes at different stages of a sequential correction process where F_{raw} are data directly from the data logger, F_{rot} are data after coordinate rotation, F_{den} are data after the density correction, and F_{BR} and F_{RS} are data after adjustment for energy balance closure using the Bowen ratio (B)- and residual-based approaches, respectively. Also shown are the vertical rotation of the sonic anemometer (degrees), B, and the percentage of energy balance closure, (H + λE)/(Rn − G) × 100.

<table>
<thead>
<tr>
<th>DOY†</th>
<th>F_{raw}</th>
<th>F_{rot}</th>
<th>F_{den}</th>
<th>F_{BR}</th>
<th>F_{RS}</th>
<th>Rotation</th>
<th>B</th>
<th>% Closure</th>
</tr>
</thead>
<tbody>
<tr>
<td>168–174</td>
<td>–26.3</td>
<td>–33.6</td>
<td>–26.6</td>
<td>–33.9</td>
<td>–36.0</td>
<td>2.4</td>
<td>0.26</td>
<td>78</td>
</tr>
<tr>
<td>175–182</td>
<td>–27.4</td>
<td>–28.6</td>
<td>–19.1</td>
<td>–22.6</td>
<td>–25.6</td>
<td>1.0</td>
<td>0.59</td>
<td>84</td>
</tr>
<tr>
<td>183–188</td>
<td>–22.9</td>
<td>–23.2</td>
<td>–12.6</td>
<td>–14.6</td>
<td>–16.3</td>
<td>0.3</td>
<td>0.94</td>
<td>88</td>
</tr>
</tbody>
</table>

† DOY, day of year.
The inherent tendency to underestimate fluxes when using eddy covariance may be linked to the errors caused by sensor separation and inadequate frequency response of the sensors. There is some debate on how to correct the data for these effects, but efforts are underway to develop a standardized approach (Massman and Lee, 2002). Unfortunately, these corrections are difficult to implement for the nonspecialist because they require calculation of cospectra using high-frequency (10 Hz) data. There is also considerable expertise and experience required to interpret the cospectra properly. Errors caused by inadequate frequency response and sensor separations are typically less than 10% but depend on wind speed, boundary-layer stability, the height of the sensors above the ground, and the type of instruments deployed. During the night, these errors are exacerbated and, along with other problems (e.g., drainage flow), greatly reduce confidence in eddy covariance measurements. All of these issues can have a profound effect on measuring the long-term C balance of a site (Goulden et al., 1996; Moncrieff et al., 1996).

Despite some problems, open-path eddy covariance is a very useful tool for examining how different agronomic practices affect field-scale processes in the soil–plant–atmosphere continuum (canopy photosynthesis, evapotranspiration, etc.). Historically, agronomic research has focused on comparing plots or fields that are under differing management regimes or treatments. Eddy covariance data from two adjacent but differently managed fields can readily identify how certain practices affect the field energy, water, and C balances. Even if the flux data were slightly biased, it is likely that the bias would be very similar at each tower location, such that the measured differences between the two fields would be quite accurate. Certainly, one can think of exceptions, but measuring differences is always easier than measuring absolutes regardless of the instruments employed. Measuring the long-term (e.g., annual) absolute C balances of fields will continue to be a challenge. However, it is probable that both advances in theory and improvements in instrumentation will progress to a point that eddy covariance can be routinely used by the nonspecialist. The concept of measuring multiple trace gas fluxes with instruments that can be deployed in a matter of minutes sounds a bit make-believe today but will most likely be a reality for the agronomist of the future.

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