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A data-driven analysis of energy balance closure across FLUXNET research sites: The role of landscape scale heterogeneity

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ABSTRACT

The energy balance at most surface-atmosphere flux research sites remains unclosed. The mechanisms underlying the discrepancy between measured energy inputs and outputs across the global FLUXNET tower network are still under debate. Recent reviews have identified exchange processes and turbulent motions at large spatial and temporal scales in heterogeneous landscapes as the primary cause of the lack of energy balance closure at some intensively-researched sites, while unmeasured storage terms cannot be ruled out as a dominant contributor to the lack of energy balance closure at many other sites. We analyzed energy balance closure across 173 ecosystems in the FLUXNET database and explored the relationship between energy balance closure and landscape heterogeneity using MODIS products and GLOBEstat elevation data. Energy balance closure per research site ($C_{EB,s}$) averaged 0.84 ± 0.20, with best

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FLUXNET
MODIS
Plant functional type

average closures in evergreen broadleaf forests and savannas (0.91–0.94) and worst average closures in crops, deciduous broadleaf forests, mixed forests and wetlands (0.70–0.78). Half-hourly or hourly energy balance closure on a percent basis increased with friction velocity (u_*) and was highest on average under near-neutral atmospheric conditions. $C_{EB,s}$ was significantly related to mean precipitation, gross primary productivity and landscape-level enhanced vegetation index (EVI) from MODIS, and the variability in elevation, MODIS plant functional type, and MODIS EVI. A linear model including landscape-level variability in both EVI and elevation, mean precipitation, and an interaction term between EVI variability and precipitation had the lowest Akaike's information criterion value. $C_{EB,s}$ in landscapes with uniform plant functional type approached 0.9 and $C_{EB,s}$ in landscapes with uniform EVI approached 1. These results suggest that landscape-level heterogeneity in vegetation and topography cannot be ignored as a contributor to incomplete energy balance closure at the flux network level, although net radiation measurements, biological energy assimilation, unmeasured storage terms, and the importance of good practice including site selection when making flux measurements should not be discounted. Our results suggest that future research should focus on the quantitative mechanistic relationships between energy balance closure and landscape-scale heterogeneity, and the consequences of mesoscale circulations for surface-atmosphere exchange measurements.

1. Introduction

The surface-atmosphere exchanges of energy, momentum, water and trace gases are central components of the Earth system. Our understanding of these processes at the ecosystem level increasingly relies on observations from single or multiple eddy covariance flux measurement towers, regional flux measurement networks (e.g. Aubinet et al., 2000; Li et al., 2005), and the global FLUXNET database (Baldocchi et al., 2001; Papale et al., 2006). Most FLUXNET studies seek to understand processes controlling the biosphere–atmosphere flux of CO_2 (e.g. Baldocchi, 2008; Jung et al., 2009; Law et al., 2002; Stoy et al., 2009). Fewer studies to date have investigated global and regional water and energy fluxes apart from their relationship to CO_2 flux, with notable exceptions (e.g. Falge et al., 2001; Law et al., 2002; Hollinger et al., 2009; Jung et al., 2011). The relative paucity of eddy covariance energy and water flux studies is disproportional to the importance of these fluxes to the climate system.

