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Partitioning carbon dioxide and water vapor fluxes using correlation analysis

Todd M. Scanlon [a,*], William P. Kustas [b]

[a] Department of Environmental Sciences, University of Virginia, Clark Hall, 291 McCormick Rd., Charlottesville, VA 22904, United States
[b] USDA-ARS Hydrology and Remote Sensing Laboratory, Bldg. 007, Rm. 104, Beltsville, MD 20705, United States

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ABSTRACT

Partitioning of eddy covariance flux measurements is routinely done to quantify the contributions of separate processes to the overall fluxes. Measurements of carbon dioxide fluxes represent the difference between gross ecosystem photosynthesis and total respiration, while measurements of water vapor fluxes represent the sum of transpiration and direct evaporation. Existing flux partitioning procedures typically require additional instrumentation and/or invoke scaling assumptions that may or may not be appropriate. Here, we present a novel flux partitioning procedure that relies upon the simple assumption that contributions to the measured high-frequency time series of carbon dioxide and water vapor concentrations derived from stomatal processes (i.e., photosynthesis and transpiration) and non-stomatal processes (i.e., respiration and direct evaporation) separately conform to flux-variance similarity. Vegetation water use efficiency is the only parameter needed to perform the partitioning. We apply this technique to eddy covariance data collected over the course of a growing season above a maize field. Results yielded by the correlation-based partitioning approach are consistent with expected trends throughout the growing season, as photosynthesis and transpiration fluxes increase in parallel with observed increases in maize leaf area. Magnitudes of the derived fluxes compare well with literature-based values, and short-term, transient features are also detected as both respiration and direct evaporation fluxes are found to respond to wetting events. These results support the validity of the theory-based partitioning approach, which has the benefit of being simultaneously applied to both carbon dioxide and water vapor fluxes, while relying solely upon standard eddy covariance instrumentation.

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1. Introduction

1.1. Background and motivation

Eddy covariance is a widely used technique for quantifying land–atmosphere exchange of carbon dioxide and water vapor, and its implementation in monitoring networks throughout the world (e.g., AMERIFLUX, CARBOEUROFLUX, ASIAFLUX) has led to significant advances in defining how ecosystem-level fluxes respond to variability in land cover and climate forcing. A key step in the use and interpretation of eddy covariance data centers on partitioning measurements into constituent fluxes associated with distinct biophysical processes (Stoy et al., 2006). Existing flux partitioning procedures typically require additional instrumentation and/or invoke scaling assumptions that may or may not be appropriate. Here we present a novel flux partitioning approach that requires only standard eddy covariance instrumentation and relies upon a limited number of assumptions for its theoretical development.

Ecosystem-scale fluxes measured by eddy covariance derive from multiple sources and sinks. Carbon dioxide flux (F_c) measured by eddy covariance is equivalent to net ecosystem exchange (NEE), the difference between gross ecosystem photosynthesis (hereafter referred to simply as "photosynthesis") and total ecosystem respiration. Water vapor flux (F_q) is evapotranspiration, which is comprised of both plant transpiration and direct evaporation from soil, litter, and vegetation surfaces. A number of approaches have been developed to partition these fluxes into their respective components. Among these is the use of isotopes which, helped by recent advances in fast-response laser spectroscopy, has a demonstrated capacity to partition carbon dioxide fluxes in eddy covariance mode (Griffis et al., 2008) and holds similar promise for water vapor (Lee et al., 2005; Welp et al., 2008). This approach is considered to be advantageous relative to other isotope-based techniques such as relaxed eddy accumulation (Bowling et al., 1999), the flask-based isoflux method (Bowling et al., 2001), and the flux-gradient method (Yakir and Wang, 1996; Knohl and Buchmann, 2005; Lee et al., 2007), all of which have been developed with the same flux partitioning objective. Despite the

* Corresponding author. Tel.: +1 434 924 3382; fax: +1 434 982 2137.
E-mail addresses: tms2v@virginia.edu (T.M. Scanlon), Bill.Kustas@ars.usda.gov (W.P. Kustas).

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conceptual appeal of isotope-based approaches, factors such as cost and technical requirements for site setup and maintenance are likely their limit widespread or long-term implementation.

More commonly, flux partitioning is carried out using regressed relationships between eddy covariance measurements and relevant forcing variables. For example, relationships between carbon dioxide flux and soil temperature established during strongly turbulent nighttime conditions are frequently adopted to estimate daytime respiration fluxes. Such relationships are established over annual or sub-annual timescales (Stoy et al., 2006). Factors such as sensitivity to the applied friction velocity threshold (Anthoni et al., 2004) and the hysteretic response of respiration fluxes to the wetting and drying of soils (Xu and Baldochhi, 2004) contribute to uncertainty associated with this flux partitioning strategy. An alternative approach is the use of daytime flux measurements to infer respiration rates from light response curves, which can be regressed against soil temperature (Lee et al., 1999; Gilmanov et al., 2003). Although this has been identified as a more accurate flux partitioning method (Stoy et al., 2006), this procedure likewise involves extrapolating to hourly timescales mean functional responses that are established over longer periods of time. In the case of water vapor fluxes, the lack of analogous methods by which to partition these fluxes precludes the extraction of transpiration and direct evaporation from standard eddy covariance measurements. Additional information on water vapor component fluxes is required.

A number of studies have combined sap flux measurements with eddy covariance as a means for partitioning water vapor fluxes (e.g., Kurpius et al., 2003; Unsworth et al., 2004; Rana et al., 2005; Tang et al., 2006). A persistent problem associated with this approach, however, pertains to converting sap flux measurements to ecosystem-level transpiration rates on a scale congruent with eddy covariance footprints (Oishi et al., 2008). Alternatively, chambers have been used to isolate the portion of the water vapor flux that derives from soil surface evaporation (Stannard and Weltz, 2006; Daikoku et al., 2008), and have been more routinely employed to partition carbon dioxide fluxes (e.g., Dore et al., 2003; Flanagan and Johnson, 2005; Kosugi et al., 2008). Scaling issues associated with using chambers in conjunction with eddy covariance are well known (Ohkubo et al., 2007; Myklebust et al., 2008), as are problems that can arise from altered airflow caused by these devices (Davidson et al., 2002).

Although a variety of approaches exist for partitioning carbon dioxide and water vapor fluxes, the extent of ongoing efforts directed toward developing new technologies and analytical procedures perhaps best underscores how vital this information is for land–atmosphere exchange models and empirical studies. Often treated separately, the joint behavior of water vapor and carbon dioxide in the atmospheric surface layer reveals much about their respective fluxes. By exploiting similarities in their transport properties, it is possible to obtain partitioning estimates for both. Our specific objectives in adopting this overall approach are: (1) to demonstrate a theoretical basis of flux partitioning that applies flux-variance similarity theory separately to the stomatal and non-stomatal portions of the water vapor and carbon dioxide fluxes, (2) to report the results of this method when applied to eddy covariance data collected over the course of a growing season, and (3) to evaluate these theoretically derived results in terms of their relationship to independently measured biophysical variables.

1.2. A conceptual overview

According to Monin–Obukhov similarity theory (MOST) (Monin and Obukov, 1954), scalar statistics for a particular height within a horizontally homogenous atmospheric surface layer are governed by the magnitude of the surface fluxes, the surface shear stress, and the buoyancy properties of the atmospheric turbulence. An implication of MOST is that scalar time series measured at the same position should exhibit perfect correlation (Hill, 1989), a property that is consistent with the concept of flux-variance similarity. Departures from this theoretical expectation occur when one or more assumptions that underlie MOST are violated. Previous work has shown that non-steadiness of time series (McNaughton and Laubach, 1998), the influence of entrainment (Mahrt, 1991; Roth and Oke, 1995), and non-identical distribution of scalar sinks/sources (Katul et al., 1995; Andreas et al., 1998; Scanlon and Albertson, 2001) are factors that could potentially contribute to less-than-perfect correlation. Where there is adequate fetch, the first two factors are driven by large-scale atmospheric processes while the last factor is associated with source/sink heterogeneity that may be present on much smaller scales.

