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Investigating the mechanisms responsible for the lack of surface energy balance closure in a central Amazonian tropical rainforest

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ABSTRACT

This work investigates the diurnal and seasonal behavior of the energy balance residual (*E*) that results from the observed difference between available energy and the turbulent fluxes of sensible heat (*H*) and latent heat (*LE*) at the FLUXNET BR-Ma2 site located in the Brazilian central Amazon rainforest. The behavior of *E* is analyzed by extending the eddy covariance averaging length from 30 min to 4 h and by applying an Information Flow Dynamical Process Network to diagnose processes and conditions affecting *E* across different seasons. Results show that the seasonal turbulent flux dynamics and the Bowen ratio are primarily driven by net radiation (R_n), with substantial sub-seasonal variability. The Bowen ratio increased from 0.25 in April to 0.4 at the end of September. Extension of the averaging length from 0.5 (94.6% closure) to 4 h and thus inclusion of longer timescale eddies and mesoscale processes closes the energy balance and lead to an increase in the Bowen ratio, thus highlighting the importance of additional *H* to E. Information flow analysis reveals that the components of the energy balance explain between 25 and 40% of the total Shannon entropy with higher values during the wet season than the dry season. Dry season information flow from the buoyancy flux to *E* are 30–50% larger than that from *H*, indicating the potential importance of buoyancy fluxes to closing *E*. While the low closure highlights additional sources not captured in the flux data and random measurement errors contributing to *E*, the findings of the information flow and averaging length analysis are consistent with the impact of mesoscale circulations, which tend to transport more *H* than *LE*, on the lack of closure.

1. Introduction

Eddy covariance has quickly become the global standard for estimating the exchange of water, heat, and trace gases between ecosystems and the atmosphere (Baldocchi, 2014, 2008; Baldocchi et al., 2001). Despite its promise as a largely non-invasive technology for the near-continuous estimates of surface-atmosphere matter and energy fluxes, most eddy covariance measurements do not fully close the energy balance (Franssen et al., 2010; Stoy et al., 2013; Wilson et al., 2002). After decades of research in developing the fundamental equations for eddy covariance, developing instruments, describing corrections, and characterizing measurement uncertainty (e.g. Gu et al., 2012; Leuning et al., 2012; Massman and Clement, 2004; Massman and Lee, 2002; Moncrieff et al., 2005; Richardson et al., 2006), fewer than half of the sites in global databases can report energy balance closure on a diurnal basis (Leuning et al., 2012). It is critical to understand what causes the lack of energy balance closure (*E*, often called the energy balance residual) to improve the instrumentation and theory that underlie the eddy covariance technique in order to gain a better understanding of the role of surface-atmosphere exchange in the Earth system.

Investigations into the mechanisms responsible for *E* are ongoing.

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Careful critiques of sonic anemometry reveal that non-orthogonal transducer placement may be responsible for up to 15% of the discrepancy of sensible heat fluxes (*H*) (Frank et al., 2013; Kochendorfer et al., 2012). Other studies argue that mesoscale meteorological motions that are not measured using conventional sonic anemometry, and/or vary at characteristic timescales longer than the conventional half-hour averaging period, are primarily responsible for *E* (Foken, 2008; Foken et al., 2011; Mauder et al., 2010, 2007; Panin and Bernhofer, 2008). An extension of this line of reasoning is that *E* may scale with the buoyancy flux (*HB*) (Charuchittipan et al., 2014). Both lines of evidence suggest that *H* may dominate *E* such that corrections based on the Bowen ratio (β) (Twine et al., 2000) may not be accurate, depending on how mismeasurement of the vertical variance of wind velocity (*w*') impacts *H versus* latent heat flux (*LE*). At the same time, mismatches between the measurement footprints of net radiation (R_n) and turbulent fluxes, whose footprint is highly variable with atmospheric stability, may be responsible for *E* at individual sites.

Acknowledging the critical roles of improvements to instrumentation and our knowledge of atmospheric boundary-layer processes, it is necessary to quantify − to the best of our ability − the causes of *E* on a site-by-site basis. Thousands of site-years of eddy covariance data exist (Baldocchi, 2008; Stoy et al., 2009), and careful interpretation of these data are required to understand trends of surface-atmosphere exchange on a changing planet (Jung et al., 2010). We argue that querying existing data to uncover the 'symptoms' of *E* using a data-driven approach can provide information to help further refine the eddy covariance technique.

Here, we study *E* using eddy covariance measurements from a rainforest in the central Brazilian Amazon (Site code: BR-Ma2). We combine a critical analysis of the eddy covariance averaging period with a novel information theory-based interpretation of information flows amongst energy balance terms. The latter analysis asks, in effect, how much information from energy flux time series is transferred to *E* (Ruddell et al., 2013). Previous research at BR-Ma2 demonstrated that the energy balance was approximately closed at longer averaging periods (Malhi et al., 2002), but did not interpret the terms responsible for *E*. Likewise, previous investigations using information networks revealed bi-directional links between surface and atmospheric processes and quantified their seasonal dynamics and states (Ruddell et al., 2015; Ruddell and Kumar, 2009a,b), but has not been used to quantify how information from different flux terms contributes to *E* from forested ecosystems to date.