Water, carbon and energy flux studies that rely on eddy covariance data are challenged by incomplete energy balance closure at most research sites (Aubinet et al., 2000; Leuning et al., 2012; Wilson et al., 2002). To date, multi-site syntheses have found an average eddy covariance energy balance closure (C_{EB}) ranging between 0.75 and 0.87 (Barr et al., 2006; Falge et al., 2001; Hendricks Franssen et al., 2010; Li et al., 2005; Wilson et al., 2002). Near-to-full C_{EB} has been reported at some sites (e.g. Haverd et al., 2007; Heusinkveld et al., 2004; Lindroth et al., 2009; Moderow et al., 2009; Vourlitis and Oechel, 1999), but these studies are in the minority. C_{EB} can be increased by measuring energy storage terms that are often excluded from conventional observations (Heusinkveld et al., 2004; Lindroth et al., 2009; Meyers and Hollinger, 2004), but additional measurements, including advective transport, often prove ineffective for closing the energy balance completely (Aubinet et al., 2010; Etzold et al., 2010; Moderow et al., 2011), in part because of the critical role of sensor accuracy for advection measurements (Dellwik et al., 2010a,b; Leuning et al., 2008). Large surface flux field campaigns have yet to report full energy balance closure (Beyrich et al., 2002; Foken, 1998; Foken et al., 1997; Kanemasu et al., 1992; Koitzsch et al., 1988; Mauder et al., 2006; Panin et al., 1998; Tsvang et al., 1991) (see Table 2 in Foken, 2008), suggesting that a fundamental aspect of surface-atmosphere exchange has yet to be ascertained.

Foken (2008) and Panin and Bernhofer (2008) concluded that buoyancy-driven turbulent circulations resulting from landscape heterogeneity are likely responsible for energy imbalance at the tower measurement level. These studies follow work by Panin et al. (1998) and Mauder et al. (2007b), who identified a relationship between energy balance closure and landscape patterns on a spatial scale on the order of tens of kilometres. In essence, this 'mesoscale hypothesis' suggests that relatively cool and dry air layers aloft are exchanged with relatively warm and moist air layers near the surface, and both the downward motion of cooler air and upward motion of warmer air result in a positive $\overline{w'T'}$ that contributes to a lack of energy balance closure if this flux is unmeasured by the eddy covariance instrumentation (Fig. 1). More experimental evidence of the interaction between surface heterogeneity and mesoscale circulations were obtained from aircraft measurements (Mauder et al., 2007a) and a multi-tower experiment (Mauder et al., 2010), but potential impacts of landscape-level heterogeneity on energy balance closure has not been tested across flux networks to date.

Other results highlight the importance of correctly measuring and interpreting energy storage terms to achieve energy balance closure. A recent study by Leuning et al. (2012) found that 45% of FLUXNET sites approached energy balance closure using daily averages after correctly accounting for lags in heat flux into soils, biomass, and the canopy air space (Gao et al., 2010; Haverd et al., 2007). Accounting for all energy storage terms results in a closed energy balance at select sites (Lindroth et al., 2009).

From these studies, it is clear that a closed energy balance can occur at certain sites, yet the energy balance at hundreds of flux sites worldwide remain unclosed. We adopt a data-driven approach (Gray, 2009; Hunt et al., 2009) and combine eddy covariance and remote sensing databases to test if millions of observations are consistent with the expectations of the mesoscale hypothesis that landscape-level heterogeneity is negatively related to energy balance closure. Our objectives are twofold. First, we characterize C_{EB} at 173 sites in the FLUXNET database as it relates to micrometeorological drivers, considering both half-hourly (or hourly) observations ($C_{EB,i}$) and site-level means ($C_{EB,s}$). We then test the hypothesis that energy balance closure is related to landscape-level heterogeneity using data products from the Moderate-Resolution

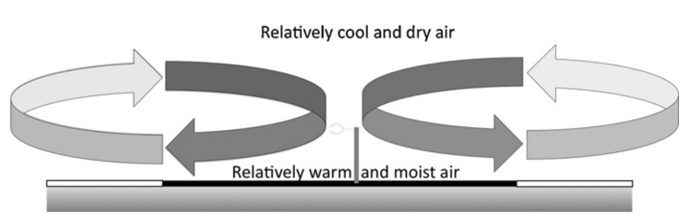

Fig. 1. Conceptual description of mesoscale circulations, driven in part by landscape-level heterogeneity, suggested by Foken et al. (2011), Mauder et al. (2010) and others to contribute to lack of energy balance closure at single-tower sites. The anisotropic nature of the mesoscale circulations is on the order of tens of kilometres in the horizontal direction.