Concerning the Measurement and Magnitude of Heat, Water Vapor, and Carbon Dioxide Exchange from a Semiarid Grassland

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ABSTRACT

Grassland environments constitute approximately 40% of the earth's vegetated surface, and they play a key role in a number of processes linking the land surface with the atmosphere. To investigate these linkages, a variety of techniques, including field and modeling studies, are required. Using data collected at the Central Plains Experimental Range (CPER) in northeastern Colorado from 25 March to 10 November 2004, this study compares two common ways of measuring turbulent fluxes of latent heat, sensible heat, and carbon dioxide in the field: the eddy covariance (EC) and Bowen ratio energy balance (BREB) methods. The turbulent fluxes measured by each of these methods were compared in terms of magnitude and seasonal behavior and were combined to calculate eddy diffusivities and examine turbulent transport. Relative to the EC method, the BREB method tended to overestimate the magnitude of the sensible heat, latent heat, and carbon dioxide fluxes. As a result, substantial differences in both the diurnal pattern and long-term magnitudes of the water and carbon budgets were apparent depending on which method was used. These differences arise from (i) the forced closure of the surface energy balance and (ii) the assumption of similarity between the eddy diffusivities required by the BREB method. An empirical method was developed that allows the BREB and EC datasets to be reconciled; this method was tested successfully using data collected at the CPER site during 2005. Ultimately, however, the BREB and EC methods show important differences that must be recognized and taken into account when analyzing issues related to the energy, water, or carbon cycles.

1. Introduction

To confront the many questions related to boundary layer meteorology, climatic processes, and surface–atmosphere interactions, both field measurements and modeling studies are used. The accuracy and reliability of these studies, however, are directly related to the quality and consistency of the underlying observations. There are a number of techniques available today for measuring trace gas fluxes, including the commonly used Bowen ratio energy balance (BREB) and the eddy covariance (EC) methods. Relative to cuvette or chamber methods, these meteorological techniques have the advantage of measuring energy and trace gas exchange over a relatively large area—on the order of hundreds of square meters—without artificially altering the environment. The EC method has been adopted as the preferred method of flux measurements by long-term programs such as AmeriFlux, EuroFlux, and Fluxnet-Canada, whereas the BREB method is the method of choice for programs such as the rangeland network AgriFlux.

The BREB method uses measures of the vertical gradients of air temperature (T) and vapor pressure (e), along with direct measures of net radiation (R_n) and the soil heat flux (G), to estimate the turbulent fluxes of sensible (H) and latent (λE) heat. Fluxes of other scalars, such as carbon dioxide (F_c), can also be measured if their vertical gradients are accurately measured. The BREB method requires that all terms in the energy

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balance are measured and accounted for, including all heat storage terms. The BREB method also requires that all scalars are transported with equal efficiency by the atmosphere. The EC method, in contrast, determines trace gases fluxes directly as a function of the covariance between vertical wind speed and the appropriate scalar quantity, both expressed as short-term (e.g., 10 Hz) deviations from a long-term (e.g., 30 min) mean. Energy balance closure is not assumed with the EC method, and studies often report a significant lack of closure when using this method (Massman and Lee 2002). The EC method requires sufficient friction velocity (u_*) and a zero mean vertical wind speed (w; Turnipseed et al. 2002). Both methods require adequate fetch (Horst and Weil 1994; Stannard 1997).

There is an extensive body of research investigating the relationship between the BREB and EC measurement methods. Studies have investigated the differences between these two methods in diverse environments, ranging from coniferous (McNeil and Shuttleworth 1975) and deciduous forests (Barr et al. 1994) to crops (Sinclair et al. 1975; Dugas et al. 1991) and, to a lesser extent, bare ground (Dugas 1993) and grasslands (Brotzge and Crawford 2003). All of these studies suggest differences in the manner in which λE and H are partitioned. While a number of competing reasons for the differences between the two methods have been proposed, there is general agreement that theoretical considerations, sensor limitations, and physical processes, such as advection, play important roles (Moncrieff et al. 1997; Laubach and Teichmann 1999; Brotzge and Crawford 2003; Gavilán and Berengena 2007). For example, Lee et al. (2004) have pointed to the assumption of similarity in the eddy diffusivities as the potential cause of error in the partition of the turbulent fluxes by the BREB system. Other researchers, such as Angus and Watts (1984), have pointed to advection as an important cause of error in the measurement system.

This study focuses on the ability of the BREB and EC methods to measure λE, H, and F_c over moderately grazed shortgrass steppe grassland. In addition to comparing and reconciling the absolute magnitude of the long-term fluxes measured by each method, we present an analysis of the behavior of the eddy diffusivities for heat, water vapor, and CO_2. Since grassland ecosystems constitute approximately 24% of the planet's terrestrial surface (Franzluebber et al. 2002) or between 32% (3.3×10^7 km^2) and 40.5% (4.2×10^7 km^2) of the earth's vegetation cover (Adams et al. 1990; White et al. 2000; Hunt et al. 2002), including nearly 41% of the land cover of the North American continent (Suyker and Verma 2001) and 22% of Europe (Soussana et al. 2007), reconciling the two methods could lead to a better understanding of the role of this ubiquitous landscape in the global climate system.

There still exists substantial uncertainty regarding the role of grasslands in the global climate system (Frank and Dugas 2001; Baldocchi et al. 2001), which can be attributed, at least in part, to the limited data describing the processes regulating turbulent exchange of heat, water vapor, and CO_2 (Bremer et al. 2001; Johnson et al. 2003). For example, it is unclear whether grasslands are in equilibrium with respect to carbon (Frank and Dugas 2001), constituting a terrestrial source or sink (Gilmanov et al. 2007; Soussana et al. 2007) of carbon, or, as suggested by Holifield Collins et al. (2008), Chou et al. (2008), and others, both depend on local environmental conditions. By better understanding of the limitations of the BREB and EC sensor systems and the differences in the datasets they produce, the interpretation of their respective datasets can be refined. In turn, this would lead to a better understanding of both the role and the factors controlling the role of grasslands in the carbon cycle on local and global scales.

The second section explains the theoretical underpinnings of both the BREB and EC methods. The third section provides a description of both the study site and the methods used to collect the micrometeorological and flux measurements. The fourth section presents the results of the study and a method for reconciling the two datasets. The fifth section presents the conclusions of this study.

2. Theoretical considerations

a. Bowen ratio energy balance method

The BREB method (Bowen 1926) estimates the turbulent fluxes of some scalar quantity x based on measured vertical gradients ($\partial x/\partial z$) multiplied by the appropriate eddy diffusivity (K_x), assuming that energy is balanced between the turbulent and nonturbulent terms. For example,

$$H = -K_h \rho_a c_p \frac{\partial T}{\partial z}, \tag{1}$$

$$\lambda E = -K_v \rho_a \lambda \frac{\partial e}{\partial z}, \quad \text{and} \tag{2}$$

$$F_c = -K_c \frac{\partial \rho_c}{\partial z}, \tag{3}$$

where K_h, K_v, and K_c are the eddy diffusivities for heat, water vapor, and CO_2, respectively; ρ_a is the density of air; c_p is the specific heat of air; λ is the latent heat of vaporization; and ρ_c is the density of CO_2. In practice, these equations are typically solved using finite differences.

