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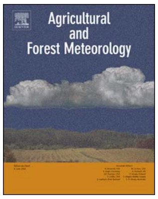

Time dependency of eddy covariance site energy balance

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ABSTRACT

Energy flow through ecosystems plays a critical role in processes at multiple spatial and temporal scales, from phonologically driven growing season or monthly temporal scales of landscapes to sub-diurnal responses of soil respiration to temperature, photosynthesis and water inputs. The interaction of short and longwave radiation and their partitioning through ecosystems is complex with terrestrial canopies and aquatic structure both connecting above- and below-ground processes via energy fluxes. Previous work has shown that at 30-min timescales, only 8% of eddy covariance sites in the La Thuile dataset observe energy closure and when averaged to 24-h timescales, this goes up to 45%. This work examines the effect of temporal lags in energy storage in both terrestrial and aquatic ecosystems. Analyses show energy storage terms have unique temporal lags that vary between ecosystem and time of year, from having zero lag to several hour timelags within terrestrial ecosystems, depending primarily on water content. Large differences between ecosystem types are also highlighted as aquatic ecosystems have lags that range between daily and monthly timescales. Furthermore, ecosystem disturbance can alter time-lags as well and results from a native bark beetle disturbance show both vegetation and soil lag increasing following changes to ecosystem processes from tree mortality. Considering energy storage lags can improve site energy closure in 20% of site-days in the FLUXNET2015 dataset and these results will lead to a better understanding of surface energy budget closure as well as highlighting the importance of time-dependency of ecosystem energy fluxes as a unique method to infer ecosystem processes.

1. Introduction

The lack of energy-balance conservation among measured terms at eddy covariance field sites (net radiation, turbulent heat fluxes, ground heat flux, soil, air, and, biomass heat storage), known as the energy balance closure problem, is an unsolved problem in the field. In recent years, multiple review papers have worked to address this issue, with the lack of energy closure thought to be from, in part, landscape heterogeneity (Foken, 2008; Stoy et al., 2013), error in flux observations (Mauder et al., 2007; Wilson et al., 2002), averaging periods and coordinate systems (Finnigan, 2004; Finnigan et al., 2003; Gerken et al., 2017; Mauder et al., 2010), horizontal advection (Oncley et al., 2007), instrument bias (Frank et al., 2016; Horst et al., 2016), incorrect assumptions from Taylor's frozen turbulence hypothesis (Cheng et al., 2017) or a combination of several issues (Leuning et al., 2012; Massman and Lee, 2002). Recent work has examined the effect on energy closure from phase differences between vertical wind velocity and water vapor (Gao et al., 2017), however, there is no consensus on how to improve energy closure. Here, we focus on the role that temporal and spatial scale of energy storage terms influences energy closure, an aspect that has not, to date, been systematically examined.

Energy terms at eddy covariance sites are measured at multiple spatial scales, from soil heat flux at cm^2 to ecosystem fluxes at dm^2 to km^2 (Baldocchi et al., 2001). As a result, a lack of closure at eddy covariance sites is typical in all land-surface types and under all environmental conditions and energy imbalance is commonly cited as being on the order of 20% (Wilson et al., 2002). One commonly discussed technique for closing the energy budget of sites is adjusting flux values in order to force energy closure (Twine et al., 2000), assuming turbulent energy flux terms are systematically biased, but this potentially adds unnecessary error to both energy and mass fluxes.

Results from eddy covariance studies are frequently scaled to regional or landscape levels, so that fluxes from an entire biome can be estimated (Desai et al., 2010; Xu et al., 2017). While scaling to larger spatial scales is a vital part of ecological science (Osmond et al., 2004; Wiens, 1989), observations at multiple scales such as stable isotopes, sap flow measurements (Williams, 2004), or chambers (Morin et al., 2017) can constrain uncertainty in eddy covariance flux estimates.

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These observational uncertainties need to be incorporated into modeling work when scaling results (Hollinger and Richardson, 2005), but are not currently considered for energy fluxes.

Ecosystem energy terms also have an inherent temporal scale, which is often not considered. It is known that for soil heat flux observations at depth to represent the surface soil heat flux, they need to be corrected for the temporal phase shift and amplitude dampening (Ochsner et al., 2007). Stomatal conductance (Phillips et al., 1997) and plant hydraulic traits (Anderegg, 2015), and hence ecosystem water flux, also has a complex time variation from tens of minutes to daily time scales. The diurnal pattern of the sum of sensible and latent heat fluxes are often lagged in time relative to the sum of available energy (Wilson et al., 2002). Energy storage contains soil and biomass heat capacity terms, which are dependent on soil and plant water content (Meyers and Hollinger, 2004) which varies in time (Matheny et al., 2015), and can often be under sampled (Oliphant, 2004) or assumed constant. Site energy balance improved when averaging length increases (Gerken et al., 2017), and often averaged to daily timescales to avoid energy storage. However, in a select number of cases energy closure is worse at daily timescales (Leuning et al., 2012), implying some processes last beyond 24-h. Seasonal changes in ecosystem processes may change both energy fluxes and site energy closure. Gu et al. (2005) highlight a clear distinction of energy budget terms and also energy closure between periods with frozen soils and non-frozen soils due to soil water content and heat capacity changes. Hao (2007) shows patterns of energy closure and terms changing due to ecosystem phenology while Bremer and Ham (1999) show similar results following burns in a grassland, primarily attributed to changes in albedo. Considering the temporal component of energy measurements provides increased confidence in eddy covariance observations in general and in specific cases can give insight into ecosystem processes.

