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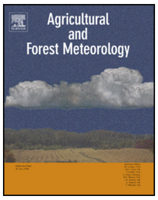

Inferring the contribution of advection to total ecosystem scalar fluxes over a tall forest in complex terrain

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ABSTRACT

Multiple data streams from a new flux tower located in complex and heterogeneous terrain at the Coweeta Hydrologic Laboratory (North Carolina, USA) were integrated to identify periods of advective flow regimes. Drainage flows were expected a priori, due to the location of the measurement site at the base of a long, gently-sloping valley. Drainage flow was confirmed by examining vertical profile measurements of wind direction and by estimating vertical advection fluxes. The vertical advection flux of CO_2 was most significant in early morning (000–0600 h) during the growing season, when it averaged $\sim 5\ \mu mol\ m^{-2}\ s^{-1}$. Horizontal advection flux of CO_2 was not directly measured in this study; however, an expected exponential relationship between nocturnal ecosystem respiration (RE) and air temperature was recovered when horizontal advection of CO_2 was assumed to be negatively correlated to vertical advection, or when data were limited to periods when measured vertical advection fluxes were small. Taken together, these data imply the presence of a negative horizontal advection CO_2 flux during nocturnal periods characterized by positive vertical advection of CO_2. Daytime periods were characterized by consistent anabatic (up-valley) flows in mid- to late-morning (0500–1200 h) and consistent katabatic (down-valley) flows in the afternoon. A combination of above-canopy flux profile measurements, energy balance closure estimates, and flux footprint estimates suggest that during periods of up-valley wind flow, the flux footprint frequently exceeds the ecosystem dimensions, and horizontal advection fluxes related to landscape heterogeneity were a significant component of the total ecosystem flux of CO_2. We used sap flux from individual trees beneath the tower to explore diurnal patterns in stomatal conductance in order to evaluate gapfilling approaches for the unreliable morning data. The relationship between stomatal conductance and vapor pressure deficit was similar in morning and afternoon periods, and we conclude that gapfilling morning data with models driven by afternoon data is a reasonable approach at this site. In general, results were consistent with other studies showing that the advection and wind flow regimes in complex terrain are highly site specific; nonetheless, the site characterization strategy developed here, when used together with independent estimates of components of the ecosystem carbon flux, could be generally applied in other sites to better understand the contribution of advection to the total ecosystem flux.

1. Introduction

The eddy covariance technique permits quasi-continuous monitoring of biosphere-atmosphere scalar fluxes directly at the ecosystem scale for long periods of time (Baldocchi, 2008; Friend et al., 2007). In most applications, the net ecosystem flux of the scalar of interest is linked to the vertical turbulent flux measured above the canopy and a storage flux estimate derived from the temporal change in within-canopy scalar concentration (Aubinet, 2008; Baldocchi, 2003). Turbulent and storage fluxes may be observed from a single measurement tower, promoting the development of an extensive network of more than 400 flux monitoring towers across a range of biomes (Baldocchi, 2008). Collectively, these data have promoted significant knowledge advancements related to the process-based controls on ecosystem carbon and water cycling and dynamic interactions between the biosphere and the atmosphere (Baldocchi, 2008; Falge et al., 2002; Friend et al., 2007; Krinner et al., 2005; Law et al., 2002; Williams et al., 2009). However, due

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to methodological challenges that complicate the interpretation of data collected from heterogeneous or complex terrain, the network has historically been biased toward flat, homogeneous sites. Following a brief review of the theory governing the interpretation of data from eddy covariance flux towers, we discuss these challenges and outline an approach for characterizing fluxes in heterogeneous and complex terrain relying on data collected from a single tower.

Following Feigenwinter et al. (2010a), and assuming negligible horizontal flux divergence, the total flux of a scalar from an ecosystem (F_S) may be expressed as:

$$F_S = \underbrace{\int_0^L \int_0^L \int_0^{z_r} \frac{\partial \overline{\rho_S(z)}}{\partial t} dz}_{\text{Term I}} + \underbrace{\overline{w'\rho'_S}(z_r)}_{\text{Term II}} + \underbrace{\int_0^{z_r} \overline{w(z)} \frac{\partial \overline{\rho_S(z)}}{\partial z} dz}_{\text{Term III}}$$

$$+ \underbrace{\frac{1}{4L^2} \int_{-L}^{L} \int_{-L}^{L} \int_0^h \left(\frac{\overline{u(z)} \partial \overline{\rho_S(z)}}{\partial x} + \frac{\overline{v(z)} \partial \overline{\rho_S(z)}}{\partial y} \right)}_{\text{Term IV}} \qquad (1)$$