The Bowen ratio (β) is given as

$$\beta = \frac{H}{\lambda E} = \frac{c_p}{\varepsilon\lambda}\frac{K_h}{K_v}\frac{\Delta T}{\Delta e} = \gamma\frac{K_h}{K_v}\frac{\Delta T}{\Delta e}, \tag{4}$$

where γ is the psychrometric constant; ε is the ratio of the molecular masses of water and air; ΔT and Δe are the changes in air temperature and vapor pressure, respectively, over height Δz (with finite differences approximating partial derivatives). The Bowen ratio can be combined with the surface energy balance equation $R_n - G = H + \lambda E + F_c$ to numerically solve for each turbulent flux:

$$\lambda E = \frac{R_n - G}{\beta + 1}, \tag{5}$$

$$H = \frac{\beta(R_n - G)}{\beta + 1}, \quad \text{and} \tag{6}$$

$$F_c = \frac{\beta C(R_n - G)}{\lambda_c[\beta(C + 1) + 1]}, \tag{7}$$

where C is the ratio of CO_2 density to the temperature gradient and can be considered to be an analog of β as the ratio of the energy required to fix carbon and H. It is defined as

$$C = \frac{-M_c\lambda_c\Delta\rho_c}{M_a\rho_a c_p\Delta T}, \tag{8}$$

where M_a and M_c are the molecular mass of air and CO_2, respectively, and λ_c is the energy of photosynthetic fixation (Price and Black 1990).

The BREB method does have a number of well-documented limitations. The first of these lies in the sensors' ability to accurately measure the nonturbulent energy terms, or the available energy, $R_n - G$. Errors in the measurements of R_n and G are propagated into the estimates of the turbulent fluxes (Ohmura 1982). Also, when β approaches -1, or when $R_n - G$ approaches zero (often during sunrise and sunset), the BREB technique becomes computationally unstable and the results have no physical meaning (Prueger et al. 1997). Finally, there are periods when this method can yield apparently countergradient fluxes (Perez et al. 1999). As pointed out by Ohmura (1982), this phenomenon typically occurs during the early morning and evening, or during periods of rainfall when the humidity gradient is small yet negative, such that evaporation would be expected but the temperature is low enough to facilitate condensation. All of these limitations are most prevalent during the overnight and especially during the sunrise and sunset periods when the direction of the fluxes is in transition.

Additional concerns of the BREB method are related to practical and theoretical limitations. First, the method forces closure of the surface energy balance; however, additional, albeit minor terms, present in the energy balance equation should be included to account for the energy associated with, for example, photosynthesis (Foken and Oncley 1995). Since these terms are typically neglected, the amount of energy available to partition into the turbulent fluxes according to the BREB method is too great; both H and λE thus tend to be overestimated. The second concern is the assumption of similarity for the eddy diffusivities. Similarity theory is based on the argument that the turbulent transport of both heat and water vapor, along with any other scalar quantity, is dependent only on the turbulent motion of the parcel of air composing the eddy (Swinback and Dyer 1967). However, the eddy diffusivities may not be similar when the sources for the various scalar quantities are not identically distributed (McNaughton and Laubach 1998) or when advective processes persist on local or regional scales (Lee et al. 2004; Gavilán and Berengena 2007). Additionally, during unstable atmospheric conditions, sensible heat may be transported more effectively than water vapor (Katul et al. 1995). Thus, while the assumption of similarity is commonplace, it should be accepted only with caution.

b. Eddy covariance method

The EC method, which is based on the theoretical framework first proposed by Reynolds (1895), measures the turbulent components of the surface energy budget independently (with the exception that w is common to all components). The turbulent fluxes are calculated from the covariance between the fluctuations in w and each scalar about their means.

Several corrections and adjustments to the raw measures are required to minimize errors or biases linked to both the limitations of the sensors and the assumptions, such as surface homogeneity and stationarity, associated with the EC method (Finnigan et al. 2003; Ham and Heilman 2003). However, even after postprocessing, the degree of energy balance closure is often less than unity (typically, the sum of the turbulent fluxes is 10%–30% less than the sum of the nonturbulent fluxes; e.g., Hui et al. 2004). Since the BREB method forces energy balance closure and the EC method does not, fluxes measured using the BREB method usually exceed fluxes measured using the EC method in proportion to the lack of energy balance closure.

3. Methods

a. Site description

The data used in this study were collected at the Central Plains Experimental Range (CPER), administered by the U.S. Department of Agriculture Agricultural Research Service (USDA–ARS), located in northeastern Colorado (40.82°N, 104.77°W) in a semiarid shortgrass steppe grassland. The elevation of the site is 1648 m. Historically, the mean monthly air temperature ranges from −4°C in January to 22°C in July, and the mean total annual precipitation is 326 mm. Approximately 225 mm, or 70%, of the annual precipitation occurs during the growing season (Lauenroth and Milchunas 1991). The vegetation is dominated by the C_4 grasses *Bouteloua gracilis* and *Buchloe dactyloides* intermixed with a mixture of C_3 grasses, cacti, and shrubs, with the grasses constituting more than 70% of the total vegetation (Milchunas et al. 1989). The distribution of the vegetation appeared homogeneous throughout the study area. Estimates of net primary production (NPP) for the shortgrass steppe using the ^{14}C turnover method and averaged over five years were 109 for aboveground biomass, 57 for crown tissues, and 326 g m^{-2} for roots (Milchunas and Lauenroth 1992). The vegetation height was as much as 30 cm during the study. The leaf area index at the site seldom exceeds 1.5 m^3 m^{-3} (LeCain et al. 2002). Additionally, the site was grazed during the study—from mid-May until October—but the instrumentation was protected with a barbed-wire enclosure. The enclosure was an irregular polygon with dimensions 10 m × 15 m × 13 m × 21 m. The grazing intensity was moderate at 10 head of cattle per 160 acres.

b. Bowen ratio measurements

The BREB dataset used in the comparative analysis was collected from late March through mid-November 2004 [day of year (DOY) 85–315 inclusive] using a Bowen ratio system (model 023/CO2 from Campbell Scientific, Inc.). Water vapor and carbon dioxide concentrations were measured using a closed-path infrared gas analyzer (model LI-6262 from LI-COR, Inc.) with intakes at 0.73 and 1.73 m above ground level (AGL). The gas analyzer was calibrated weekly following the methods described in the instruction manual (Campbell Scientific 1998a); the CO_2 span was calibrated using a dry gas of known CO_2 concentration (365 ppm), whereas the water span was calibrated against the ambient humidity measured with a temperature and relative humidity probe (model HMP45C from Campbell Scientific, Inc.). The air temperature was measured using a pair of fine-wire thermocouples (model FW3 from Campbell Scientific, Inc.) collocated with the gas analyzer intakes. Net radiation was measured using a net radiometer (model Q*7 from Radiation and Energy Balance Systems, Inc.) at 1.3-m AGL. Precipitation was measured with a tipping-bucket rain gauge (model TE-525mm from Texas Electronics). Volumetric soil moisture content (θ) integrated over the first 15 cm of soil depth was measured using a time-domain reflectometry probe (model CS615 from Campbell Scientific, Inc.) that had been field calibrated against gravimetric measurements collected at installation and nine subsequent days. By sampling on 10 different days, it was possible to collect data across a range of moisture conditions, from near the wilting point to saturation. Soil temperature was measured using two pairs of soil thermocouples (model TCAV from Campbell Scientific, Inc.). Each set of soil thermocouples was positioned 1 m apart at depths of 0.02 and 0.06 m. Collocated with the soil thermocouples was a pair of soil heat flux plates (model HFT3 from Radiation and Energy Balance Systems, Inc.), placed at the depth of 0.08 m. All of the measurements were stored in a datalogger (model 23X from Campbell Scientific, Inc.) as 20-min averages.

