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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.

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

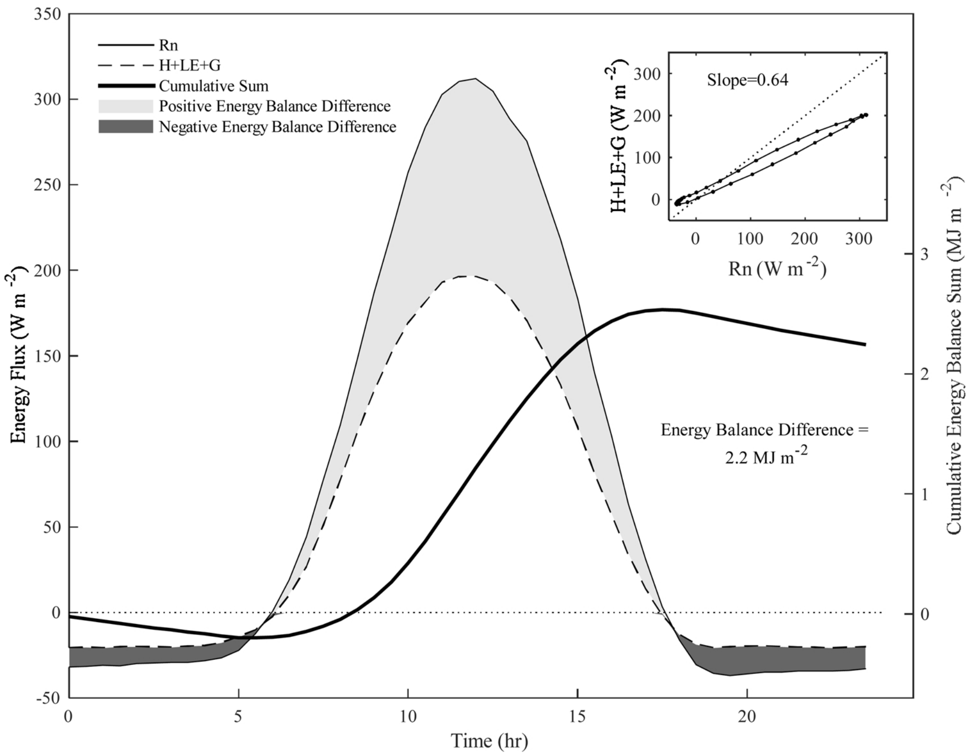

Fig. 1. Daily average net radiation (solid line) and sum of energy fluxes plus soil heat flux (dashed line) from 13 site-years at Lost Creek (US-Los). Positive (grey) and negative (black) energy differences shaded, with net sum energy balance difference shown. Inset shows 30-min fluxes as a function of site net radiation, which the site's energy balance slope for the 13 site-years was derived from.

For canopy vegetation energy storage at Chimney Park, Eq. (3), vegetation mass density and vegetation water mass density (m_v, m_{H_2O}) were based on lodgepole pine allometric relationships developed in the region (Pearson et al., 1984) and measured wet/dry biomass ratios were estimated seasonally from dried biomass weights. Specific heats of vegetation and water(C_v, C_{H_2O}) were constant. Change in vegetation temperature (T_v) over the 30 min time interval (Δt) was modeled from differences in air temperature at 30 min timescales. For limited parts of the study period, tree bole temperature at the site was measured at breast height (1.3m) using thermocouples, and results were similar using air temperature or bole temperature. Similar to J_g, a partial differential solution to canopy vegetation energy storage of Haverd et al. (2007) was not used due to limitations in vegetation temperature measurements.

$$J_v = \frac{(m_v C_v + m_{H_2O} C_{H_2O})\Delta T_v}{\Delta t} \tag{3}$$

For all sites, the energy budget slope, for each daily, monthly or annual time period was defined as the regression of the sum of energy terms ($H+LE+G$) as a function of R_n, in which the intercept term of the regression was not forced to zero. Regression of daily time periods was done using all available hourly data from that day of year, e.g. Jan 1st regression results were from Jan 1st data binned from all site-years. When calculating average regression results from the FLUXNET2015 data, the energy slope by day was calculated for each site first, and then all sites were averaged for that day of year. The Energy Balance Difference (EBD), Eq. (4) was calculated as the sum of the difference between R_n and the sum of the energy flux terms ($H+LE+G$). To quantify seasonality, a sine equation with a period of one year was used to describe trends in the energy budget slope and energy balance difference.