Focusing on carbon dioxide, c, and water vapor, q, concentrations, let us first consider a hypothetical case in which photosynthesis and transpiration are the sole contributors to the measured fluxes (i.e., respiration and direct evaporation are both negligible). Since they both derive from stomatal exchange, the source/sink distributions of these flux components are identical. According to flux-variance similarity theory (and in the absence of large-scale factors such as non-stationarity and entrainment) the correlation coefficient between the c and q time series, $\rho_{c,q}$, would be equal to -1. The correlation is negative because the vegetation acts as a sink for carbon dioxide and a source for water vapor. Fig. 1a and b depicts the Reynolds averaged time series of c' and q', respectively, for this hypothetical case. The relationship between c' and q', shown in Fig. 1c, exhibits a perfectly negative correlation with a slope equivalent to the water use efficiency (*WUE*) of compositionally uniform vegetation. *WUE* is a leaf-level property that describes the amount of carbon dioxide gain per unit water loss.

Just as the stomatal components of the fluxes are assumed to conform to flux-variance similarity, a second major assumption is that the non-stomatal flux components, respiration and direct evaporation, separately adhere to this theoretical construct. Having source/sink distributions largely distinct from the previously described leaf-level exchange and being independent of stomatal control, these primarily sub-canopy fluxes are assumed to be transported similarly with one another yet differently from the stomatal components. Considering a hypothetical case in which only respiration and bare soil evaporation are active, the time series of c' and q' might look like Fig. 1d and e, respectively. Since both fluxes are positive during the daytime, flux-variance similarity would imply that $\rho_{c,q}$, would be equal to +1 as depicted in Fig. 1f.

Given a more realistic scenario in which both stomatal and non-stomatal processes contribute to the overall fluxes, $|\rho_{c,q}|$ would be less than 1 on account of the distinct source/sink distributions (and thus turbulent transfer characteristics) associated with the stomatal versus non-stomatal processes. Alone, the photosynthesis and transpiration components of the fluxes would exhibit perfectly negative c–q correlation (Fig. 1c); the addition of respiration and direct evaporation can be thought of as "contamination" that degrades this correlation between the c and q time series. For a case in which both stomatal and non-stomatal processes contribute to the fluxes, the time series of c' (Fig. 1g) and q' (Fig. 1h) would exhibit reduced correlation (Fig. 1i). The degree of this reduced correlation provides a piece of information that can be used to infer the relative magnitudes of the flux components. Another piece of information, presented here on a conceptual level, derives from the fact that the addition of either (or both) non-stomatal component alters the slope of the c' versus q' relationship such that its magnitude becomes less than that of *WUE* (Fig. 1i). The

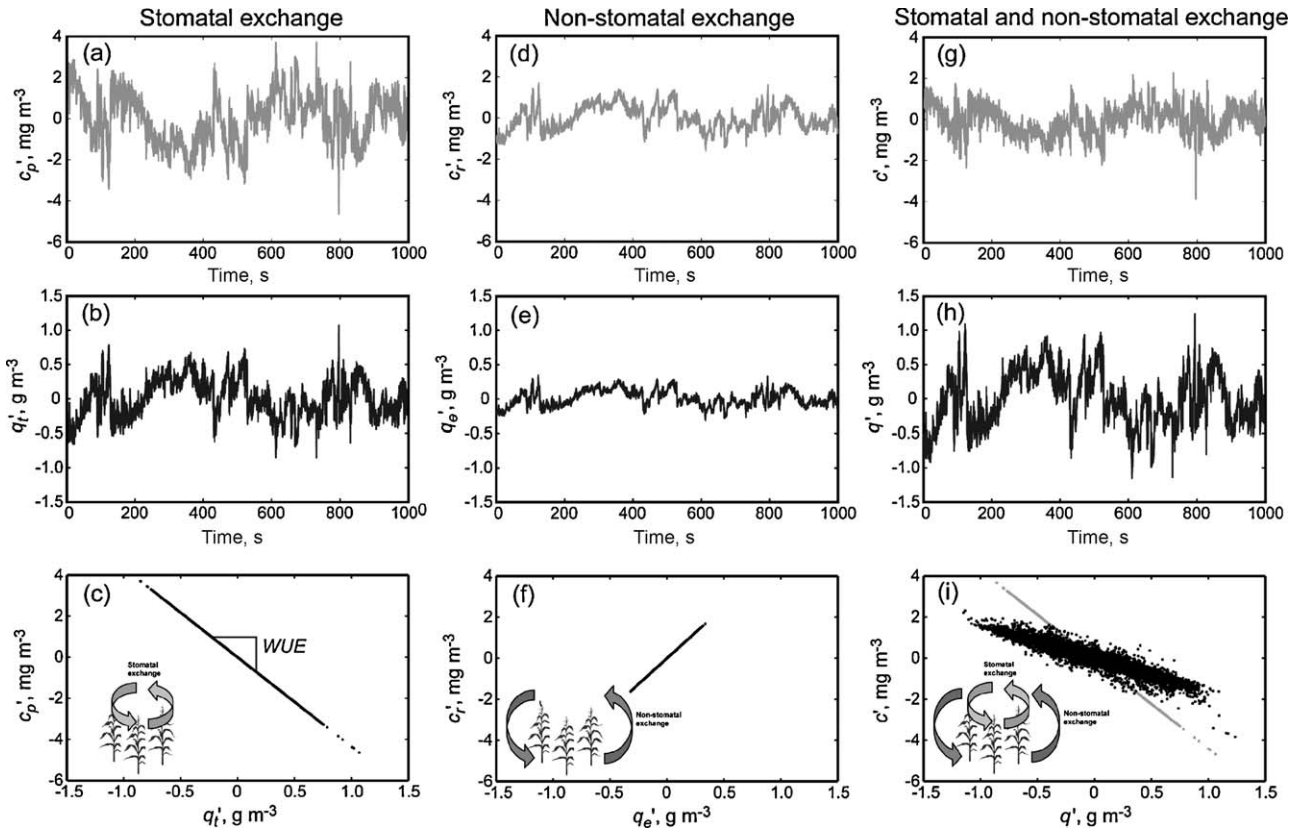

Fig. 1. High frequency time series of (a) carbon dioxide and (b) water vapor for a hypothetical case in which only stomatal exchange is active. (c) Flux-variance similarity applies to the stomatal exchange, implying perfectly negative correlation with a slope equivalent to the water use efficiency, *WUE*, of the vegetation. High frequency time series of (d) carbon dioxide and (e) water vapor for a hypothetical case in which only non-stomatal exchange is active. (f) Flux-variance similarity applies to the non-stomatal exchange, implying perfectly positive correlation. High frequency time series of (g) carbon dioxide and (h) water vapor for a more realistic case in which stomatal and non-stomatal exchange are both active. (i) The relationship between these time series exhibits less-than-perfect correlation with a slope deflected from *WUE*.

degree of the deflection in slope away from *WUE* provides more evidence about the compositions of the measured fluxes. A confounding factor for flux partitioning is the unknown degree of similarity between the stomatal and non-stomatal transport, which affects both the c–q correlation and slope. An analytical approach is needed to partition the measured carbon dioxide and water vapor fluxes based on flux-variance similarity theory applied separately to the stomatal and non-stomatal fluxes.

1.3. An analytical overview

Measured carbon dioxide (F_c) and water vapor (F_q) fluxes are comprised of components that cannot be isolated from standard eddy covariance measurements. These basic components are:

$$F_c = \overline{w'c'} = F_{\text{photosynthesis}} + F_{\text{respiration}} \tag{1a}$$

$$F_q = \overline{w'q'} = F_{\text{traspiration}} + F_{\text{evaporation}} \tag{1b}$$

where the overbar ($^{-}$) represents temporal averaging and the primes ($'$) represent departures from the mean values using Reynolds averaging (e.g., $c' = c - \bar{c}$). The fluctuating terms c' and q' are influenced by the turbulent exchange associated with both of their flux components. For example, a time series of c' measured by a gas analyzer, as shown in Fig. 2a, can be thought of as the superposition of two signals separately attributed to the photosynthesis and respiration fluxes. These signals have a negative correlation due to the opposite directions of the fluxes, but not a perfectly negative correlation due to distinct source/sink distributions and contrasting controls on the fluxes. Likewise, the measured q' time series can be thought to consist of the superposition of two signals separately attributed to the transpiration and direct evaporation fluxes, as shown in Fig. 2b. These signals would exhibit a general positive correlation.