where u, v, and w represent wind speeds in the x, y, and z directions, respectively, ρ_s is the mass density of the scalar, and z_r is the flux measurement height and the height of a representative control volume over which F_S is calculated. The variable L represents the length of the sides of the control volume, and h is the canopy height. The first term on the right hand side (Term I) represents the storage flux, or the change in concentration with time, integrated from $z = 0$ to z_r. This storage flux is negligible over daily and longer time-scales; at finer temporal resolutions, it may be estimated from vertical profile measurements of CO_2. Term II represents the vertical turbulent flux, which may be measured using the eddy covariance technique with a sonic anemometer and fast-response gas analyzer co-located above the canopy. Term III represents the vertical advection of the scalar into or out of the control volume by a non-zero mean vertical wind velocity ($\overline{w(z)}$). In most cases, $\overline{w(z)}$ is assumed to be zero, such that vertical advection of the scalar is also assumed to be zero; however, estimates of the vertical advection flux occurring during periods of non-negligible $\overline{w(z)}$ can be derived from scalar profile measurements and wind profile measurements on a single tower (Lee, 1998; Leuning et al., 2008). Term IV represents the horizontal advection of the scalar into or out of the control volume, generated primarily by horizontal gradients in scalar source intensity or surface roughness (Baldocchi et al., 1999). Horizontal advection is difficult to measure and requires an array of towers (Aubinet et al., 2010; Feigenwinter et al., 2008). In most sites, the land surface around the tower is usually assumed to be horizontally homogeneous, such that horizontal advection fluxes are also negligible. With these assumptions, F_S reduces to the sum of the vertical turbulent flux (Term II), which may be augmented by storage flux estimates (Term I) at hourly time scales.

The interpretation of the sum of vertical turbulent fluxes and storage fluxes as representative of the total ecosystem flux is challenged whenever the assumptions of negligible vertical and horizontal advection (i.e., Terms III and IV), or negligible horizontal flux divergence, are invalidated. The contribution of advection fluxes to the total ecosystem flux is likely greatest in (a) heterogeneous sites where horizontal advection is driven by scalar gradients associated with land cover transitions, and (b) sites characterized by complex topography where vertical wind speed is often non-negligible and elevation gradients produce horizontal gradients in wind and scalar fields.

A growing number of flux monitoring sites are situated in complex or heterogeneous terrain (Baldocchi et al., 2000; Feigenwinter et al., 2008; Gockede et al., 2004; Kutsch et al., 2008; Rebmann et al., 2005; Yi et al., 2005). Furthermore, a growing body of work suggests that advection may often be non-negligible even in relatively 'flat' sites (Feigenwinter et al., 2010a; van Gorsel et al., 2009; Loescher et al., 2006), where even a small vertical wind speed superimposed over a large vertical scalar gradient can produce a significant vertical advection flux. In some experiments, multiple observation towers have been erected to quantify both horizontal and vertical advection fluxes (Staebler and Fitzjarrald, 2004; Sun et al., 2007); in general, results from these studies show that the advection flux regime is highly site specific (Aubinet et al., 2010; Yi et al., 2008), and that the advection flux estimates themselves are characterized by a high level of uncertainty (Aubinet et al., 2010; Loescher et al., 2006). Given these results, and that the cost of erecting multiple above-canopy observation towers is often prohibitive, a multi-tower experimental design may not be a practical approach for accurately measuring advection fluxes. However, knowledge gained from these advection studies, taken together with techniques for estimating vertical advection from a single tower (Lee, 1998; Leuning et al., 2008) and an improved understanding of the components of ecosystem energy balance (Foken, 2008; Lindroth et al., 2010; Wilson et al., 2002) may permit the identification of flux measurements collected during periods when advection is significant (Loescher et al., 2006), even if the magnitude of the advection fluxes is not known with certainty. These data could then be removed from the data records and gapfilled according to a number of established approaches (Reichstein et al., 2005; van Gorsel et al., 2009) that may be augmented with independent biometric observations.

In this study, we applied such a framework in a new eddy covariance site located in heterogeneous and complex terrain near the Coweeta Hydrologic Laboratory in western NC, USA. We used a comprehensive suite of observations collected from a single tower to answer the following question: *Can periods characterized by significant horizontal and vertical advection be identified with observations from a single flux tower, even if the magnitude of their sum is not known?* Specifically, our analysis relied on the following observations and approaches:

(1) Characterization of within- and above-canopy wind flows focused on the occurrence of non-negligible vertical wind speed (a necessary condition for vertical advection) and within-canopy divergence in wind direction (which could indicate a decoupling between above- and below-canopy wind flows).
(2) Characterization of the flux footprint to identify periods when the footprint exceeds the dimensions of the study system, or when land cover heterogeneity near the edge of the footprint may contribute to horizontal advection.
(3) Exploration of vertical advection fluxes determined from observations of the vertical profile of the scalars.
(4) Evaluation of the divergence between fluxes measured at two heights above the canopy, noting that if fluxes measured at two points in the constant flux layer agreed (after correction for differences in storage), then the sum of horizontal and vertical advection fluxes was likely near zero (Baldocchi et al., 2000, Yi et al., 2000), unless horizontal advection was confined to the lower canopy.
(5) Evaluation of the energy balance closure for various wind regimes, noting that poor energy balance closure could indicate significant advection fluxes of latent or sensible heat (Foken, 2008).
(6) Comparison of the carbon fluxes measured above the canopy and in the sub-canopy. At night, the above-canopy fluxes should be greater than sub-canopy fluxes reflecting the contribution of above-ground autotrophic respiration to total ecosystem respiration; however, the ratio of above- to below-canopy carbon fluxes may be decreased if much of the respiration flux is carried away by horizontal advection in the canopy airspace.