$$EBD = \sum (Rn - (H + LE + G)) \tag{4}$$

The energy budget slope was also calculated at US-Cpk with both energy storage terms lagged independently from each other in time in Eq. (5)a–b, as well as on sensible and latent heat fluxes in Eq. (5)c–d and finally all heat fluxes in Eq. (5)e. Yearly energy budget slopes at US-Cpk were calculated over the growing season period only. The energy storage terms were then lagged in time (Δt) in steps of 0.5 h for up to 7 h at US-Cpk and 4.5 h for the FLUXNET2015 dataset. Best-fit was defined as the highest energy budget slope and if two time periods were within 0.01 of each other, best-fit was the time step with the smallest lag. For the FLUXNET2015 dataset, a threshold of improvement greater than or equal to 1 percent was used when counting site-days with increased closure.

$$R_n(t) = LE(t) + H(t) + G(t) + J_g(t + \Delta t_1) \tag{5a}$$

$$R_n(t) = LE(t) + H(t) + G(t) + J_v(t + \Delta t_2) \tag{5b}$$

$$R_n(t) = LE(t) + H(t + \Delta t_3) + G(t) \tag{5c}$$

$$R_n(t) = LE(t + \Delta t_4) + H(t) + G(t) \tag{5d}$$

$$R_n = LE(t + \Delta t) + H(t + \Delta t) + G(t + \Delta t) \tag{5e}$$

PhenoCam data were used to calculate site canopy greenness at US-Los, as quantified by the green chromatic coordinate (GCC) as the relative brightness of the green channel compared to the brightness of the sum of the red blue and green channels (Richardson et al., 2009; Richardson et al., 2013).

$$GCC = \frac{Green\ Channel\ Brightness}{Total\ RBG\ Brightness} \tag{6}$$

3. Results

3.1. Wetland water discharge and site energy balance at lost creek, WI

As a first step in answering question one, average energy closure for all Lost Creek site-years was plotted in Fig. 1. The energy balance difference is shown as the shaded areas of the figure with dark shading for a net negative energy balance and a net ground-to-atmosphere energy flux, while lighter shading is net positive energy balance and a net atmosphere-to-ground energy flux. For an average site-day the energy balance difference was 2.2 MJ m^{-2} and the energy closure slope was 0.64. Throughout the 24 h period, the energy balance cumulative sum