The separate components of the c' and q' time series thus can be expressed in a modified Reynolds averaging form:

$$c' = c'_p + c'_r \tag{2a}$$

$$q' = q'_t + q'_e \tag{2b}$$

where c'_p and c'_r are the components of c' associated with the photosynthesis and respiration fluxes, respectively, and q'_t and q'_e are the components of q' associated with the transpiration and direct evaporation fluxes, respectively. Through flux-variance similarity, the stomatal exchange components are linked by vegetation water use efficiency according to:

$$c'_p = WUEq'_t \tag{3}$$

as in Fig. 1c, where it follows that the standard deviations (σ) and variances (σ^2) for these components are related by:

$$\sigma_{c_p} = -WUE\sigma_{q_t} \tag{4a}$$

$$\sigma^2_{c_p} = WUE^2\sigma^2_{q_t}. \tag{4b}$$

The components of the total carbon dioxide and water vapor fluxes can be expressed in covariance form:

$$F_c = \overline{w'c'} = \overline{w'c'_p} + \overline{w'c'_r} = WUE\overline{w'q'_t} + \overline{w'c'_r} \tag{5a}$$

$$F_q = \overline{w'q'} = \overline{w'q'_t} + \overline{w'q'_e}. \tag{5b}$$

Since only c' and q', and not the individual components, can be detected with a gas analyzer, some additional considerations are required to estimate the flux terms.

As depicted in Fig. 1, flux-variance similarity between the stomatal-derived variables (q'_t and c'_p) and between the non-stomatal variables (q'_e and c'_r) implies:

$$\rho_{c_p,q_t} = -1 \tag{6a}$$

$$\rho_{c_r,q_e} = +1. \tag{6b}$$

Flux-variance similarity does not hold for the cross-correlations between the stomatal and non-stomatal variables, but the following relationship must apply:

$$\rho_{c_p,c_r} = -\rho_{q_t,q_e}. \tag{7}$$

The transfer efficiencies of the stomatal-derived scalars (i.e., ρ_{w,c_p} and ρ_{w,q_t}) are assumed to be greater than the efficiencies of the non-stomatal scalars (i.e., ρ_{w,c_r} and ρ_{w,q_e}), due the sources for the latter being primarily situated in the subcanopy. Therefore, according to Katul et al. (1995) and Bink and Meesters (1997), we can make the following estimations:

$$\rho_{c_p,c_r} \approx \frac{\rho_{w,c_r}}{\rho_{w,c_p}} = \frac{\overline{w'c'_r}}{\overline{w'c'_p}}\frac{\sigma_{c_p}}{\sigma_{c_r}} \tag{8a}$$

$$\rho_{q_t,q_e} \approx \frac{\rho_{w,q_e}}{\rho_{w,q_t}} = \frac{\overline{w'q'_e}}{\overline{w'q'_t}}\frac{\sigma_{q_t}}{\sigma_{q_e}}. \tag{8b}$$

A final property of the time series to be characterized is the variance. Since the components of the c' and q' time series are not independent (as shown in Fig. 2) the variances are given as:

$$\sigma_q^2 = \sigma_{q_t}^2 + \sigma_{q_e}^2 + 2\rho_{q_t,q_e}\sigma_{q_t}\sigma_{q_e} \tag{9a}$$

$$\sigma_c^2 = \sigma_{c_p}^2 + \sigma_{c_r}^2 + 2\rho_{c_p,c_r}\sigma_{c_p}\sigma_{c_r}. \tag{9b}$$

Scanlon and Sahu (2008) demonstrated how (2)–(9) could be combined and, by noting that *WUE* is also equivalent to $\overline{w'c'_p}/\overline{w'q'_t}$, developed a single equation that contains only two unknown parameters. The equation

$$WUE = \frac{\overline{w'c'}}{\overline{w'q'}}\frac{(-2\sigma_{c_p}^2 WUE^{-2} \pm \sqrt{4\sigma_{c_p}^4 WUE^{-4} - 4\sigma_{c_p}^2 WUE^{-2}\rho_{c_p,c_r}^{-2}(\sigma_{c_p}^2 WUE^{-2} - \sigma_q^2)})/(2\sigma_{c_p}^2 WUE^{-2}\rho_{c_p,c_r}^{-2}) + 1}{(-2\sigma_{c_p}^2 \pm \sqrt{4\sigma_{c_p}^4 - 4\sigma_{c_p}^2\rho_{c_p,c_r}^{-2}(\sigma_{c_p}^2 - \sigma_c^2)})/(2\sigma_{c_p}^2\rho_{c_p,c_r}^{-2}) + 1}, \tag{10}$$

can be further manipulated to solve for $\sigma_{c_p} = f(\rho_{c_p,c_r})$, but in practice the enormous length of the analytical solution makes it preferable to numerically determine the values of σ_{c_p} over the physically meaningful range $-1 \le \rho_{c_p,c_r} \le 0$ using the measured values of $\overline{w'c'}$, $\overline{w'q'}$, σ_c, and σ_q. Estimates of *WUE* may be derived from either leaf-level measurements or stomatal gradient considerations, as done in the present paper. The quadratic nature of (10) makes it possible for multiple real positive values of σ_{c_p} to exist for given values of ρ_{c_p,c_r}.

With the relationship(s) between σ_{c_p} and ρ_{c_p,c_r} thus established, the magnitudes of the individual flux components can also be solved as a function of ρ_{c_p,c_r}. These components are subject to the constraints $\overline{w'c'_p} \le 0$, $\overline{w'c'_r} \ge 0$, $\overline{w'q'_t} \ge 0$, and $\overline{w'q'_e} \ge 0$, which are reasonable during daytime conditions when the available energy flux at the land surface is positive. If any of these constraints are violated, then the solution is considered to be invalid over the corresponding values of ρ_{c_p,c_r} and σ_{c_p}. This narrows the range of possible solutions for the flux components, but another argument is needed to identify the value(s) of ρ_{c_p,c_r} where an exact solution (or solutions) exists. This is accomplished by deriving an expression for $\rho_{q,c}$ as a function of ρ_{c_p,c_r} and the other variables by again applying the arguments given in (2)–(9). Actual values of ρ_{c_p,c_r} are defined where the calculated $\rho_{q,c}$ matches the observed. A more detailed description of this analytical procedure is given in Scanlon and Sahu (2008).

Despite the relative complexity of its implementation, this flux partitioning technique is based on the extremely simple concept that flux-variance similarity applies separately to the stomatal and non-stomatal portions of the fluxes. Analytical complexity arises as a result of the need to explore parameter space and apply constraints to ultimately identify the magnitudes of the flux components. Large-scale factors such as entrainment or non-stationarity that potentially influence the time series statistics are dealt with through wavelet filtering, a step that is described in Section 2. Such scale issues were the main focus of Scanlon and Sahu (2008), in which the flux partitioning procedure was implemented for the limited timeframe of two days. Here, the method is extended to the timeframe of an entire growing season and the partitioned fluxes are evaluated with respect to independently measured biophysical variables.

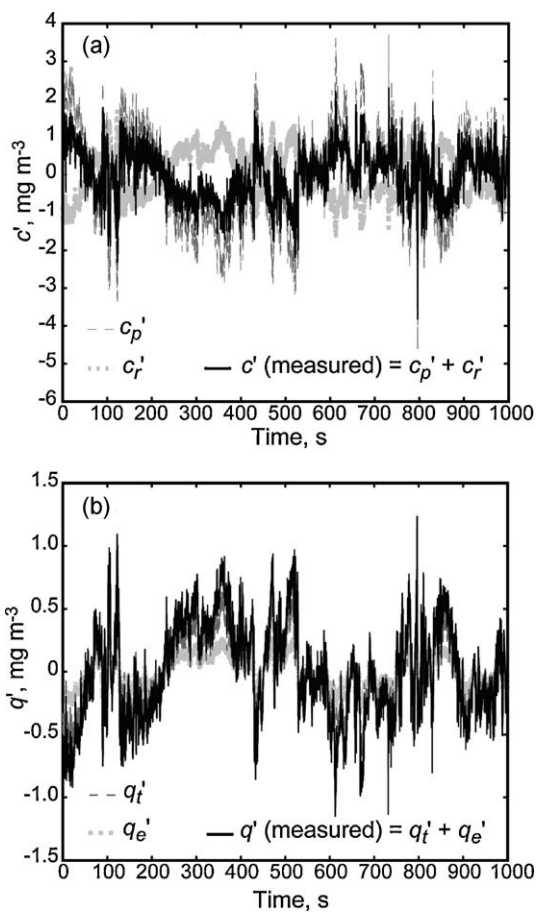

Fig. 2. Hypothetical time series showing how measured Reynolds-averaged concentrations can be decomposed into fluctuations associated with constituent fluxes. (a) Perturbations from the mean carbon dioxide concentrations, c', are caused by fluctuations associated with photosynthesis, c'_p, and respiration, c'_r. These fluctuations have a general negative correlation. (b) Perturbations from the mean water vapor concentrations, q', are caused by fluctuations associated with transpiration, q'_t, and direct evaporation, q'_e. These fluctuations have a general positive correlation.

