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Effects of inhomogeneities within the flux footprint on the interpretation of seasonal, annual, and interannual ecosystem carbon exchange

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ABSTRACT

Carbon flux measurements using the eddy covariance method rely on several assumptions, including reasonably flat terrain and homogeneous vegetation cover. An increasing number of flux sites are located over partially or completely inhomogeneous areas, but the implication of such inhomogeneities on carbon budgets, and particularly the influence of year-to-year variations in wind patterns on annual budgets, remains unclear. Moreover, directional homogeneity of climatic drivers of carbon fluxes is often assumed, although climatic variables vary with wind direction at many locations. In this study, we examined the directional flux characteristics, incorporating the combined effects of variable surface characteristics and climatic drivers on the annual carbon budgets of an evergreen forest. Our study area was characterized by moderate variation in surface characteristics (leaf area index: 1.5–2; topographic wetness index: 4–16), and significant variation in the key drivers of carbon fluxes with wind direction (such as temperature, VPD and turbulence). Interactions among surface characteristics and climatic variables resulted in carbon uptake 'hotspots'. These localized hotspots influenced mean CO_2 fluxes from several wind directions, and were most distinctive during the summer months. Hotspot contributions to yearly budgets varied from year to year, depending on prevailing weather conditions. Consequently, directional variations in flux characteristics affected quarterly estimates of carbon budgets by up to 22%, and annual budgets by up to 25%. We present a procedure to quantify and adjust for the effects of year-to-year variations in directional flux characteristics on interannual comparisons of carbon budgets. Any remaining differences in budgets (after the adjustment) can then be linked more accurately to variations in ecophysiological drivers. Our study clearly highlights that directional variations in flux characteristics can have a significant influence on annual carbon budgets, and that these should be accounted for in interannual comparisons.

1. Introduction

Flux tower measurements are increasingly used to examine in situ carbon and water fluxes in various ecosystems across a broad range of climates. Although the method has been around since the early 1970s, it has gained increasing popularity in recent years due to more automated data processing solutions, which have made it accessible to a wider scientific community. The ultimate goal of many flux tower measurements is to construct multi-year budgets and to determine the key factors affecting interannual variability. Concomitant observational weather data are also used to calibrate environmental models (e.g. Randerson et al., 2009; Keenan et al., 2012a,b; Haverd et al., 2013a), which allow predictions of long-term variations in ecosystem characteristics under changing climates.

Flux tower measurements utilize meteorological methods such as eddy covariance (see e.g. Baldocchi, 2003; Burba, 2013), which results in ecosystem-scale measurements that are integrated from

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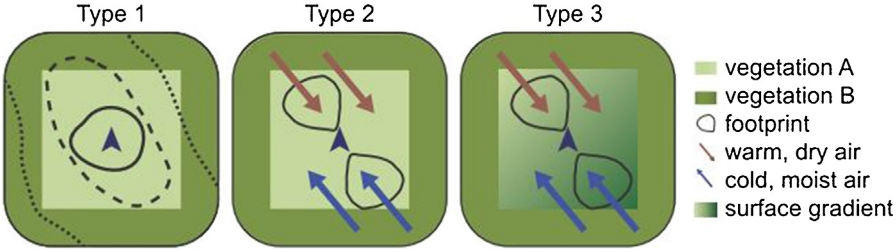

Fig. 1. Hypothetical flux footprints for contrasting vegetation types, climate conditions and surface gradients. Type 1: Footprint climatology (following Goeckede et al., 2008) under unstable (solid line), neutral (dashed line) and stable (dotted line) conditions over two adjacent homogeneous source areas. Type 2: Footprints (following Chasmer et al., 2011) under contrasting local climate conditions (warm and dry versus cold and moist) as a function of wind direction. Type 3: Addition of surface heterogeneity in combination with differences in climate conditions.

a spatial source area, termed the flux footprint. Measurements are taken at a stationary point in space (the flux tower) and are subject to the following key assumptions: (i) measurements at that point represent an upwind area; (ii) measurements are within the surface layer; (iii) conditions are predominantly turbulent (adequate mixing, most of the net vertical transfer is done by eddies); and (iv) the terrain is flat and the vegetation is uniform (i.e., footprint homogeneity following Lee et al., 2004; Foken, 2008; Aubinet et al., 2012). However, many existing flux sites are characterized by non-flat terrain and not fully homogeneous vegetation cover, indicating frequent violation of the fourth assumption (Schmid and Lloyd, 1999; Goeckede et al., 2008; Belcher et al., 2012).