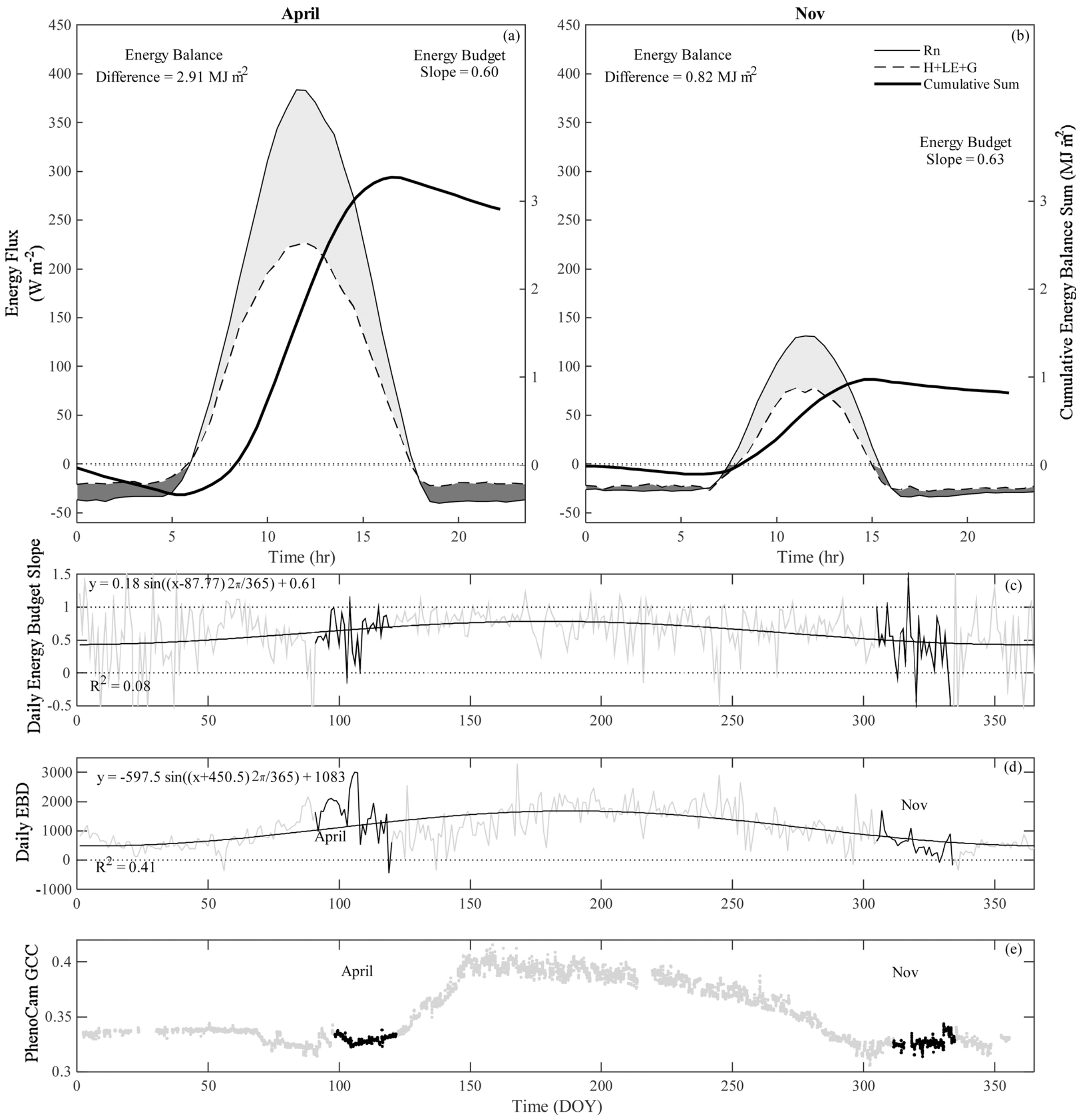

Fig. 2. Average net radiation (solid line) and sum of energy fluxes (dashed line), along with sum of energy balance difference and enough budget slope for the month of April (a) and November (b) from all 13 site-years at Lost Creek (US-Los). Average daily energy budget slope (c) and energy budget difference (d) is show for an average site-year as well as site greenness index (e) from DOY 220, 2014 to DOY 150, 2015.

is shown and is slightly negative before 8AM, increases quickly and peaks near 4PM and then decreases until the end of the day value of 2.2 MJ m^{-2}.

Energy balance at Lost Creek throughout a year is shown in Fig. 2. All site-years are averaged together and then plotted for the month of April (Fig. 2a) and November (Fig. 2b). Site energy balance and closure slope varies from 291 MJ m^{-2} and 0.60 in April and 0.82 MJ m^{-2} 0.63 in November. Daily energy budget slope (Fig. 2c) and daily energy balance difference (Fig. 2d) vary throughout the year, peaking during summer. When a sine curve was fit to the data, the R^2 for the daily energy budget slope was 0.08 while the R^2 for the daily energy budget difference was 0.41. As a reference, site greenness index based on PhenoCam data (Richardson et al., 2009; Richardson et al., 2013) is plotted for 2014–2015, when data at the site was available. The greenness index highlights how similar the site radiative characteristics are to each other in April and November. Both months are outside of the growing season.

When site energy balance is considered interannually, June was chosen as a representative summer month in Fig. 3, with single site-months plotted during the course of the long term drought for 2002, 2004, 2006, and 2008 (Fig. 3a–d). Energy balance difference vary from 0.78 (2004) to 4.75 (2008) MJ m^{-2} and energy budget slope from 0.84 (2002) to 0.53 (2008). The environmental factor that varies the most interannually is the amount of surface runoff from the site, which is shown in Fig. 3e, and during the drought the variation in water discharge for each respective growing season was large as discharge declined.

When the daily differences of energy balance in Figs. 1–3 are summed over each month, a relationship between the energy balance and monthly mean discharge at Lost Creek (Fig. 3e) is revealed in Fig. 4. Plotted monthly, this relationship shows a wide range in monthly energy closure, with November through February having an average