2. Methods

2.1. Field methods

Eddy covariance data used in this study were collected at the Optimizing Production Inputs for Economic and Environmental Enhancement (OPE^3) site located at the USDA-ARS Beltsville Area Research Center in Beltsville, Maryland. The relatively homogeneous vegetation cover consisted of cultivated maize in the area surrounding the micrometeorological tower, having a minimum fetch of 200 m in the southeast direction. Maize was planted on June 26 during the 2008 growing season and reached maturity by late August. Surveys of the maize made throughout the growing season tracked the crop height (h_o) and leaf area index (LAI) measured by a LAI2000 light meter on repeatable transects generally upwind of the flux tower site. Between survey dates, we estimate h_o and LAI by linear interpolation. Eddy covariance time series used in the present analysis commenced on June 28 and ended on August 24, thereby covering the full range of crop growth stages throughout the season.

Key instrumentation at the site included a three-dimensional sonic anemometer (CSAT3, Campbell Scientific Inc.) and infrared gas analyzer (LI-7500, LI-COR), which were placed at a height of 4 m above the ground surface. The former measured coordinate wind speeds and air temperature while the latter measured carbon dioxide and water vapor concentrations, all of these at a frequency of 10 Hz. Other relevant instrumentation on the meteorological tower included an incoming photosynthetically active radiation (PAR) radiometer (LI 190SA, LI-COR) and a tipping bucket rain gage (TE525, Texas Instruments). Soil temperature was measured at a depth of 0.02 m with a Type-T thermocouple. For a description of the full range of instrumentation at the OPE^3 site, see Crow et al. (2008).

2.2. Data analysis

The flux partitioning procedure was applied to half-hour time series collected during the daytime, as defined by periods when downwelling shortwave radiation was greater than 10 W m^{-2}. During the nighttime, it is assumed that F_c consists solely of respiration, while the low levels of F_q consist of some combination of transpiration, direct evaporation, and condensation. The first step in the time series analysis is to adjust for density fluctuations that can arise due to external factors such as temperature and water vapor, as accounted for in flux calculations by the Webb et al. (1980) correction. We used the approach of Detto and Katul (2007) to adjust the 10-Hz time series of c' and q', a necessary step for computing higher-order statistics associated with these signals.

Wavelet filtering is applied to remove low-frequency information from the time series, which can be introduced by large-scale processes associated with entrainment or non-stationarity. Such large-scale processes do not typically contribute much to the eddy covariance-derived fluxes but can significantly influence $\rho_{c,q}$ (Scanlon and Sahu, 2008). Each half-hour time series was truncated to consider only the first 27.31 min (=2^{14} samples), since orthonormal wavelet transforms are applied most efficiently on a dyadic basis. For each time series we used the Haar wavelet to remove the first two wavelet levels, which correspond to eddy diameters on the order of 10^3–10^4 m. With this low-frequency information removed, we apply the flux partitioning procedure outlined above to the filtered time series of c' and q'. If no solution is attained, then we remove the next wavelet level to further reduce the influence of large-scale processes such that the c' and q' time series are solely governed by vegetation-atmosphere exchange, as assumed by theory (Fig. 1). Scanlon and Sahu (2008) showed that scalar statistics describing this exchange, such as the ratio F_c/F_q, are remarkably consistent over a wide range of small to intermediate eddy scales. Wavelet levels are progressively removed until a solution is reached (in some cases, however, no solution is reached). We recover the originally measured fluxes, $\overline{w'q'}$ and $\overline{w'c'}$, by assuming that the "missing" portion of the fluxes (due to its removal by the high-pass wavelet filtering) has a composition that is proportional to that determined from the remainder of the data.

Leaf-level water use efficiency, *WUE*, is the only parameter needed to implement the flux partitioning procedure. In the absence of leaf-level measurements, we employ a relatively simple approach to estimate *WUE* from gradient considerations. According to Campbell and Norman (1998), *WUE* (mg g^{-1}) can be estimated as:

$$WUE = 0.7\frac{\overline{c_s} - \overline{c_i}}{\overline{q_s} - \overline{q_i}} \tag{11}$$

where the coefficient 0.7 accounts for the differences in diffusion and convection between water vapor and carbon through the stomatal aperture, and the subscripts "s" and "i" relate to the within-canopy and inter-stomatal values, respectively, of c and q. We estimate $\overline{c_s}$ and $\overline{q_s}$ at the displacement height (=2/3 h_o) by considering logarithmic mean concentration profiles with stability corrections (Brutsaert, 1982), and determine $\overline{c_i}$ using the relationship $c_i = 0.44c_s$, which is drawn from leaf-level measurements of maize (Kim et al., 2006). Values of $\overline{q_i}$ were estimated based on 100% relative humidity at foliage temperature, T_L. We did not calculate T_L by considering mean profiles because the sensible heat flux is influenced by both the vegetated and bare soil components of the land surface, which could lead to an overestimation of T_L. Instead, we approximated T_L as being equivalent to the measured air temperature, T_a. Direct measurements of T_L would be preferable where available, as we note that this approximation would be less appropriate during times of vegetation stress. Alternative approaches for estimating *WUE* could certainly be used in conjunction with the flux partitioning procedure, especially in settings were auxiliary measurements may facilitate its estimation.

The partitioning procedure for the carbon dioxide and water vapor fluxes relies solely upon direct measurements of c' and q' time series, plus estimates of *WUE*. These limited number of inputs aids independent comparison with other measured biophysical variables. We evaluate the partitioning results for the carbon dioxide fluxes with respect to LAI, PAR, and soil temperature and examine how the relative magnitudes of transpiration and direct evaporation vary through time following precipitation events.

3. Results

Over the course of the growing season, $\rho_{c,q}$ is strongly influenced by the status of the vegetation and its role in governing carbon dioxide and water vapor exchange. Daytime values of $\rho_{c,q}$ calculated after the removal of the first two wavelet levels (which contain low-frequency information) are close to +1 at the beginning of the growing season when respiration and direct evaporation fluxes dominate (Fig. 3). As the LAI of the maize increases, the correlation coefficient rapidly transitions toward −1 as the land surface becomes a net sink for carbon dioxide. Scatter that exists in $\rho_{c,q}$ time series is due primarily to the impact of large-scale processes that are separate from the land-atmosphere exchange associated with the maize field. This illustrates the need for wavelet filtering beyond the first two wavelet levels, as is sometimes implemented as part of the flux partitioning procedure.