Prior to analysis, the data were checked to insure accuracy and adjusted as required. For example, the Webb adjustment (Webb et al. 1980; Price and Black 1990) was applied to both the moisture and CO_2 fluxes. Also, the G data were corrected to account for heat storage above the plates using the measured θ and soil bulk density to estimate the soil heat capacity. The BREB data at the CPER site were filtered using the method outlined by Ohmura (1982). For example, data were excluded when β approached −1 or when there were apparently countergradient fluxes. The BREB data were linearly interpolated to 30-min time steps, so that the time scales of both the BREB and EC measurements were consistent.

The available energy, which is defined as R_n less G, is critical not only to the BREB method but also to the EC method as an indicator of the quality of the flux measurement in terms of energy balance closure. To eliminate issues that could arise in the estimates of the turbulent fluxes due to differences in the placement, calibration, and heat storage correction of the R_n and G measurements, only the measurements from the BREB were used in this study.

BREB data collected from 1 January to 15 August 2005 using the same instrumentation and processed in exactly the same manner were used to validate the empirical corrections of the eddy diffusivities presented below.

c. Eddy covariance measurements

The EC data were collected simultaneously with the BREB data using instruments located on a separate small tower located approximately 30 m from the Bowen ratio system. Wind speed and air temperature were measured using a sonic anemometer (model CSAT3 from Campbell Scientific, Inc.) mounted at 1.32 m AGL, facing southwest perpendicular to the prevailing wind direction. This height was calculated to best match the turbulent flux sampling area (flux footprint) of the BREB system (Stannard 1997; Horst 1999). The height was 6 times the maximum roughness length (3 cm) or displacement height (20 cm), calculated using the empirical relationships with vegetation height provided by Campbell and Norman (1998). This configuration is similar to that used during the First International Satellite Land Surface Climatology Project Field Experiment (FIFE) (Verma et al. 1992; Kanemasu et al. 1992) and during other field studies (e.g., Savage et al. 1995; Wolf et al. 2008).

Since the primary objective of this study was to compare the turbulent fluxes as measured from the two methods, the optimum height of the EC sensors was calculated to best match the turbulent flux footprint of the BREB system. The BREB intakes were located at 0.73 and 1.73 m AGL to maximize the potential to measure small gradients near the surface. Stannard (1997) and Horst (1999) have both shown that the fetch requirements for the BREB and EC methods are different and that the effective height for gradient-based BREB measurements is not halfway between measurement levels but is skewed and depends on factors, including atmospheric stability. In our experiment, the effective BREB height varied from 1.32 m AGL under neutral or unstable conditions to 1.43 m AGL under stable stratification. The EC system was positioned at 1.32 m AGL to match the effective height of the BREB system. A further discussion of the configuration of the EC instruments is provided below.

Water vapor density was measured with an open-path krypton hygrometer (model KH20 from Campbell Scientific, Inc.) and a gas analyzer (model LI-7500 from LI-COR, Inc.) collocated with the sonic anemometer. The LI-7500 was factory calibrated just prior to use and was also used to measure the CO_2 density and atmospheric pressure. Per discussions with LI-COR (D. Johnson 2008, personal communication), this calibration is sufficient to maintain an accurate calibration, provided the instrument is properly maintained in the field. These instruments sampled at a rate of 20 Hz and fluxes were calculated over a 30-min averaging period using a datalogger (model 23X from Campbell Scientific, Inc.). Measurements at a low sampling rate (5-s intervals) of relative humidity and air temperature were made with a humidity probe (model HMP35D from Vaisala, Inc.) positioned 1.32 m AGL.

The EC data were postprocessed with a suite of standard corrections. The turbulent fluxes were recalculated based on a coordinate rotation of the wind speed data (Pond et al. 1971; Kaimal and Finnigan 1994). This technique was compared with the planar fit method (Wilczak et al. 2001), and the resulting fluxes agreed to within 2.4%; this is not altogether unexpected given the level, homogeneous nature of the terrain. The turbulent fluxes were corrected both for the heat storage in the volume of air beneath the sensors and for sensor separation following Horst (2006). The KH20 water vapor density was corrected for oxygen absorption (Campbell Scientific 1998b). Corrections as a result of H_2O–CO_2 cross contaminations were performed in real time using LI-7500 software. The Webb adjustment (Webb et al. 1980; Suyker and Verma 2001) was applied to both the moisture and CO_2 fluxes. Finally, erroneous data points resulting from precipitation events were eliminated. The eliminated data accounted for 4.3% of the flux measurements on average; the data were not gap filled. The 30-min averages for all measurements were stored using a datalogger (model CR23X from Campbell Scientific, Inc.).

d. *Additional soil moisture measurements*

An additional soil moisture profile was measured to a depth of 50 cm. This is just beyond the rooting zone, which at this site extends through the upper 45 cm of soil (LeCain et al. 2006). Volumetric soil moisture content was measured at four depths (5, 10, 30, and 50 cm) using time-domain reflectometry probes (model CS616 from Campbell Scientific, Inc.) inserted horizontally into the soil. Measurements at each depth were collected hourly and stored as daily averages on a datalogger (model CR23X from Campbell Scientific, Inc.). The sensors were field calibrated gravimetrically using soil samples collected at each depth.

4. Results and discussion

a. *Analysis of the flux footprint and path-length averaging*

Calculations of the turbulent flux footprints (Schuepp et al. 1990) revealed that 80% of the cumulative footprint originated within an upwind distance of 65 and 137 m from the measurement points during typical daytime neutral and unstable atmospheric conditions, respectively. The upwind distances where the flux measurements were most sensitive were 7.2 and 15.2 m during typical daytime neutral and unstable conditions, respectively. Both the 80% cumulative and peak footprint distances were well beyond the small enclosure surrounding the instruments and continued into the region of homogenous vegetation that extended several hundred meters in all directions around the instrument site.

The potential underestimate of the fluxes as a result of spectral attenuation from spatial averaging was calculated using the method proposed by Massman (2000),