We focus our investigation on a tropical forest for a number of reasons. Tropical forests help regulate the amount of heat and moisture that enters the atmosphere and is available for deep convection and thereby contribute to regional and global heat transport (Avissar and Werth, 2005). Tropical ecosystems are also amongst the Earth's most threatened (Kim et al., 2015), with consequences not only for biodiversity, but also for global climate services such as carbon assimilation and water resources (e.g. Medvigy et al., 2013). Land surface models are in the nascent stages of recognizing the functional diversity of tropical forests (Pavlick et al., 2013), and recent approaches that incorporate species-specific hydrology demonstrate that they may be more resilient to hydrologic and climate disturbances (Levine et al., 2016) than previously assumed (Cox et al., 2000).

At the same time, global syntheses indicate that tropical forests are amongst the most isohydric of any terrestrial ecosystem (Fisher et al., 2006; Konings and Gentine, 2016), suggesting that they strictly regulate stomatal conductance in response to increases in atmospheric vapor pressure deficit (VPD), argued to be an increasingly important constraint on ecosystem function in the future as global temperatures rise (Novick et al., 2016; Sulman et al., 2016). Other studies argue that anisohydric strategies may be preferred in tropical systems with little risk of water stress (Kumagai and Porporato, 2012) and that Trees − including tropical species − exhibit a range of isohydric to anisohydric hydraulic behaviors (Klein, 2014). Eddy covariance measurements of water and energy flux can help us understand these dynamics at the ecosystem scale. Evapotranspiration from tropical forests is well-known to be energy limited on average (Mallick et al., 2016; Williams et al., 2012), but moisture limitation exists during drought (Gatti et al., 2014). It is also important to understand how seasonal patterns of light and water availability interact with canopy hydraulic behavior to impact water and heat flux from tropical forests (Huete et al., 2006; Morton et al., 2014; Saleska et al., 2016, 2007). Vertical transport via the buoyancy flux − dominated by *H* − is a limiting factor in tropical cloud formation and precipitation (Badiya Roy and Avissar, 2002) and its accurate determination is critical for understanding such processes, which differ among wet and dry seasons. On average, the seasonal patterns of *H* and *LE* tend to be more muted in tropical forests than other global ecosystems, but important differences in energy flux partitioning emerge across the dry and wet seasons at specific sites (da Rocha et al., 2009, 2004; Fuentes et al., 2016; Mallick et al., 2016), which are changing due to shifts in the intertropical convergence zone (Sultan and Janicot, 2000; Voigt et al., 2014; Zeng et al., 2008). Combined, these studies make it clear that improving our understanding of tropical forests in the Earth system requires accurate diurnal and seasonal estimates of *H* and *LE*.

Here, we investigate eddy covariance observations from a tropical rainforest in the central Brazilian Amazon using averaging period and transfer entropy (information flow) analyses to gain insight into the causes of *E* for the purpose of better-understanding diurnal and seasonal patterns of *H* and *LE*. Following studies on mesoscale dynamics, we hypothesize that increasing the eddy covariance averaging period likewise be will be associated with increased values of measured *H*. We further hypothesize that information flow from *H* to *E* will increase during states when mesoscale processes are stronger (e.g. during midday during the dry season), and that this process network signature will help us infer the causes of *E*. We first describe the measurements and techniques used to study the hypotheses and discuss how findings impact our understanding of diurnal and seasonal patterns of *H* and *LE*.

2. Materials and methods

2.1. Site description

Measurements for the energy balance averaging analysis were made as part of the GoAmazon Boundary Layer Experiment, hereafter the "GoAmazon" suite of sensors described in Fuentes et al. (2016), which is part of the US Department of Energy funded Observations and Modeling of the Green Ocean Amazon (GoAmazon 2014/5, Martin et al., 2016). Observations come from the BR-Ma2 tower (also called the K34 tower at ZF2 and designated as T0k during GoAmazon 2014/5) (Araújo et al., 2002; Jardine et al., 2015; Kruijt et al., 2004; Malhi et al., 2002, 1998; Tóta et al., 2012) located in the Cuieiras Biological Reserve at 2.60191°S, 60.2093°W approximately 60 km NNW from Manaus, Brazil and managed by the Brazilian National Institute for Amazon Research (INPA). The tower itself is 50 m tall and located in primary tropical rainforest with characteristic canopy heights on the order of 30–40 m and leaf area index values estimated to be between 5.7 $m^2\,m^{-2}$ and 7.3 $m^2\,m^{-2}$ (McWilliams et al., 1993; Marques Filho et al., 2005; Tóta et al., 2012). The tallest trees near the tower reach 35 m, which we take to be the effective canopy height (*h*). Topography surrounding the tower is characterized by a sequence of plateaus and valleys, with approximate height differences of 50 m across a spatial domain of tens of kilometers.

2.2. Measurements

Turbulent flux quantities necessary for the calculation of *H* and *LE* were measured using a sonic anemometer (model CSAT-3, Campbell Scientific Inc., Logan, UT, USA) for the three wind components (*u*, *v*, *w*) and an open path infra-red gas analyzer (model LI-7500A, Licor,