Carbon dioxide fluxes measured by eddy covariance were positive at the onset of the growing season, indicating that respiration fluxes were dominant throughout the early emergence

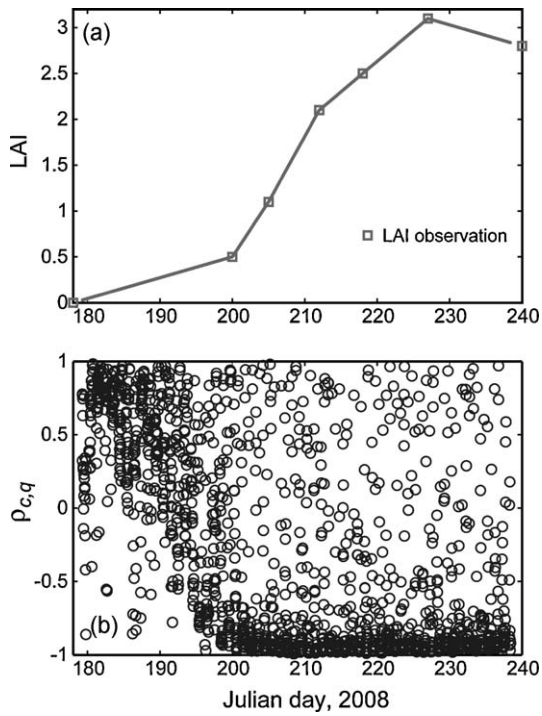

Fig. 3. (a) Time series of leaf area index (LAI) for the maize over the growing season, with linear interpolation between field-based observations. (b) Correlation coefficient between carbon dioxide and water vapor concentrations, $\rho_{c,q}$, for each half-hour time series measured during the daytime. Wavelet filtering applied to the time series removed the first two wavelet levels, which contain information associated with eddies on the order of 10^3–10^4 m.

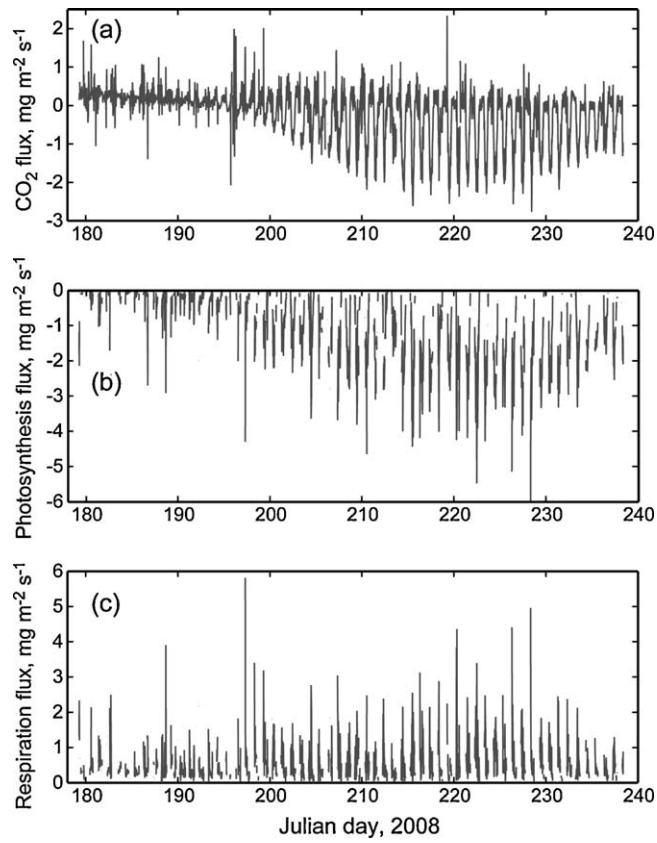

Fig. 4. (a) Measured carbon dioxide fluxes, and (b) photosynthesis fluxes and (c) respiration fluxes determined by the separation procedure. All fluxes are calculated on a half-hourly basis.

of the maize crop (Fig. 4a). By Julian day 200, daytime fluxes were negative as photosynthetic uptake rates began to exceeded respiration losses. The vegetated surface became more and more of a carbon dioxide sink until around day 220, after which the sink strength diminished. By the end of the growing season, field surveys reported that the maize showed signs of wilting. Flux partitioning results reveal that the photosynthesis component followed a similar trend to that of F_c (Fig. 4b), peaking in magnitude at about the same time and diminishing toward the end of the growing season. Partitioning results for respiration (Fig. 4c) show more stable temporal dynamics, with no obvious changes throughout the growing season.

Measured water vapor fluxes also appear to be influenced by the maize growth, although the contrast between the early and late growing season is not as pronounced as that for the carbon dioxide fluxes (Fig. 5a). Evapotranspiration is substantial in the early portion of the growing season, even in the absence of significant vegetation cover. Flux partitioning reveals an overall increase in transpiration throughout the growing season that tracks the maize LAI (Fig. 5b). Direct evaporation exhibits ramp-like patterns (Fig. 5c), with sudden increases followed by multiple days of decreasing evaporation.

Partitioning results for the half-hour fluxes are shown in greater detail for sequences of several days in Fig. 6. Changes in the composition of the measured water vapor fluxes are evident over the course of the growing season. Shortly following planting, direct evaporation accounts for the vast majority of the water vapor flux (Fig. 6a), but its relative contribution becomes less during the early to middle portions of the growing season (Fig. 6b), and an even less during the late growing season (Fig. 6c). Photosynthesis fluxes are found to be close to zero during the post-planting period and increase in magnitude with greater crop biomass. Respiration fluxes derived from the partitioning procedure during the daytime are generally higher than those measured directly during the nighttime, and this contrast tends to increase throughout the growing season. Some scatter is observed in the flux partitioning results, most commonly during the early morning and late evening periods when the measured fluxes are small. Also apparent from Fig. 6 are half-hour periods when no flux partitioning solutions are obtained, such as a stretch during day 183. For the entire growing season, this was the case for 22% of the half hours to which the partitioning procedure was applied. Due to the quadratic nature of (10), multiple solutions are sometimes encountered, which resulted in an additional 1.4% of the half hours being discarded.

3.1. Carbon dioxide flux results

We evaluate the results of the flux partitioning procedure by placing them in the context of independently measured biophysical variables. For the photosynthesis fluxes, we determine the canopy light use efficiency, α_G, as the ratio of $F_{\text{photosynthesis}}$ to PAR. Fig. 7 shows the mean daily values of α_G, calculated as the geometric mean of the half-hourly ratios observed within each day. Consistent with expectations, α_G ramps up throughout the growing season, closely following LAI (Fig. 3a). Toward the end of the growing season as the maize showed signs of wilting, α_G drops off more rapidly than can be explained by LAI alone. Scatter in α_G is expected due to the differences in the apportioning of direct versus diffuse radiation, but we do not have measurements to confirm that the scatter observed in Fig. 7 can attributed to this factor. Using traditional methods of determining gross primary productivity (GPP) based on extrapolating respiration rates from nighttime flux measurements, Suyker et al. (2005) found that α_G peaked at around 0.43 μmol μmol^{-1} for rainfed maize, and reported

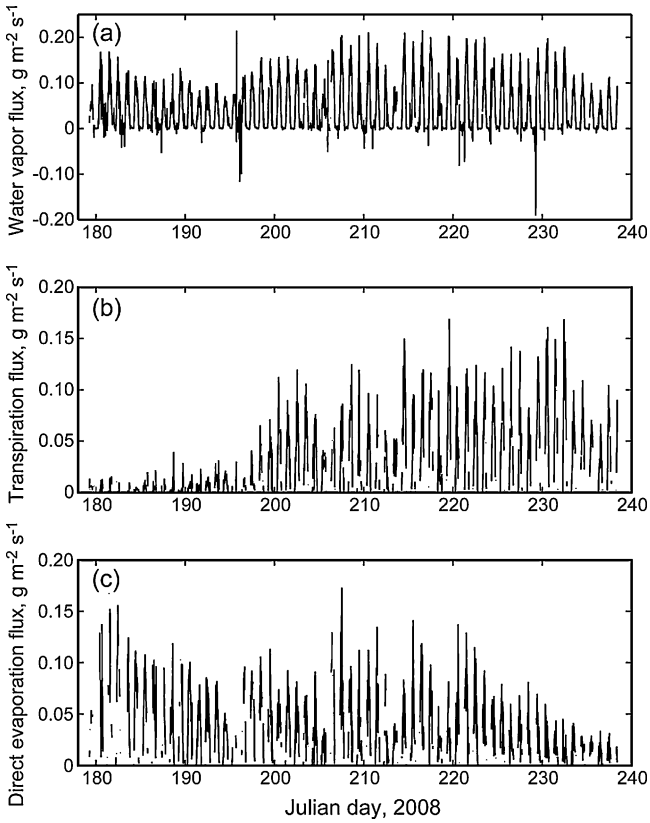

Fig. 5. (a) Measured water vapor fluxes, and (b) transpiration fluxes and (c) direct evaporation fluxes determined by the separation procedure. All fluxes are calculated on a half-hourly basis.