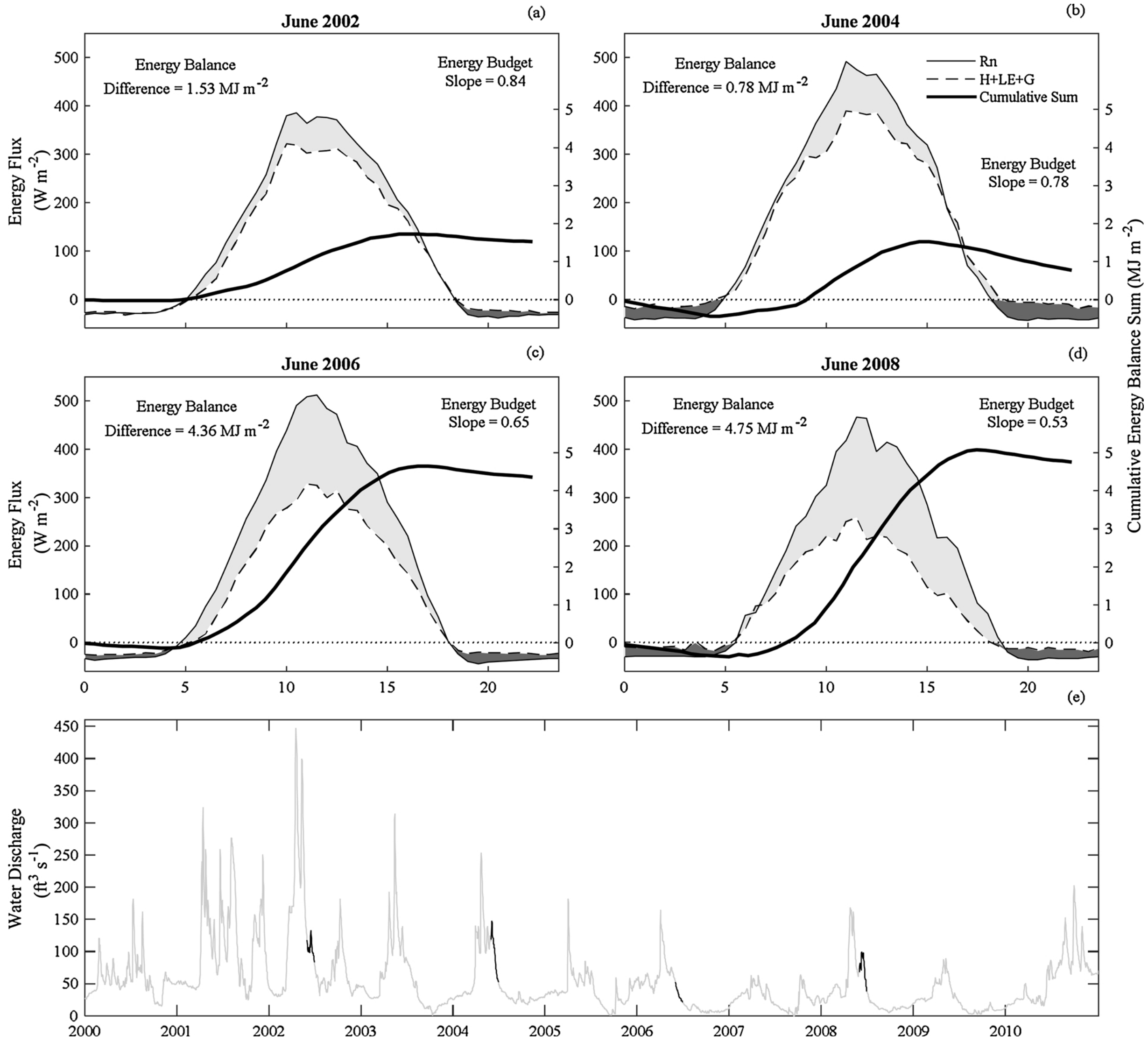

Fig. 3. Average net radiation (solid line) and sum of energy fluxes (dashed line) of the month of June from four years, 2002 (a), 2004 (b), 2006 (c) and 2008 (d), is shown along with Water Discharge (e) from 2000 to 2010 from a USGS gauge station downstream of the eddy covariance footprint at Lost Creek (US-Los).

negative closure, meaning more measured outgoing energy than incoming at the site, while March through September having on average a positive closure. October has outgoing and incoming energy nearly in balance and the transitions between positive and negative energy difference are close to the autumnal and vernal equinoxes. The relationship between energy balance and water discharge is statistically significant (each slope coefficient 95% confidence interval is < 0 and F statistic *p-value* < 0.05) 6 months out of the year and the majority of the growing season months (May-Sept) with increased water discharge being correlated with more negative energy balance difference. In all months with a significant relationship it is negative, implying water is moving energy out of the ecosystem and downstream.