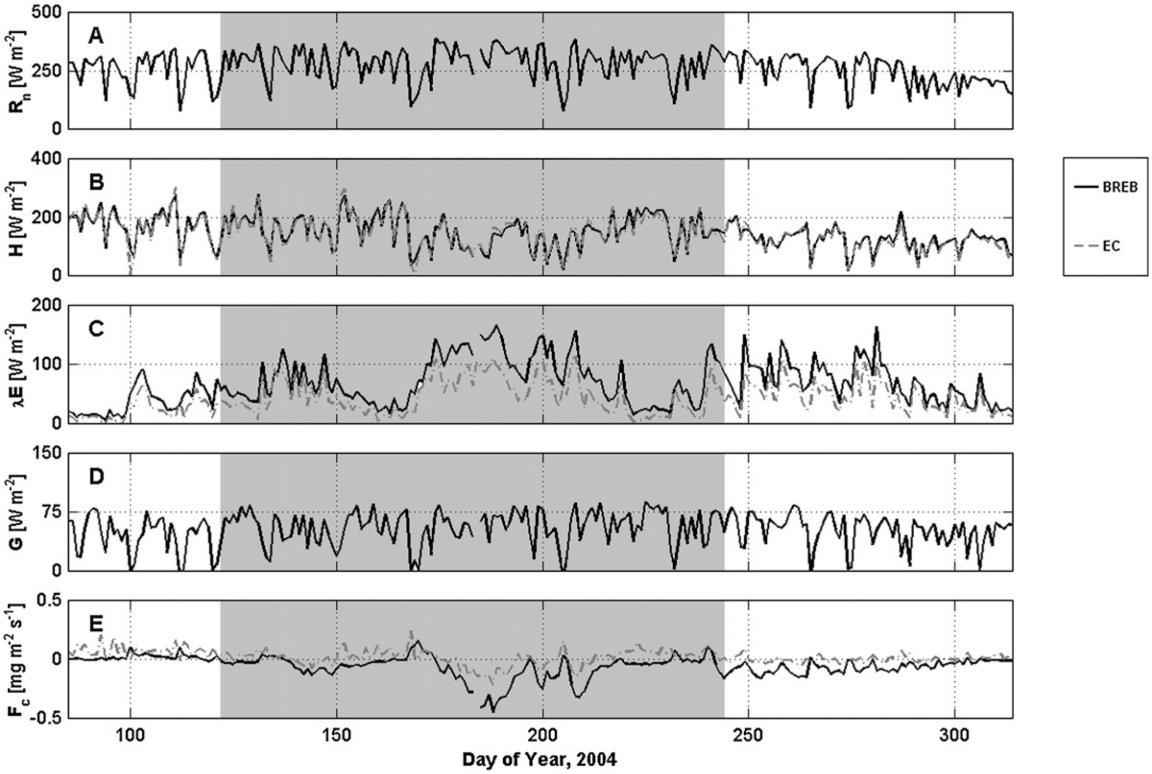


FIG. 1. Daytime mean values for (a) R_n, (b) H, (c) λE, and (d) soil heat fluxes, and (e) CO_2 flux from both the BREB (solid lines) and EC (dashed lines) methods. The shaded area indicates the growing season.

which extents the approach developed by Horst (1997) and includes corrections for frequency attenuation effects as a result of sensor response, sensor separation, signal processing, and flux-averaging periods. Applying the Massman's (2000) frequency response correction resulted in a less than 2% increase in the turbulent fluxes during unstable atmospheric conditions and a less than 6% increase during stable atmospheric conditions. Energy balance closure was 79.8% during the full diurnal cycle and 90.7% for the daytime period only. The EC-measured turbulent fluxes did not vary with u_*; the windy, turbulent conditions over the flat, extensive shortgrass prairie (mean u_* and U are 0.31 and 3.5 m s^{-1}, respectively) precluded the need to filter the turbulent flux data on the basis of a low u_*.

Additionally, the potential effects of self-heating by the LI-COR 7500 gas analyzer on the measurements of the moisture and carbon dioxide fluxes were investigated following Burba et al. (2008) using their "Method 4." As it discussed in that paper, the temperature within the path of the gas analyzer may differ from the ambient temperatures because of radiative forcing and heating from the electronic components of the instrument itself. This self-heating effect can result in an overestimate of F_c, particularly during cool periods. Although no seasonal patterns in the effects of this correction were evident, a modest impact was found for diurnal time scales. During the day, λE increased by 1.4% and F_c increased by 5.8%. During overnight periods, the magnitude of λE increased by approximately 10.0%, whereas the magnitude of F_c increased by 13.5%. Although the cumulative effects of this correction may be important when estimating long-term water or carbon budgets, the small change in the measured fluxes as a result of this correction had only a modest impact on this study. It did not significantly affect the comparisons between the BREB and EC measurements.

b. *Comparison of flux measurements*

The seasonal patterns of the turbulent (λE, H, and F_c) and nonturbulent fluxes (R_n and G) from both the BREB and EC methods are shown in Fig. 1. Based on the historical record for the first and last frost-free days in northeast Colorado, the measurements were divided into two distinct periods: the dormant period (DOY 85–121 and DOY 245–315) and the growing season (DOY 122–244). The daytime—here daytime is defined as that period for which the incident solar radiation exceeded 100 W m^{-2}—mean R_n over the entire measurement period varied from 77.4 (DOY 205) to 388.3 W m^{-2}

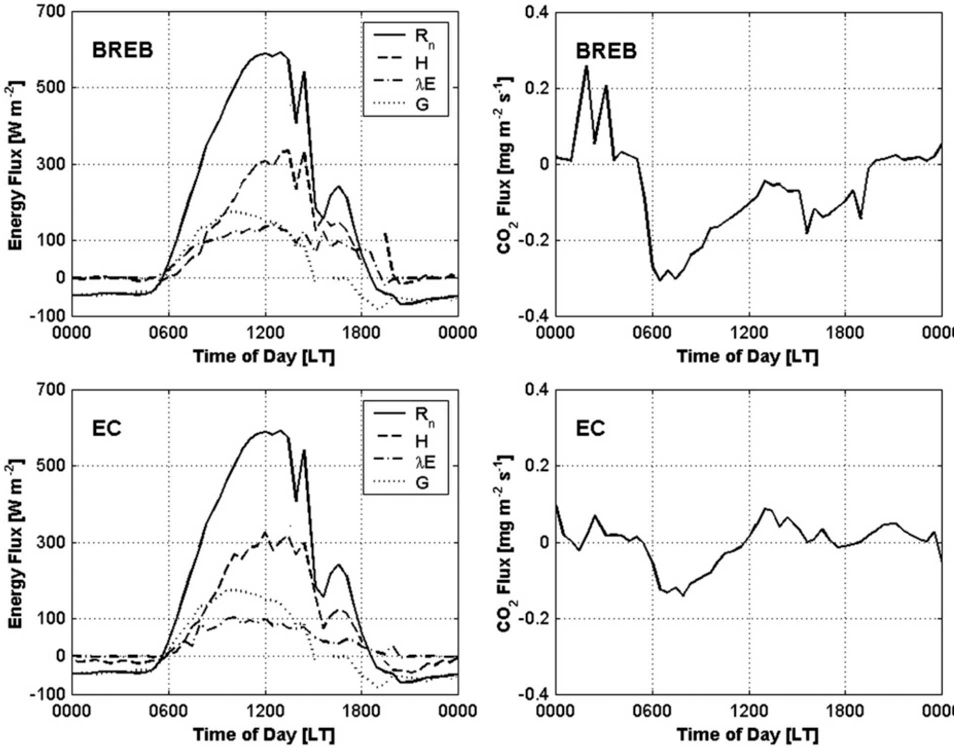


FIG. 2. Typical diurnal patterns of the (left) energy balance and (right) CO_2 fluxes as measured using the (top) BREB and (bottom) EC approaches. DOY 193 from 2004 is shown.

(DOY 174), for about a mean of 265.2 W m^{-2} (22.9 MJ m^{-2} day^{-1}). The soil heat flux, on average, was a relatively large portion of R_n (19.0% during the daytime), which is not uncommon in sparsely vegetated semiarid grasslands (Kustas et al. 2000; Heusinkveld et al. 2004). The soil heat flux constituted a nearly equal proportion of G at 19.2% and 18.8% during the dormant and growing seasons, respectively. The magnitude of the soil heat storage correction above the soil heat flux plates was also large (12% of R_n during the daytime), indicating the importance of appropriate placement of not only the heat flux plate but also the soil temperature probe and soil moisture probe required for the heat storage correction in this environment.