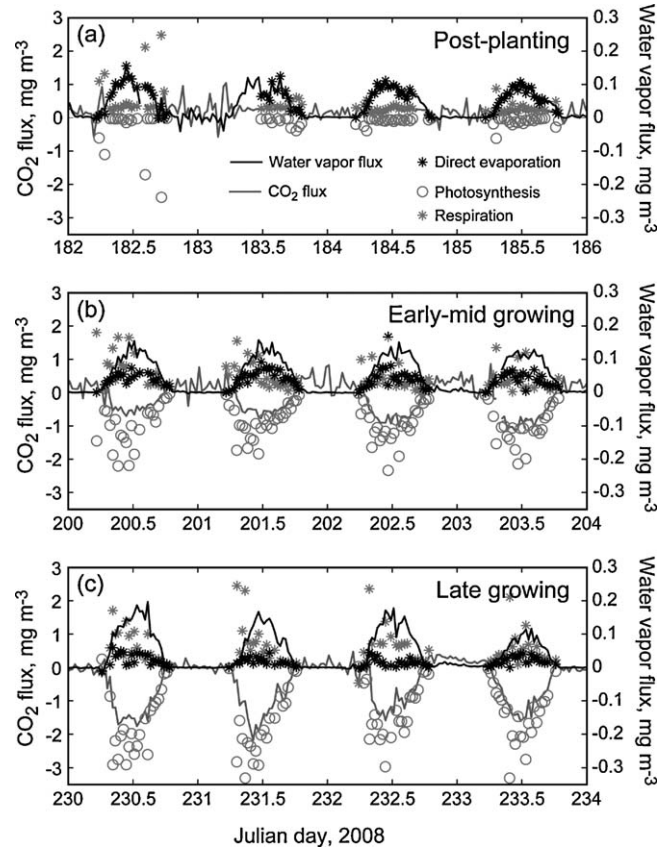

Fig. 6. Partitioning results for the half-hourly fluxes, showing selected periods from (a) post-planting, (b) early to mid growing season, and (c) late growing season.

literature values ranging from 0.43 to 0.50 μmol μmol^{-1}. Loomis and Amthor (2005) suggested a theoretical maximum of 0.60 μmol μmol^{-1} for this value, which is met or slightly exceeded for some of the days during the peak growing season.

Confidence in the accuracy of the partitioned photosynthesis fluxes implies confidence in the partitioned respiration fluxes since the latter is the residual between the measured carbon dioxide fluxes and the photosynthesis fluxes. Soil temperature (T_s) and volumetric soil moisture (θ), the two variables typically used to develop empirical relationships for respiration fluxes, are shown in Fig. 8a. Soil temperatures were lower in the second half of the growing season (despite increased air temperatures) due to the presence of the above-ground biomass and its effect of reducing the radiation that reaches the soil surface. Measurements of respiration during the nighttime were plagued by low wind speeds, as only 17% of the half-hour periods met the modest friction velocity ($u*$) threshold of 0.1 m s^{-1}, while only 6% met the more stringent threshold of 0.2 m s^{-1}. Analysis of the nighttime flux data indicated that this higher threshold was perhaps warranted, but we settled on a threshold of 0.1 m s^{-1} in the interest of maintaining a sufficient quantity of data for display. Fig. 8b shows the mean nighttime respiration fluxes throughout the growing season. Missing values are common in the latter half of the growing season, corresponding to nights when none of the half hours exceeded the 0.1 m s^{-1} $u*$ threshold. Relationships between nighttime respiration rates and biophysical drivers such as T_s and θ are not obvious and indeed are not statistically significant ($p > 0.05$).

Mean daytime respiration fluxes, as derived by the partitioning analysis, are shown in Fig. 8c. A general increase in respiration is observed throughout the growing season, a large portion of which can be accounted for by increases in autotrophic respiration associated with the increased plant biomass. For reference, estimates of autotrophic respiration are added to Fig. 8c as the sum of modeled maintenance and growth respiration (Appendix A). Heterotrophic respiration then corresponds to the dark shaded portions of the bars in this figure. A feature of the respiration time series derived from the daytime eddy covariance measurements is the existence of transient increases in respiration in the days following rainfall events (the timing of these events is indicated by the stars above Fig. 8c). No such response is detected from the nighttime data (Fig. 8b).

3.2. Water vapor flux results

Daily rainfall over the course of the growing season is shown in Fig. 9a, and partitioning results for transpiration and direct evaporation are shown in Fig. 9b, expressed as a fraction of the

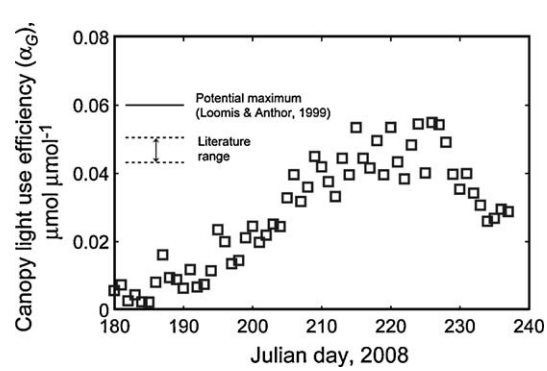

Fig. 7. Canopy light use efficiency, α_G, calculated at the daily time step throughout the growing season. Also shown are literature-based ranges and the potential maximum α_G.

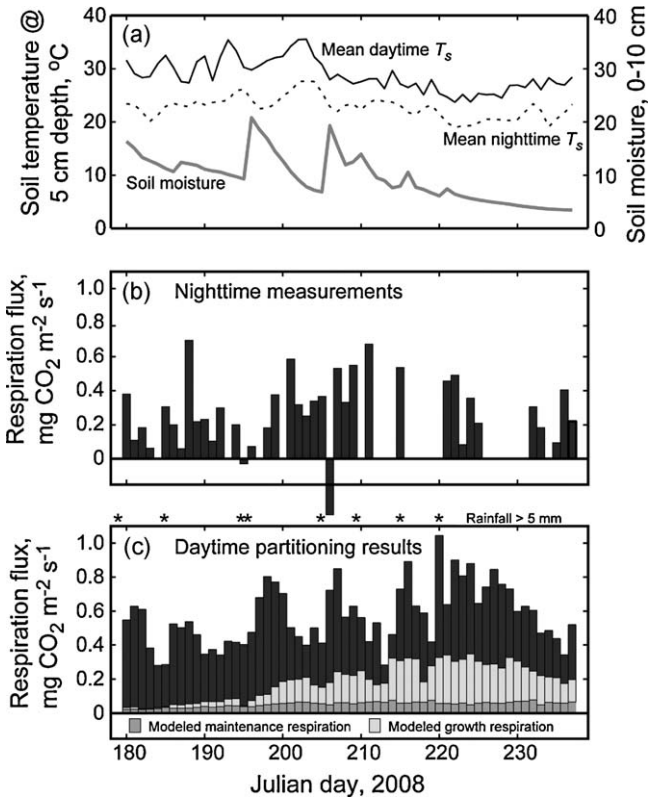

Fig. 8. (a) Daily time series of mean daytime and nighttime soil temperatures measured at a depth of 5 cm below the surface, and volumetric soil moisture averaged over 0–10 cm below the surface. (b) Mean nighttime fluxes, as calculated with a u_* threshold of 0.10 m s^{-1}. Missing data indicate nights that lacked half hours when the u_* threshold was exceeded. (c) Mean respiration fluxes during the daytime, as determined by the flux partitioning procedure. Also shown are model estimates of maintenance and growth respiration. Peaks in respiration tend to occur following rainfall, as indicated by the stars above this time series.