3.2. Ecosystem disturbance and site energy balance at chimney park, WY

The research site at Chimney Park WY has been the focus of previous energy budget work, which showed energy storage decreasing in the canopy due to hydrologic failure within infected tress, while soil energy storage increased from higher soil moisture levels (Reed et al., 2016). A summary of the site energy partitioning is shown in Fig. 5. Half hourly energy slope is 0.67 for the site and increases to 0.75 when energy storage terms are included. The site's energy balance difference is 5.23 MJ m^{-2}. When energy storage terms are added, the main result is a 1 h temporal shift forward in the outgoing energy flux, as well as a maximum increase in outgoing energy flux during midday of 100 W m^2 and a corresponding decrease during the afternoon and early night. The addition of the energy storage terms largely doesn't change the site energy balance difference, as expected since energy storage averages to zero in time, and it should be noted that there is no gradual decline in cumulative energy sum during the morning (Midnight-6AM) as observed in Figs. 1-3. Instead, the cumulative energy sum is near zero and then shows a larger maximum negative sum mid-morning (8AM). Similarly, there is little evening decline in the cumulative sum as observed without energy storage terms, however, as previously mentioned, the final daily cumulative sum shows little difference with the addition of energy storage terms.

When the soil storage and canopy vegetation storage terms were added individually to energy closure and then lagged in time steps of 30 min, the slope of the energy closure at the site increased (Fig. 6). With only soil energy storage considered, energy closure was on average 0.65 and, depending on the time lag applied and the year, increased to between 0.72 and 0.76, with the maximum value of 0.76 happening in 2010. With only the canopy biomass energy storage term considered, site energy closure increased from 0.55 without time lags to