Not altogether unexpected given the dry climate of the region—the total precipitation was 223 mm during the observation period—the sensible heat flux represented the major energy term throughout most of the measurement period (Fig. 1). The daytime mean H with the BREB system was 146.2 W m^{-2} (12.6 MJ m^{-2} day^{-1}) or 54.0% of R_n and varied from 17.4 (19.2% of R_n; DOY 274) to 278.5 W m^{-2} (80.8% of R_n; DOY 111). The daytime mean H with the EC system was 143.2 W m^{-2} (12.4 MJ m^{-2} day^{-1}) or 53.2% of R_n and varied from 1.7 (1.9% of R_n; DOY 100) to 302.8 W m^{-2} (87.8% of R_n; DOY 111). The portion of R_n partitioned into H (daytime means) was high during both the dormant period (56.7% and 54.4% for the BREB and EC systems, respectively) and the growing season (53.0% and 52.1% for the BREB and EC systems, respectively), indicative of the large vertical air temperature gradients. The BREB and EC estimated H (H_{BREB} and H_{EC}, respectively) demonstrated similar diurnal patterns (Fig. 2), with the half-hour values also being quite similar during the dormant and growing seasons (Fig. 3). The positive slopes of the linear regression best-fit lines shown in Fig. 3 (3.5%–4.5%) were offset by the negative y intercepts (from -12.9 to -16.5 W m^{-2}), indicating the H_{BREB} exceeded H_{EC} when H_{BREB} was less than 365 W m^{-2}; this is the case for more than 99% of the half-hourly measurements during the course of the measurement period in 2004. In fact, throughout the entire measurement period, the 24-h mean difference (MD) and mean absolute difference (MAD) between H_{EC} and H_{BREB} were 11.9 and 24.5 W m^{-2}, respectively. If only the daytime period data were considered, then H_{EC} would typically be 2.7 W m^{-2} less than H_{BREB}.

The latent heat flux was substantially less than H throughout the measurement period, with three distinct periods evident from Fig. 1: DOY 85–160, 160–225, and 225–315. These three periods of relatively high λE corresponded to periods of relatively high soil moisture,

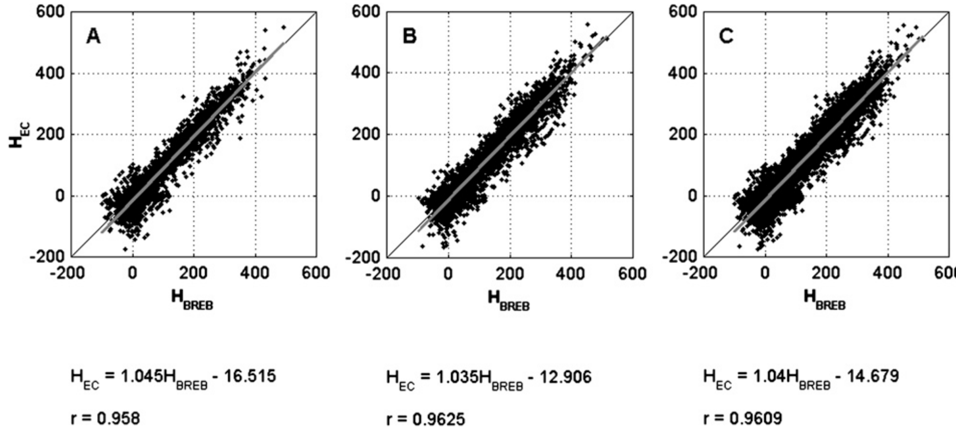


FIG. 3. Scatterplots of the 30-min sensible heat flux as measured by the BREB and EC methods for the (a) dormant period, (b) growing season, and (c) entire measurement period using the full 24-h dataset. The equation of the least squares linear regressions (thick gray lines) and correlation coefficients (r) are provided under each plot.

indicating the important role of available water to drive evaporation. Using the same periods as above to define the dormant and growing seasons, the proportion of R_n partitioned into λE was 24.3% and 27.7%, respectively, and 26.1% over the entire measurement period for the BREB system. The portion of R_n partitioned into λE was 15.2%, 17.3%, and 16.3%, respectively, for the dormant period, growing season, and the entire measurement period for the EC system. Based on 30-min means, the diurnal λE patterns behaved similarity for both measurement systems (e.g., DOY 193; Fig. 2); however, $\lambda E_{\mathrm{BREB}}$ systematically overestimated λE relative to λE_{EC} (Fig. 4). Throughout the entire measurement period, the 24-h MD and MAD between λE_{EC} and $\lambda E_{\mathrm{BREB}}$ were 12.6 and 18.7 W m^{-2}, respectively. If only the daytime period data were considered, then the MD and MAD would be 24.6 and 24.7 W m^{-2}, respectively.

The cumulative effect of the discrepancy between λE_{EC} and $\lambda E_{\mathrm{BREB}}$ [expressed as millimeters of evaporation and transpiration; evapotranspiration (ET)] in comparison with the total precipitation over the entire measurement period is shown by Fig. 5. Both methods captured the three longer-term evaporation periods and the shorter-term evaporation events driven by convective storms (especially between DOY 225–365); however, the estimated total ET was much greater for the BREB (285 mm) than for the EC (181 mm) method. This has important implications for any water balance estimates at the site. The ratio of ET to precipitation P was 1.28 and 0.81 for BREB and EC, respectively, representing a 58% difference in the ratio of ET to

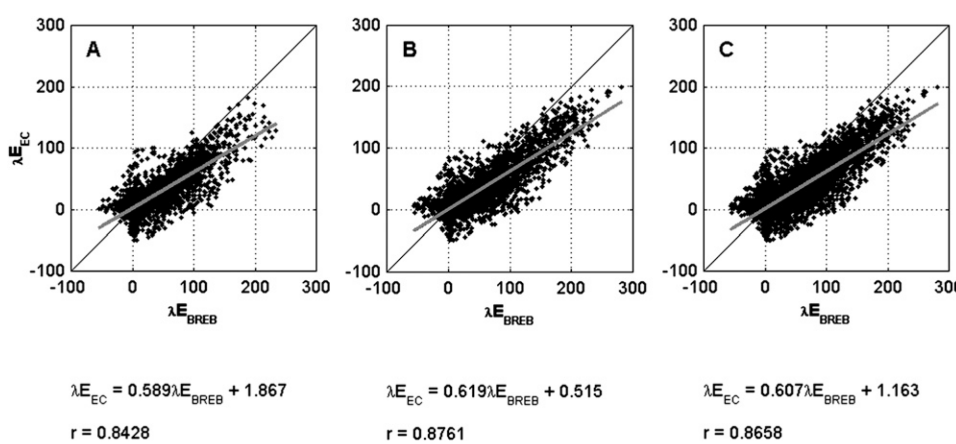


FIG. 4. As in Fig. 3, but for the 30-min latent heat flux.