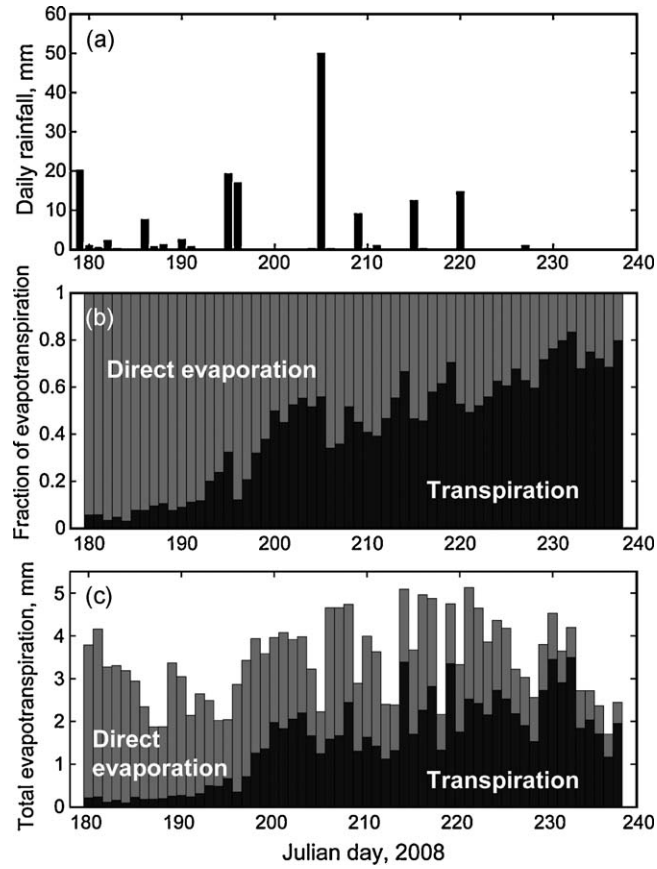

Fig. 9. (a) Daily hyetograph. (b) Fraction of the measured daytime evaporation attributed to transpiration and direct evaporation, as determined by the flux partitioning procedure. (c) Magnitudes of the evapotranspiration components throughout the growing season, as determined by the flux partitioning procedure.

measured evapotranspiration. Partitioning results are consistent with the expected shift in the dominance from direct evaporation at the beginning of growing season to transpiration in the latter portion of the growing season as the maize leaf area increases. The partitioning results also appear to pick up the impact of individual rainfall events, as for each event there is an increased fraction of the evapotranspiration that derives from direct evaporation, which comes at the expense of the fractional contribution from transpiration (Fig. 9b). Magnitudes of daily transpiration and direct evaporation, which sum to total evapotranspiration, are shown in Fig. 9c. Atmospheric forcing, soil moisture, and leaf area are among the factors that contribute to the observed variability in these daily totals.

Focusing on the direct evaporation, we evaluate this time series with respect to its behavior over the course of a dry-down period. We select the only extended stretch of time that lacks significant rainfall, the two-and-a-half week period following the 14.7-mm event on day 220. According to the two-stage theory of evaporation from bare soils (see, for example, Brutsaert, 2005), evaporation during the first stage after wetting is limited by atmospheric demand, followed by a transition to a second stage in which evaporation is limited by the supply of water the to surface. During this second stage, cumulative evaporation, $\sum E_2$, is expected to proceed through time according to:

$$\sum E_2 = \mathrm{De}_0 t^{1/2}, \tag{12}$$

(Brutsaert and Chen, 1995), where De_0 is known as the capillary desorptivity, and t is time since the onset of the second stage of evaporation. Since the water content of the sandy loam soil is initially low (Fig. 8a), we follow Black et al. (1969) and Parlange et al. (1992) by dispensing with the first stage and assume that the second stage begins immediately after the rainfall, on day 221. Cumulative direct evaporation is plotted as a function of $t^{1/2}$ in Fig. 10, which exhibits good agreement with (12). Also plotted is cumulative transpiration, which diverges substantially from a

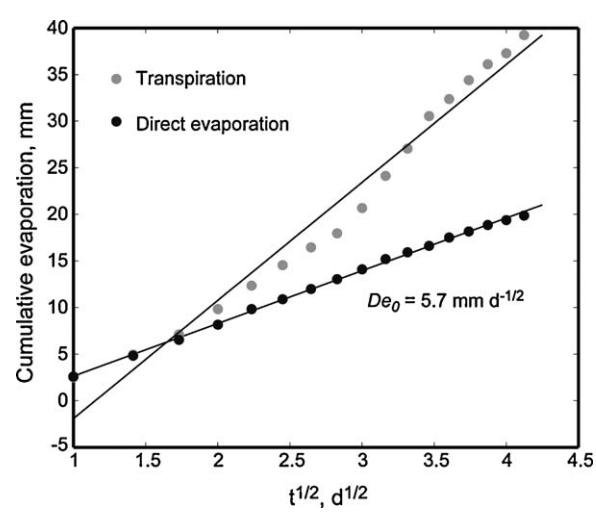

Fig. 10. Cumulative transpiration and direct evaporation as a function of time to the one-half power. Direct evaporation conforms to this theoretical expectation, while transpiration does not.

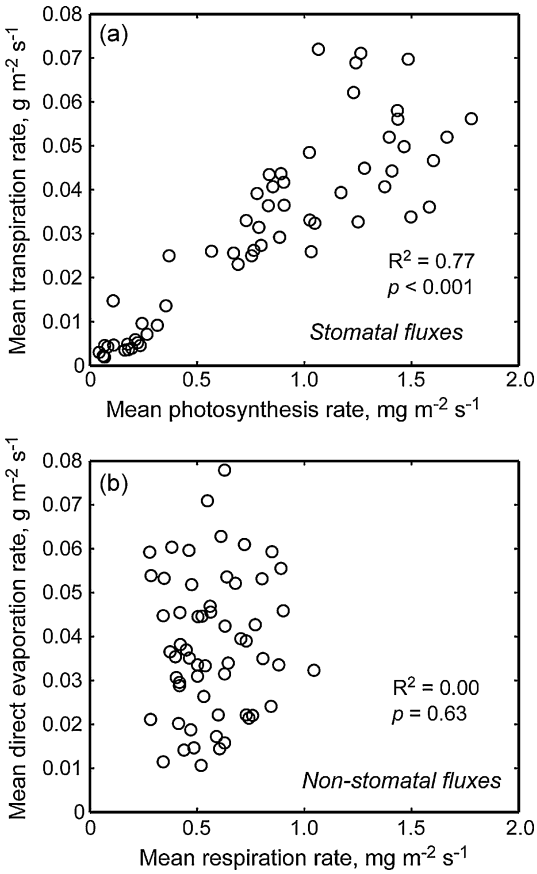

Fig. 11. (a) Mean daily transpiration rate versus mean daily photosynthesis rate. (b) Mean daily direct evaporation rate versus mean daily respiration rate. Flux-variance similarity applied to the high-frequency data does not imply perfect correlations between fluxes at the half-hour or daily time scales.

straight-line fit. There is no reason to expect that (12), which was derived for bare soil evaporation, would be appropriate for describing the transpiration dynamics during the dry-down period. Based on the regressed relationship, De_0 associated with the partition-derived direct evaporation had a value of 5.7 mm day$^{-1/2}$, which we note is similar to the value of 5.8 mm day$^{-1/2}$ determined by Parlange et al. (1992) from a bare soil lysimeter experiment conducted in an irrigated field and is within the range of other experimentally derived values as summarized by Kustas (2002).

4. Discussion

Results yielded by the correlation-based partitioning approach are consistent with expected trends throughout the growing season, as photosynthesis and transpiration fluxes increase in parallel with observed increases in maize leaf area. Magnitudes of the fluxes are also found to be reasonable, as mean daily light use efficiencies derived from the photosynthesis flux reach levels comparable to those reported in the literature (Fig. 7). Respiration fluxes determined during the daytime exhibit a general increase throughout the growing season, counter to decreasing trends in soil temperature and soil moisture. This somewhat surprising result can be readily explained, however, by increases in autotrophic respiration associated with the increasing vegetation biomass (Fig. 8). The trajectory of the decline in direct evaporation during a dry-down period is consistent with theory and is in good agreement with prior measurements of bare soil evaporation (Fig. 10). Short-term, transient features are also detected by the partitioning procedure, as both respiration and direct evaporation fluxes are found to respond to wetting events (Figs. 8 and 10). Such comparisons of the flux separation results with independently measured variables cannot be considered to be true "validation" of the procedure, but these do lend support to the validity of the theory-based flux partitioning approach.