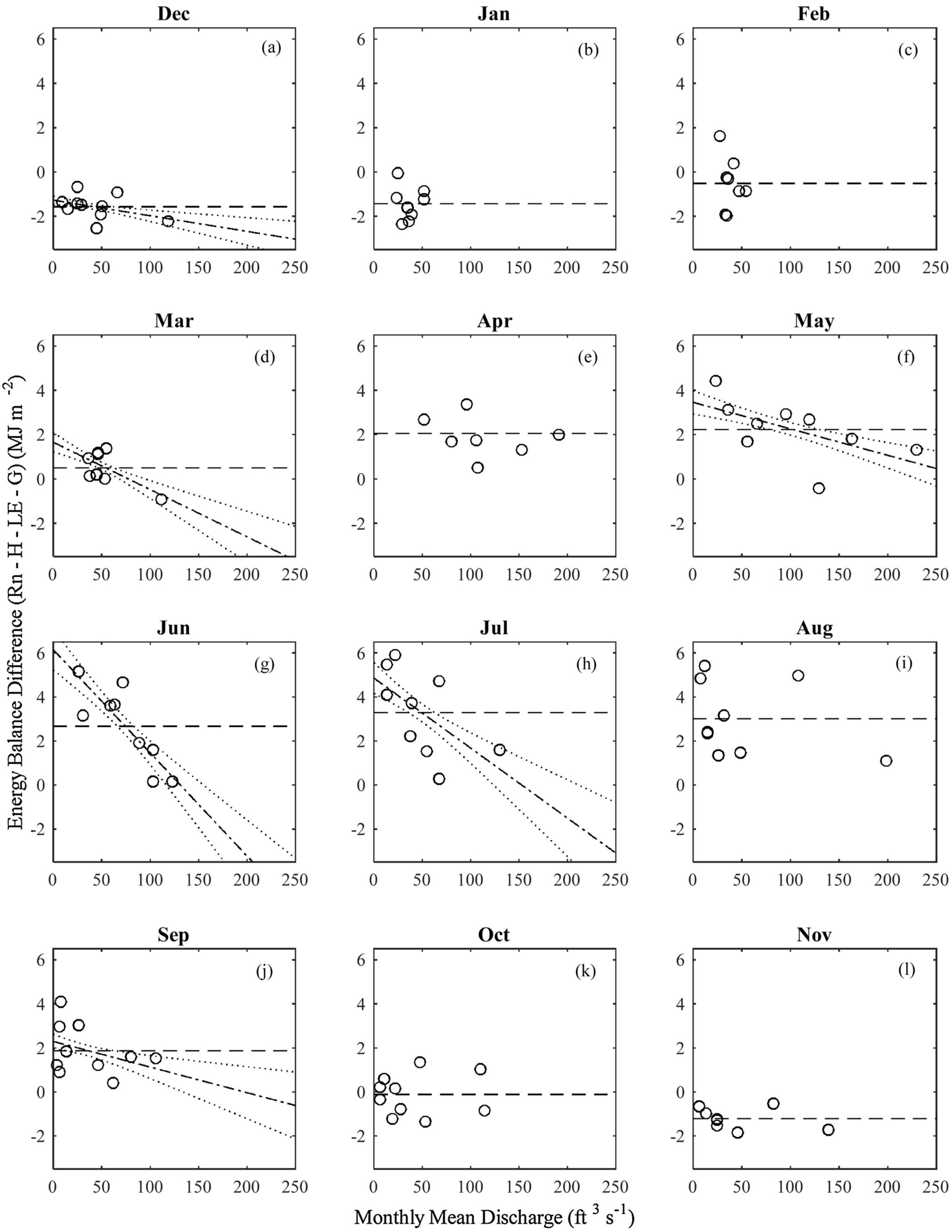

Fig. 4. All 13 site-years of energy balance difference data at Lost Creek (US-Los) is shown by month, as a function of monthly mean water discharge.

between 0.56 and 0.59 after time lags were considered. During this time, the amount of mortality based on tree basal area at the site increased from 55% to 78% over the tower footprint while LAI declined from 2.16 $m^2\,m^{-2}$ to 1.69 $m^2\,m^{-2}$ (Reed et al., 2014). When energy storage terms were lagged in time, the best-fit time-lag for the first year of available data for both energy storage terms was 2.5 h lag. Each year the best-fit time-lag moved back 0.5 h, from 2.5 in 2009 to 3.5 in 2011. For canopy vegetation storage time-lag in 2011, a lag of 3.5 and 4 h yielded identical energy closure, and the time-lag of 3.5 is reported as the best-fit lag since it is the smaller time-lag of the two.