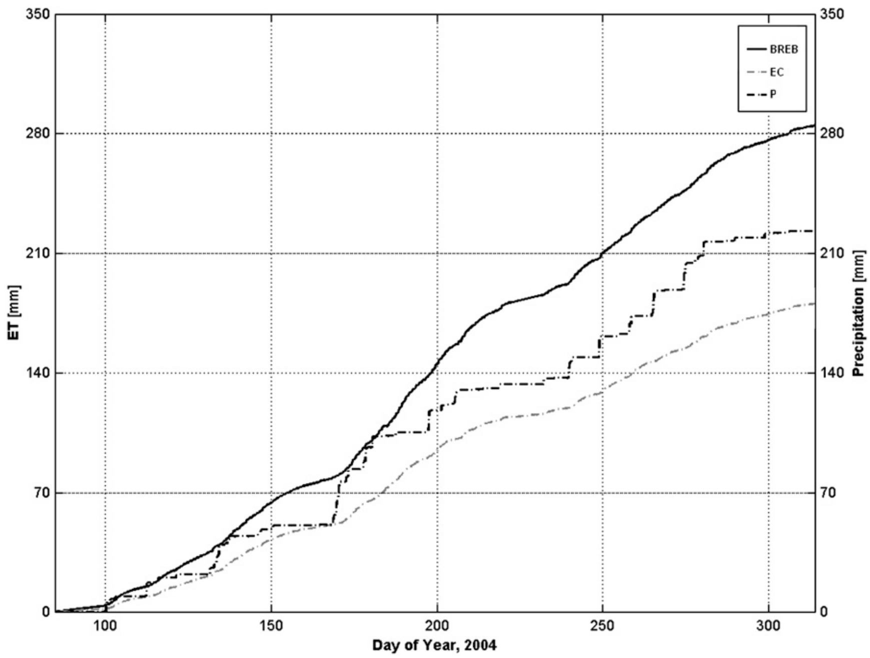


FIG. 5. Comparison between the cumulative evaporated water and precipitation as measured by the BREB and EC methods.

P depending on which method was used to estimate ET. Note also that the total ET as measured by BREB exceeded P by 52 mm, or nearly 24%.

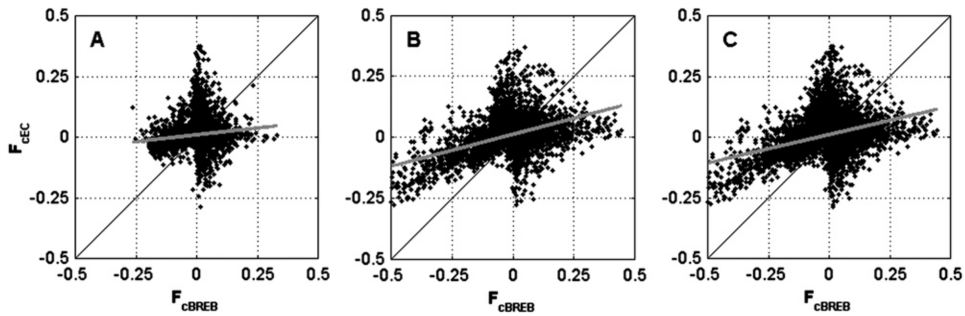
Recognizing that both surface runoff and deep infiltration are minimal in this region (Lauenroth and Bradford 2006) and using the 50-cm profiles of θ, it is possible to construct a water budget for the site as

$$\mathrm{ET} = P - \Delta S - I, \tag{9}$$

where ΔS is the change in the amount of water stored in the soil and I is the amount of deep drainage. For the observational period (DOY 85 through DOY 315), the total precipitation was 223 mm, the soil storage increased by 2 mm ($\Delta S = 2$ mm), and the total water loss as a result of deep drainage was estimated to be no more than 5 mm. The estimated ET was 216 mm. For the EC system, ET was measured as 181 mm, whereas for the BREB system it was 285 mm. This reaffirms the above conclusion that the BREB system tends to overestimate ET; the estimate of ET derived from the BREB data exceeded the value calculated from the water budget by 69 mm, or nearly 32%. At the same time, the EC system is underestimating the flux by approximately 35 mm, or 16%. Furthermore, if the energy needed to evaporate the 35 mm of water that is not accounted for by the EC system is added to λE, the closure of the energy budget approaches unity. While it might be possible to reduce the underestimate by forcing closure of the energy budget and adjusting both of the turbulent fluxes upward using, for example, the Bowen ratio as a guide, this would introduce additional uncertainty into the analysis that could further confound the interpretation of the data. Overall, the result of this analysis would support both the hypothesis that the EC method tends to underestimate λE, and that the method provides a better, albeit imperfect, estimate of the moisture flux than the BREB method.

As expected from a semiarid grassland with a sparse vegetation cover, the period of net CO_2 uptake (i.e., negative values of F_c; Fig. 1) was short and coincided with the second period of maximum λE (roughly between DOY 170 and 210). The BREB estimate of F_c ($F_{c\mathrm{BREB}}$) in comparison with the EC estimate ($F_{c\mathrm{EC}}$) showed similar seasonal and diurnal patterns (Figs. 1 and 2, respectively); however, $F_{c\mathrm{BREB}}$ consistently overestimated F_c (i.e., F_c more negative), and $F_{c\mathrm{EC}}$ indicated net CO_2 uptake later into the season (e.g., between DOY 250 and 300; Fig. 1). Although the 1:1 relationship between $F_{c\mathrm{EC}}$ and $F_{c\mathrm{BREB}}$ showed much scatter when $F_{c\mathrm{BREB}}$ was near zero (Fig. 6), the slopes of the linear regressions were 0.11, 0.26, and 0.23 for the dormant period, the growing season, and the entire measurement period, respectively, indicative of the overestimate of F_c from the BREB method relative to the EC method.

Following the hypothesis that the weak relationship in the CO_2 fluxes measurements was due to the low



$F_{cEC} = 0.110F_{cBREB} + 0.009$ $F_{cEC} = 0.262F_{cBREB} + 0.011$ $F_{cEC} = 0.233F_{cBREB} + 0.010$

r = 0.1211 r = 0.4501 r = 0.3555

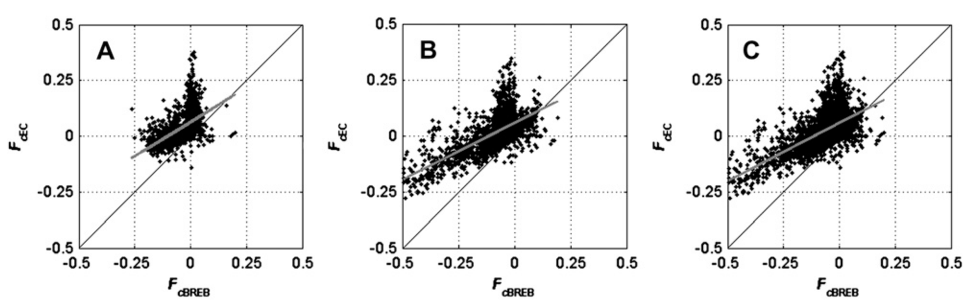
FIG. 6. As in Fig. 3, but for the 30-min CO_2 flux.

magnitude of the fluxes and the relatively stable atmospheric conditions during the overnight period, the above analysis was repeated using only daytime measurements, that is, periods when R_n is greater than 100 W m^{-2}. As can be seen in Fig. 7, eliminating the overnight period greatly reduced the amount of scatter in the data and improved the correlation between F_{cEC} and F_{cBREB}. For example, when the entire measurement period during 2004 was considered, the correlation between F_{cEC} and F_{cBREB} increased from 0.35 when the full diurnal cycle was considered to 0.69 when only the daytime measurements were considered. Also, both MD (0.082 μmol m^{-2} s^{-1}) and MAD (0.085 μmol m^{-2} s^{-1}) indicate a strong overestimate of F_c when measured using the BREB system as compared with the EC system.