Here, we used micrometeorological and site thermodynamic observations to investigate the time dependency of energy balance terms first seasonally in a Northern Wisconsin wetland which has 13 site-years of data to compare seasonal changes, second interannually at a high elevation Wyoming pine forest which has been the focus of previous energy balance work, and third as analysis of 159 sites in the FLUXNET2015 database. Using the observations to quantify the slope of the relationship between a site's net radiation to the other components of the energy balance, as well as the total sum of energy difference at the sites, we focused on three main questions: 1) Does a site's ecosystem energy closure vary in annual or sub- annual timescales? 2) If there is temporal variation in a site's energy closure, can that variation be explained by underlying ecosystem processes at that site? 3) Can a site's energy closure be improved by factoring in time dependency of energy balance terms?

2. Methods

2.1. Site descriptions and data collection

Data were collected from the wetlands study site established in 2000, in the Northern Highlands State Forest in North Central Wisconsin, at the Lost Creek shrub fen AmeriFlux (US-Los) wetland site (Latitude: 46.0827 Longitude: −89.9792 Elevation: 485 m). The site has a 10.2 m tall tower, with data collected from 2000 to 2010 and 2013–2014, featuring a CSAT3 (Campbell Scientific Inc., USA) sonic anemometer and latent heat fluxes measured from a LI-COR (Li-Cor Inc., USA) 6262 (2000–2001 and 2013) and 7500 (2014). Soil heat flux measurements were at a depth of 75 mm at the site.

The canopy at this site was approximately 2 m tall with the dominate vegetation being alder (*Alnus incana ssp. rugosa*) and willow (*Salix* spp.) with the understory dominated by sedges (*Carex sp*.). Poorly drained and peat accumulating soils surrounding the tower included a Totagatic-Bowstring-Ausable complex and Seelyeville and Markey mucks.

At Lost Creek, standing water was common during summers and the site experienced a long term drought from 2000 to 2007 (Sulman Desai et al., 2009) from which the site has since recovered. Water table depth measurements were recorded at the site for a portion of the study period. To extend these observations, a comparison to annual water discharge observations from a downstream United States Geological Survey flow gauge at Bear River (Lat: 46.048889 Lon: −89.984444 Drainage Area: 211 km^2) was made ($R^2 = 0.95$, *p-value* = 0.00015), and water discharge was used for this study as a water table depth proxy.

Data from the forested site were collected from the predominately evergreen forest Chimney park AmeriFlux (US-Cpk) site (Latitude: 41.0680 Longitude: −106.1187 Elevation: 2750 m) from 2009 to 2011. The main tree species present was lodge pole pine *(Pinus contorta)*. This site had a large-scale outbreak of mountain pine bark beetles *(Dendrotonus ponderosae)* and the associated blue-stain fungi (*Grosmannia clavigera*) during the onset of the data collection period first noted in 2007. The resulting tree mortality was measured at 30% in 2008 and increased to 78% in 2011 (Reed et al., 2014).

Data from Chimney Park AmeriFlux (US-CPk) was collected from 2009 to 2011 using an open path gas analyzer (LI-7500) and sonic anemometer (CSAT3) both at 17.7 m and net radiation (CNR1; Kipp & Zonen, the Netherlands) at 17.1 m. Soil energy measurements consisted of soil temperature at depth of 10, 20, 30, 50 and 70 cm, two soil heat flux plates (HFP01SC; Hukseflux, Netherlands) at 5 cm depth and soil moisture probes (CS616; Campbell Scientific Inc., USA) over depth ranges of 0–15, 15–45, and 45–75 cm.

The FLUXNET2015 data were collected from 159 Tier 1 sites with seven sites removed from analysis since they were lacking net radiation observations. All 159 sites had gap filled net radiation, sensible, latent heat and soil heat fluxes data available at 30 min timescales and averaged monthly data (Vuichard and Papale, 2015). Data were rejected if it was below the 0.85 quality control threshold (Papale et al., 2006). Further information on the dataset can be found at the FLUXNET 2015 website (http://fluxnet.fluxdata.org/data/fluxnet2015-dataset/data-processing/).

2.2. Data processing

Eddy covariance data from both study locations were collected on Campbell Scientific data loggers (CR23X, CR3000 and CR5000, Campbell Scientific, Logan, UT, USA) and processed following standard eddy covariance protocols (Lee et al., 2004) as detailed in Reed et al. (2014; 2016) and Sulman Desai et al. (2009).

Energy balance can be described in several ways. The methods of Leuning et al. (2012) were followed here where energy balance for the field site was defined with net radiation (R_n), measured latent (LE) and sensible (H) heat fluxes, soil heat flux at depth (G) and energy storage within the soil profile (J_g) and energy storage within the canopy (J_v) at each 30 min time scale (Eq. (1)). The net radiation is positive for energy flux toward the surface; the other values are positive for energy leaving the surface.

$$R_n = LE + H + G + J_g + J_v \tag{1}$$

Energy storage at Chimney Park was approximated based off of Meyers and Hollinger (2004) and in Eq. (2), soil energy storage at one soil depth, specific heats of soil water and soil solids(C_w, C_s), soil bulk density (ρ_s), and soil water mass density (m_{sw}) were assumed to be stationary in time. Volumetric soil water (θ_w) and the soil temperature change (ΔT_s) over the 30 min time interval (Δt) were both measured at 10 cm depth (z_s). A partial differential solution to soil energy storage was not used since measurements of soil temperature at multiple depths as well as at the surface were not available.

$$J_g = \frac{(\theta_w m_{sw} C_w + \rho_s C_s)\Delta T_s z_s}{\Delta t} \tag{2}$$