3.3. Energy closure across the FLUXNET2015 dataset

To investigate further whether the above presented temporal

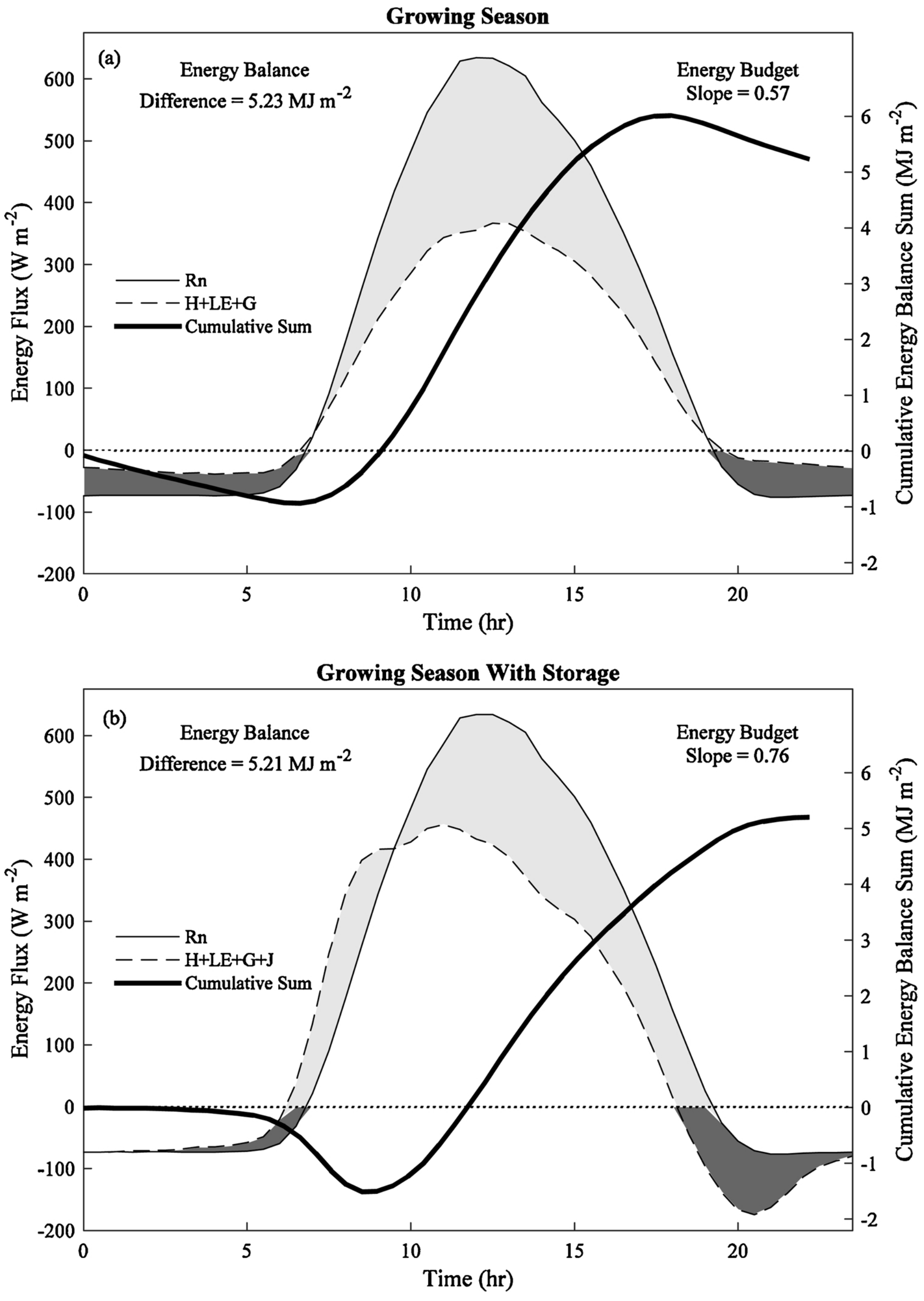

Fig. 5. Average net radiation (solid line) and sum of turbulent energy fluxes plus soil heat flux at depth (dashed line) (a) and the sum of energy fluxes, soil heat flux and energy storage (dashed line) (b) over 3 site-years at Chimney Park (US-Cpk), as well as energy balance difference and energy budget slope.

aspects of energy closure are only limited to just a select number of eddy covariance sites, results from 159 Tier 1 FLUXNET2015 sites were analyzed and shown in Fig. 7. When first grouped into northern (n = 132) and southern hemisphere (n = 27) locations for seasonal timing differences, average daily energy budget regression slopes show variation throughout the year. Sites show an increase in daily energy budget slopes from 0.48 and 0.55, in the north and south hemisphere respectively, to 0.69 and were highest during local growing seasons (JJA in the northern hemisphere and DJF in the southern hemisphere). When monthly time periods are used, e.g. monthly averages are first computed from 30-min data and diurnal patterns are no longer present, then regression results are calculated, the annual patterns of energy closure are opposite in that there is higher energy budget slopes in the winter time periods (DJF in the northern hemisphere and JJA in the southern hemisphere). Monthly energy closure varies from 0.61 and 0.46–0.92 and 0.95 in the north and south hemispheres respectively.

When the standard energy terms (H, LE, G, and excluding storage terms) of the FLUXNET2015 dataset are lagged in time between 0.5 and 4.5 h, site energy closure can be improved as shown in Fig. 8. Also shown in Fig. 8 are diurnal patterns of net radiation and the sum of surface heat fluxes (H + LE + G). The diurnal surface flux sums and its standard deviation is skewed relative to diurnal net radiation, with increased variation in surface heat fluxes in the afternoon. 8.4% of site-days had improved closure by at least 1% when H was lagged 0.5 h, 5.6% site-days improved when LE was lagged and when all three terms (H, LE, and G) were lagged, 19.9% site-days showed improvement of energy closure. The effect of improvement of closure from lagging all terms decreases with increasing time lags and at 4.5 h, 5.1% of sites-days show increased closure with all terms lagged, compared to 6.4% with H lagged and 5.5% with LE lagged.