Using the 24-h data, the cumulative effects of this overestimation on the carbon budget are shown in Fig. 8. Throughout most of the measurement period, F_{cBREB} was less than F_{cEC}, indicating a larger net CO_2 uptake by the surface. By the end of the measurement period, this resulted in a cumulative difference of 62 g m^{-2} of CO_2, with a F_{cBREB} showing a net sink of 45 g m^{-2} compared to a F_{cEC}, which showed a net release of 17 g m^{-2} of CO_2. Clearly, the magnitude of the carbon budget was influenced by which method was used to estimate the net CO_2 flux.

c. *Analysis of eddy diffusivity and reconciliation of the datasets*

This and numerous other studies (e.g., Li et al. 2006) have shown that semiarid grasslands are high-energy environments. The high net radiation is largely partitioned into sensible heat, with a significant portion into the soil heat flux as a result of the sparse vegetation cover. During much of the year, convection is large with a windy, turbulent atmospheric environment resulting in water vapor and CO_2 exchange between the surface and atmosphere. Although the vegetation cover is sparse, evaporation can be episodic in response to precipitation events, and because of the large surface area



$F_{cEC} = 0.615F_{cBREB} + 0.063$ $F_{cEC} = 0.506F_{cBREB} + 0.058$ $F_{cEC} = 0.522F_{cBREB} + 0.059$

r = 0.5556 r = 0.7310 r = 0.6857

FIG. 7. As in Fig. 3, but for the 30-min CO_2 flux and for when only the daytime, i.e., R_n greater than 100 W m^{-2}, was considered.

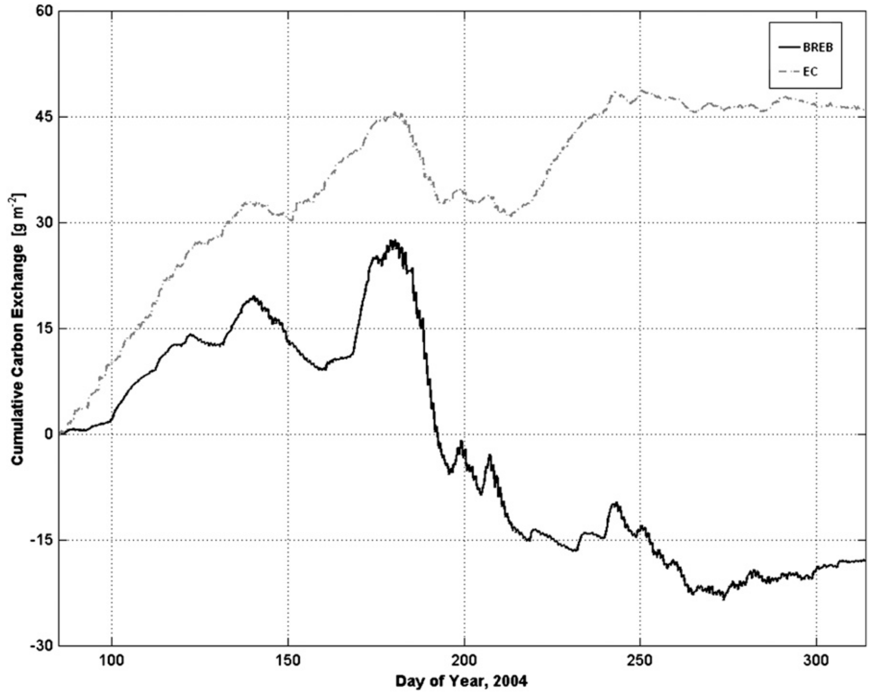


FIG. 8. Cumulative carbon budget over the course of the measurement period as measured by either the BREB or EC method.

of semiarid grasslands, the CO_2 budget can be a significant component at the regional and global scales.

Two popular and widely used methods are used to assess the behavior and magnitude of the water and carbon budgets from this and other surfaces: the Bowen ratio and eddy covariance methods. As shown in this paper, each method provides different estimates of the water and carbon budgets, with the BREB method typically overestimating the EC method. To better understand the causes of these differences, the eddy diffusivities were investigated.

The eddy diffusivities were determined by combining the EC-determined fluxes with the BREB-measured gradients. Figure 9 shows that the eddy diffusivities were not similar for all scalars and also that they varied with atmospheric stability (decreasing as the atmosphere became more stable), as indicated by the Richardson number. The K was greatest for H, followed by that for λE and F_c. The magnitude of the differences between the K for heat, water vapor, and CO_2 were proportional to the difference in magnitude between the BREB and EC-determined H, λE, and F_c. The differences in K shown in Fig. 9 indicate that heat was much more effectively transported through the atmosphere than water vapor or CO_2 under unstable atmospheric conditions.

Therefore, an empirical approach was used to reconcile the two methods. Using bin-averaged values for the Richardson number and eddy diffusivity, a best-fit curve was generated for K_h, K_v, and K_c as a function of atmospheric stability. The relationships have the following form:

$$K_x = K_1 + K_2, \quad \text{with} \tag{10}$$

$$K_1 = k_o + \frac{\alpha}{1 + e^{\left(\frac{\mathrm{Ri}_o - \mathrm{Ri}}{\beta}\right)}} \quad \text{and} \tag{11}$$

$$K_2 = \begin{cases} 0 & \mathrm{Ri} \geq 0 \\ k_o' + \dfrac{a}{1 + e^{\left(\frac{\mathrm{Ri}_o' - \mathrm{Ri}}{b}\right)}} & \mathrm{Ri} < 0, \end{cases} \tag{12}$$

with α, β, a, b, k_o, k_o', Ri_o, and Ri_o' being empirical constants that are unique for each eddy diffusivity. The values of the constants are given in Table 1. The fluxes resulting from calculations with these relationships (Fig. 10) compare quite favorably to the fluxes measured by the EC method. Using the relationships with data from 2004, it was found that the MD and MAD for H_{EC} and the recalculated H_{BREB} using the eddy diffusivities from the best-fit curve were 4.0 and 23.8 W m^{-2}, respectively. Similarly, for λE_{EC} and the recalculated $\lambda E_{\mathrm{BREB}}$, MD and MAD were 2.6 and 13.4 W m^{-2}, respectively. Finally, for F_{cEc} and the recalculated F_{cBREB}, MD and MAD were 0.13 and 0.21 mg m^{-2} s^{-1}.

The empirical relationships were also evaluated using data from 2005. A sample result is shown in Fig. 11. It

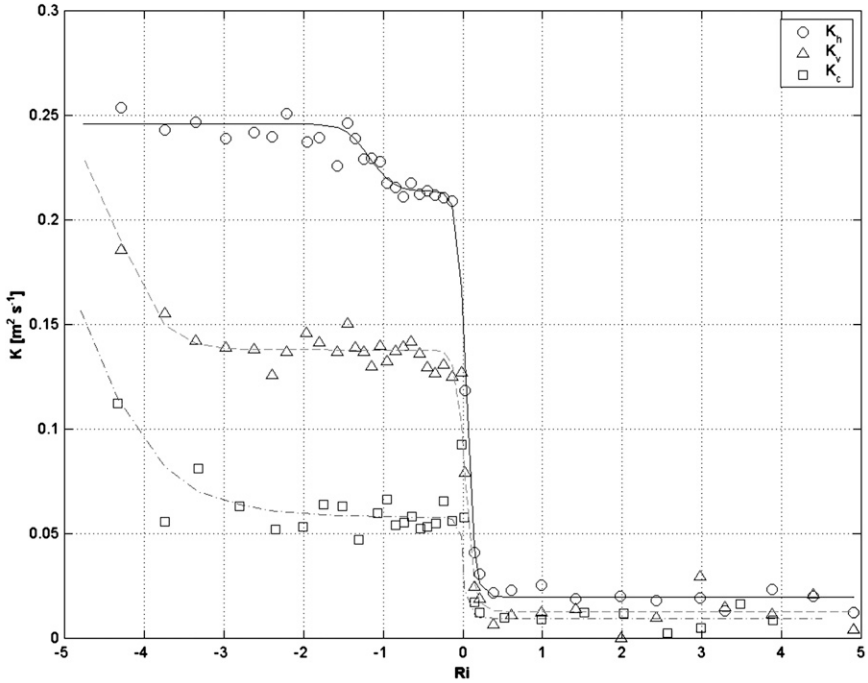


FIG. 9. Scatterplots of the eddy diffusivities and their respective best-fit curves plotted against the bin-averaged atmospheric stability (expressed using the Richardson number).