The extent of the surface area contributing to a flux depends upon measurement height above the canopy, characteristics of the underlying vegetation (surface roughness) and the turbulent state of the atmosphere (Horst and Weil, 1992; Schmid, 2002; Vesala et al., 2008). Sophisticated footprint modelling has been developed to construct footprints for various atmospheric stratifications and over multiple time scales, from instantaneous to annual (Hsieh et al., 2000; Kormann and Meixner, 2001; Kljun et al., 2002). Over a longer period (like a season or a year) the footprint climatology integrates footprints and fluxes as a cumulative source function in which each individual footprint is weighted by the flux during its measurement period (Amiro, 1998; Chen et al., 2009). A detailed footprint analysis allows identification of atmospheric conditions leading to flux contributions from outside the targeted area, which can then be excluded. This reduces uncertainties in linking flux measurements to ecosystem characteristics (Leclerc and Thurtell, 1990; Horst and Weil, 1994; Hsieh et al., 2000). In the case of a potentially inhomogeneous source area, accounting for spatial heterogeneity to explain flux variability has been enhanced by the increasing availability of remotely sensed vegetation indices (Chasmer et al., 2011; Chen et al., 2009, 2011, 2012). This is particularly relevant for measurements from tall towers (Wang et al., 2006; Barcza et al., 2009) or when measuring fluxes of gases like CH_4, which show large spatial variability of multiple orders of magnitude (Baldocchi et al., 2012; Budishchev et al., 2014; Matthes et al., 2014).

Thus far, footprints are traditionally used as a quality control tool to analyze fluxes in relation to contributions from outside the target area (Foken et al., 2004; Rebmann et al., 2005; Goeckede et al., 2008) or to account for different vegetation compositions and structures (e.g. a cropped paddock surrounded by grazed land, Fig. 1, Type 1). However, there has been little evaluation of directional variations in flux characteristics that might influence the observed magnitude of fluxes *within* the footprint. These directional variations in flux characteristics can result from variations in climatic drivers as a function of wind direction (e.g. air temperature or vapour pressure deficit), as well as variations in surface properties (e.g. topography, gradients in soil moisture distribution or in vegetation patterns). Ultimately, continental-scale wind patterns will alter the relative proportions of flux contributions from various wind directions, which are then integrated over time to determine the site-specific CO_2 budgets. Such directional variations in flux characteristics become relevant in situations where the footprint is influenced by weather that varies with wind direction, as is characteristic of maritime sites or Mediterranean climates (e.g. Sun et al., 2006; Montaldo and Oren, 2016). In these ecosystems the key drivers of carbon exchange can vary consistently with wind direction even if the source area is compositionally homogeneous, as ocean breezes typically bring cooler and moister air (and are often associated with frontal rain events), whereas overland breezes are drier and warmer (Fig. 1, Type 2). This is expected to affect ecosystem productivity as a function of wind direction by, for example, increasing available soil water content for plant uptake after rain events when winds are from the ocean, or inhibiting stomatal conductance due to high vapour pressure deficits associated with drier inland air. Such wind-weather effects can become more complex when they are confounded with an inhomogeneous source area (Fig. 1, Type 3), where the surface characteristics (e.g., the composition and structure of vegetation or available soil moisture) vary with wind direction and/or topography. While many sites could potentially have such climate variability and surface gradients, they are rarely accounted for when constructing intra- and interannual carbon budgets.

In this study we examined interannual variations in climate and surface characteristics as a function of wind direction in a native mixed-species *Eucalyptus* forest. Our research objectives were (i) to examine the spatial variability of surface characteristics (topography, topographic wetness index and leaf area index) within the flux footprint, (ii) to analyze variations in the key flux drivers (LAI, temperature, VPD and turbulence) with wind direction, and ultimately (iii) to examine the effects of directional variations in flux characteristics on seasonal, annual and interannual carbon budget estimates. In addition, we present a procedure to account for the variation in carbon budget estimates resulting from directional variations in flux characteristics that is independent of utilizing a footprint model and simply relies on existing flux tower data.

2. Methods

2.1. Study site description

The Wombat Flux study site is located in the Wombat State Forest in central Victoria, south-eastern Australia (37°25′19.988″ S, 144°05′39.998″ E). The dry sclerophyll forest is classified as open forest (Specht, 1981), which is widespread in south-eastern Australia. The species composition is relatively uniform consisting of three dominant eucalypt species in the canopy: *Eucalyptus obliqua* (Messmate Stringybark), *Eucalyptus rubida* (Candlebark), and *Eucalyptus radiata* (Narrow-leaved Peppermint). The average canopy height is ~22 m, with tree heights typically ranging from