Limitations of traditional methods for partitioning NEE are evident from the eddy covariance time series analyzed in the present study. Low nighttime turbulence is a problem that was encountered throughout much of the growing season, which resulted in the elimination of 83% of the nighttime flux data, even with the use of a relatively low u_* threshold of 0.10 m s^{-1}. Remaining data display a great deal of scatter (Fig. 8b), which impedes the development of significant relationships between respiration fluxes and commonly used variables such as soil temperature and soil moisture. An alternative strategy is to use daytime eddy covariance data to establish light response curves, from which respiration rates may be derived (e.g., Lee et al., 1999; Gilmanov et al., 2003), but a large number of days are needed to generate any relationships between the respiration fluxes and soil or air temperatures, and within-day variability in respiration can lead to errors. A confounding factor relevant to both daytime- and nighttime-based regression techniques is the dynamic nature of the vegetation cover and its effect upon respiration fluxes. Autotrophic respiration, which accounts for a significant portion of the respiration fluxes, increases throughout the growing season (Fig. 8c). Regression approaches used to partition NEE at this setting could therefore be adversely affected by this non-stationary component of the respiration fluxes. Other potential drawbacks of estimating flux components through extrapolation of regressed relationships, apart from these site-specific issues, have been well documented (e.g., Reichstein et al., 2005; Stoy et al., 2006).

Field-based measurement techniques have also been widely employed to partition carbon dioxide and water vapor fluxes. A practical advantage of the technique described here, which sets it apart from these previous approaches, is that no additional equipment is needed beyond standard eddy covariance flux instrumentation. From a conceptual standpoint, the correlation-based approach also has the advantage of being relatively straight forward. The theoretical underpinnings of this approach can be reduced to the primary assertion that flux-variance similarity theory applies separately to the stomatal and non-stomatal portions of the fluxes. It should be noted that the assumption of perfect correlation of the high-frequency time series (Fig. 1) does not imply that the fluxes themselves are perfectly correlated. Fig. 11 shows the relationships between the components of the carbon dioxide and water vapor fluxes at the daily time scale. The stomatal fluxes, which are related through the water use efficiency (*WUE*), are significantly correlated (Fig. 11a), while the non-stomatal fluxes are not (Fig. 11b). With regard to the latter, the respiration and direct evaporation fluxes both respond to wetting events, but their opposite trends throughout the growing season have the effect of eliminating any significant correlation.

Implicit in the assumption that flux-variance similarity applies to stomatal fluxes is that *WUE* is constant throughout each half-hour period. Although *WUE* can change from one half hour to the next depending upon leaf temperature and ambient $\overline{c_s}$ and $\overline{q_s}$ as in (11), the partitioning approach requires *WUE* to remain at a fixed value for each high-frequency time series that is analyzed. This constraint may be particularly problematic for applying this procedure to settings where, for example, heterogeneity is present in the vegetation composition. Another example of a setting in which the assumption of a unique *WUE* would not be met is a forested site that has a significant understory. In such a setting, vertical gradients in air temperature, $\overline{c_s}$, and $\overline{q_s}$ could lead to significant differences in *WUE* between the understory and the

overlying vegetation. We apply the partitioning technique to measurements collected over a maize field, which is relatively ideal in terms of promoting compliance with theoretical assumptions. Extending this analysis to flux data collected over non-ideal vegetation would demand careful consideration as to how deviations from these assumptions could influence the accuracy of the partitioning estimates.

Traditional application of similarity theory would not account for the spatial offset in source/sink distributions for the stomatal versus non-stomatal fluxes, as we do here. As such, our adaptation of similarity theory represents a conceptual improvement over traditional applications. Yet the assumptions of perfect correlations for these individual components, as illustrated in Fig. 1 and given in Eq. (6), inevitably fall short of being strictly satisfied in real settings. Aside from the factors mentioned above for the stomatal fluxes, the non-stomatal fluxes may depart from flux-variance similarity due to the sources of respiration and evaporation being both the soil surface and canopy, with relative contributions from each being unequal. The fact that the non-stomatal transport is strongly controlled by aerodynamic processes that vent the sub-canopy air space would push ρ_{c_r,q_e} close to +1, but conformity to flux-variance similarity would remain imperfect. Like all methods used for flux separation, certain assumptions and approximations are required. The theoretical framework outlined in Sections 1.2 and 1.3 is idealized to a certain extent. Strict adherence to flux-variance similarity is elusive, even when modified as we have done to account for similarity arising from multiple sources.

Aside from serving as an independent basis for separating measurements of NEE into photosynthesis and respiration, the partitioning technique has a number of other potentially useful applications. For instance, it could compliment flux-gradient methods that employ stable carbon isotopes by improving estimates of canopy conductance, g_c, a necessary parameter for implementing this method (Zhang et al., 2006). Typically g_c is derived through inversion of the Penman–Monteith equation. Due to lack of additional information, this inversion process usually considers total evapotranspiration rather than just the transpiration component, as would be more appropriate for calculating the stomatal-controlled g_c.

Partitioning of water vapor fluxes has almost exclusively relied upon additional in situ measurements such as sap flow sensors, evaporation chambers, or microlysimeters (Moran et al., 2009), due to the lack of techniques that are based solely on eddy covariance data. Methods analogous to those used for carbon dioxide flux partitioning, in which nighttime eddy covariance data can be extrapolated to the daytime, do not exist. This has resulted in a scarcity of observational evidence used to inform the development of evapotranspiration models, particularly with respect to how they handle direct evaporation (i.e., evaporation from interception stores and bare soil evaporation). Partitioned information can be used to ensure that evapotranspiration models match flux observations for the right reasons, which is needed for reliable extension of these models to areas with different vegetation cover or soil type.

Prior flux partitioning studies have focused on either carbon dioxide or water vapor. We show that by considering the high-frequency behavior of these atmospheric constituents in tandem, we can gain insight about their respective fluxes. Measurements made over a maize field throughout a growing season reveal that c and q time series do not obey flux-variance similarity, but it is this departure from perfect correlation that allows us partition the fluxes by adopting a framework of flux-variance similarity for both the stomatal and non-stomatal processes. In doing so, we demonstrate an ability to partition long-term flux measurements through the analysis of standard eddy covariance data.

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Appendix A. Maintenance and growth respiration calculations

Components of autotrophic respiration were calculated separately as maintenance (R_m) and growth (R_g) respiration. Maintenance respiration, which supports turnover of protein, is calculated based on the nitrogen content of foliage, stem, and roots (Choudhury, 2000). Lafitte and Loomis (1988) suggest the relationship for R_m (mol CO_2 m^{-2} day^{-1}) at 20 °C:

$$R_m = 2.1 \times 10^{-4}(n_l + n_s + 2n_r) \tag{A1}$$

where n_l, n_s, and n_r refer to the nitrogen content in leaf, stems, and roots, respectively (mmol N m^{-2}). In the absence of field measurements at our study site, we developed regressed relationships from data reported by Qinxue et al. (2005), who tracked LAI and carbon content and C:N ratios for separate components of a maize crop over a growing season. These were:

$$\begin{aligned} n_l &= 19.5\ln(\mathrm{LAI}) + 85.0 \\ n_s &= 34.9\ln(\mathrm{LAI}) + 130.9 \\ n_r &= 11.6\ln(\mathrm{LAI}) + 50.6 \end{aligned} \tag{A2}$$

The temperature dependency of R_m is accounted for by:

$$R_m(T) = R_m(T = 20)Q_{10m}^{(T-20)/10} \tag{A3}$$

where Q_{10m} is assumed to be equal to 2 (Amthor, 1989), T is taken as the air temperature, and R_m is calculated for each half hour.

Growth respiration is a function of gross photosynthesis, A_g, which we determine at the daily timescale by summing the partitioning-derived photosynthesis fluxes (light use efficiency is used to fill in missing half hours). R_g (mol CO_2 m^{-2} day^{-1}) is calculated at each half hour according to:

$$R_g = (1 - Y_g)\{A_{gd}(T) - R_m(T)\} \tag{A4}$$

where Y_g is the growth conversion efficiency, taken as 0.74 for the maize crop (Choudhury, 2000), and $A_{gd}(T)$ is the gross photosynthesis rate distributed throughout the entire day according to a Q_{10} function, as suggested by Dufrêne et al. (2005), where Q_{10g} is assumed to be 2.

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