was found that the MD and MAD for H_{EC} and the recalculated H_{BREB} using the eddy diffusivities from the best-fit curve were 1.6 and 24.2 W m^{-2}, respectively. Similarly, for λE_{EC} and the recalculated λE_{BREB}, MD and MAD were 2.2 and 16.8 W m^{-2}, respectively. Finally, for F_{cEC} and the recalculated F_{cBREB}, MD and MAD were 0.25 and 0.50 mg m^{-2} s^{-1}. The results are similar to the results using the data collected in 2004. This suggests that the relationships, which were developed using data from 2004, could be used during other periods to adjust fluxes measured with the BREB method at this site. Furthermore, similar empirical relationships could be generated using measurements at other sites and following this technique. Those results then could be developed to reconcile BREB and EC data at those sites.

5. Conclusions

Based on the results from this study, it is clear that the BREB and EC methods tend to yield substantially different measures of the same surface flux. In part, these differences may be attributed to differences in the sensor systems themselves. However, much more important are the differences that arise as a result of the fundamental differences in the theoretical underpinnings of the two techniques. Especially important is the requirement of the BREB method that the surface energy balance be closed. Since the BREB method uses a simplified surface energy balance relationship, all of the available energy must be partitioned into one of the turbulent fluxes. This yields estimates of the turbulent fluxes that are not only inaccurate—for example, they are too great

TABLE 1. The empirical constants used to estimate the eddy diffusivities as a function of Richardson number. The range indicates the 95% confidence interval.

	α	β	Ri_o	k_o
K_h	0.1943 ± 0.0010	−0.0518 ± 0.0018	0.0387 ± 0.0018	0.0198 ± 0.0005
K_v	0.1217 ± 0.0011	−0.0570 ± 0.0027	0.0293 ± 0.0018	0.0128 ± 0.0007
K_c	0.0454 ± 0.0027	−0.0428 ± 0.0022	−0.0480 ± 0.0018	0.0095 ± 0.0008
	a	b	Ri'_o	k'_o
K_h	0.0326 ± 0.0008	−0.1482 ± 0.0215	−1.1690 ± 0.0244	−0.0006 ± 0.0005
K_v	0.1107 ± 0.0136	−0.2734 ± 0.0314	−4.3251 ± 0.2115	0.0034 ± 0.0006
K_c	0.1968 ± 0.0173	−0.5139 ± 0.0205	−4.7564 ± 0.1718	0.0029 ± 0.0007

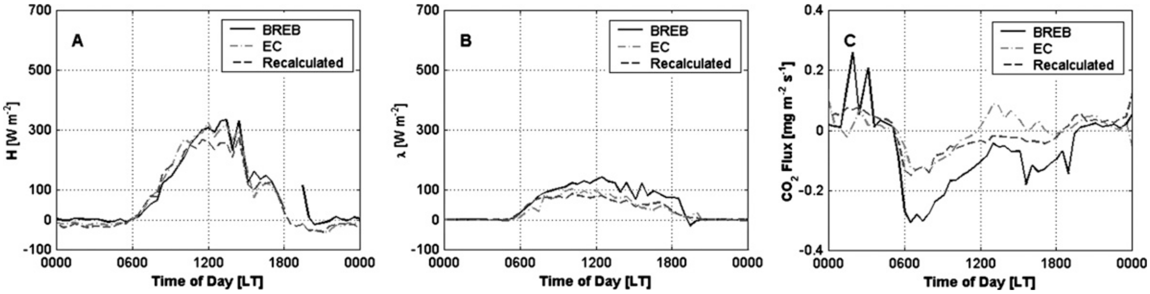


FIG. 10. Typical diurnal patterns of the recalculated energy balance and CO_2 fluxes as determined using the empirical eddy diffusivity functions and BREB data. DOY 193 of 2004 is shown.

during unstable (daytime) conditions—but they also have an impact on the estimates of other trace gas fluxes, such as F_c. Since the measurement of trace gas fluxes relies on an assumption of similarity for eddy diffusivity and eddy diffusivity values are derived from the turbulent fluxes, the errors resulting from forced closure will propagate into the estimates of these fluxes as well.

Furthermore, the very assumption of similarity that underlies the BREB method may not be valid. In this study it was found that K_h was typically greater than either K_v, or K_c during unstable conditions. In other terms, heat was transported more effectively than either water vapor or CO_2 under unstable conditions. Additionally, while K_v and K_c are much more alike, perhaps as a result of differences, such as modest surface heterogeneity or advective processes, they were not identical as similarity would suggest they should be. As a result, this assumption could explain a portion of the differences seen between the flux measurements made by the BREB and EC methods.

Regardless of their cause, however, this research shows important differences between the measurements made by the BREB and EC methods. Whereas with care it may be possible to account for these difference so that both methods can yield reliable flux estimates over shortgrass steppe grassland, it is important to recognize not only the existence of these differences but also their potential impacts on the results and conclusions drawn from any research conducted with data collected by these methods. For example, since the AgriFlux network operated by the USDA–ARS employs a network composed primarily of BREB stations, whereas the AmeriFlux network uses the EC method, the differences inherent in the two methods must be considered when analyzing, comparing, or merging those two datasets to insure that the results are valid and the appropriate conclusions are reached.

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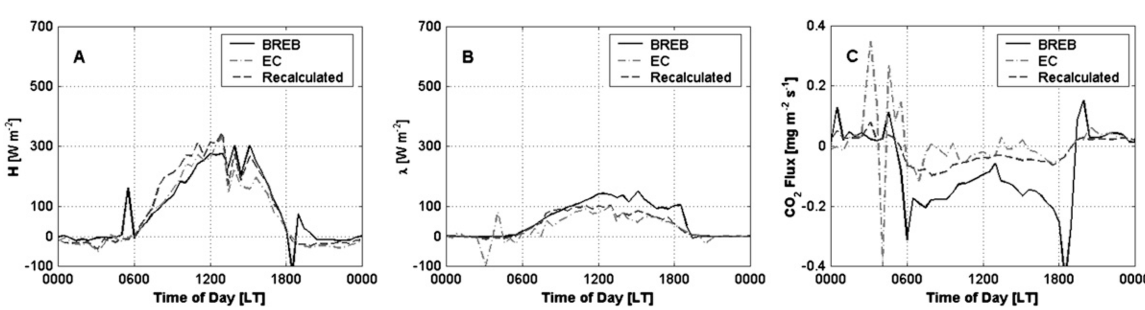

FIG. 11. As in Fig. 10, but for DOY 193 of 2005.

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