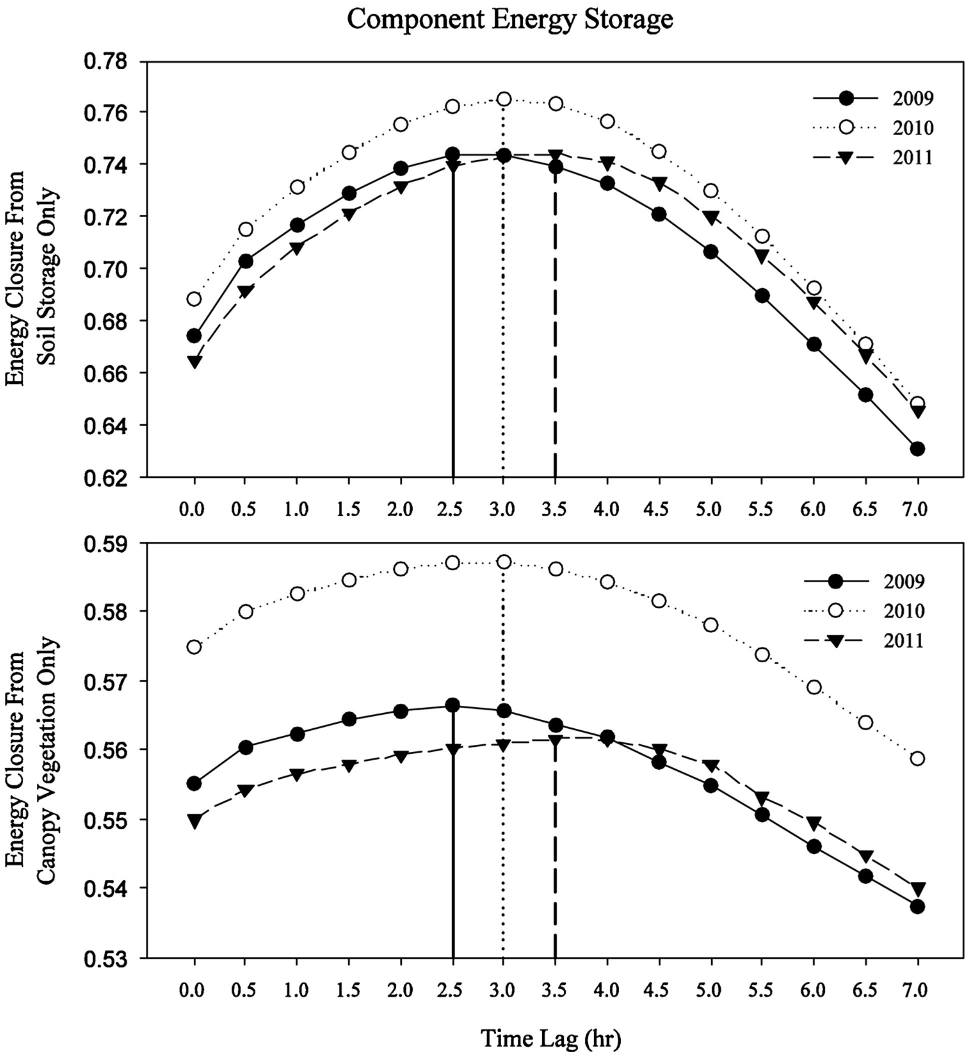

Fig. 6. Site energy closure slope, calculated as the regression of sum of energy fluxes, soil heat flux and energy storage terms as a function of net radiation, when soil heat storage (a) and canopy biomass storage (b) are lagged in time for three years of site data from Chimney Park (US-Cpk).

It also should be noted at FLUXNET2015 sites, when energy closure was compared using 30 min data to energy closure using monthly mean data, the relative importance to energy closure of the R_n, H, LE and G terms shifts. Due to the amount of daily variation of these terms at 30 min timescales that is averaged out when taking a daily, weekly or monthly mean value, the relationship during the course of the year of energy budget slopes changed. In the summer, closure was higher at 30 min timescales than when calculated from monthly means. Due to higher R_n and turbulent fluxes during summer days compared to winter days, there is also higher variation in the 30 min data, while the variation is lost when computing a daily, weekly or monthly mean, which lowers the energy closure.

4. Discussion

4.1. Variation in energy closure

The first motivating question for this study asked if ecosystem energy closure varies in time and this work presents a detailed analysis of variation of energy closure at annual and sub-annual timescales. At the Lost Creek wetland site, using eleven site-years of data, energy closure is shown to vary throughout an average site-year. When computed daily, both energy budget slope and energy budget differences were highest in the growing season and ranged from 0.43 in the non-growing season to 0.78 during the peak growing season. This is due to the relative importance of each energy term and their seasonal trends, which is similar to the results of Gerken et al. (2017). With higher net radiation and flux terms in the summer, energy closure is improved potentially for reasons as simple as an increased signal-to-noise ratio. When comparing individual months between years, differences in energy budget slope of were also observed. Data presented from June at US-Los showed variation in energy budget slope of up to 0.30 (0.53-0.84) between years, highlighting how much energy closure can vary under the best possible field conditions.

While similar analysis of energy closure variation in the literature is rare, the *meta*-analysis of Wilson et al. (2002) shows a similar yearly variation in energy closure slope over the course of a year, with the average energy closure slope over 19 site-years throughout North America being 0.66 in January and February to 0.80 in July and August. It is more common for studies focused on growing seasons to provide average energy closure over the period of study and then note that energy closure is different during the non-growing season. Amiro (2006) calculated energy closure ratio with large gaps during the winter, then applied corrections to annual fluxes.

Our second question examined what possible ecosystem processes could explain variation in energy closure and the annual variation is correlated with the site's phenology, as measured by the greenness index. The interannual variation is correlated with the amount of water being discharged from the ecosystem.

The correlation between water drainage from the ecosystem and partitioning of energy fluxes from wetlands seems to be dependent on the site and the timescale of the data. Results from the same wetland

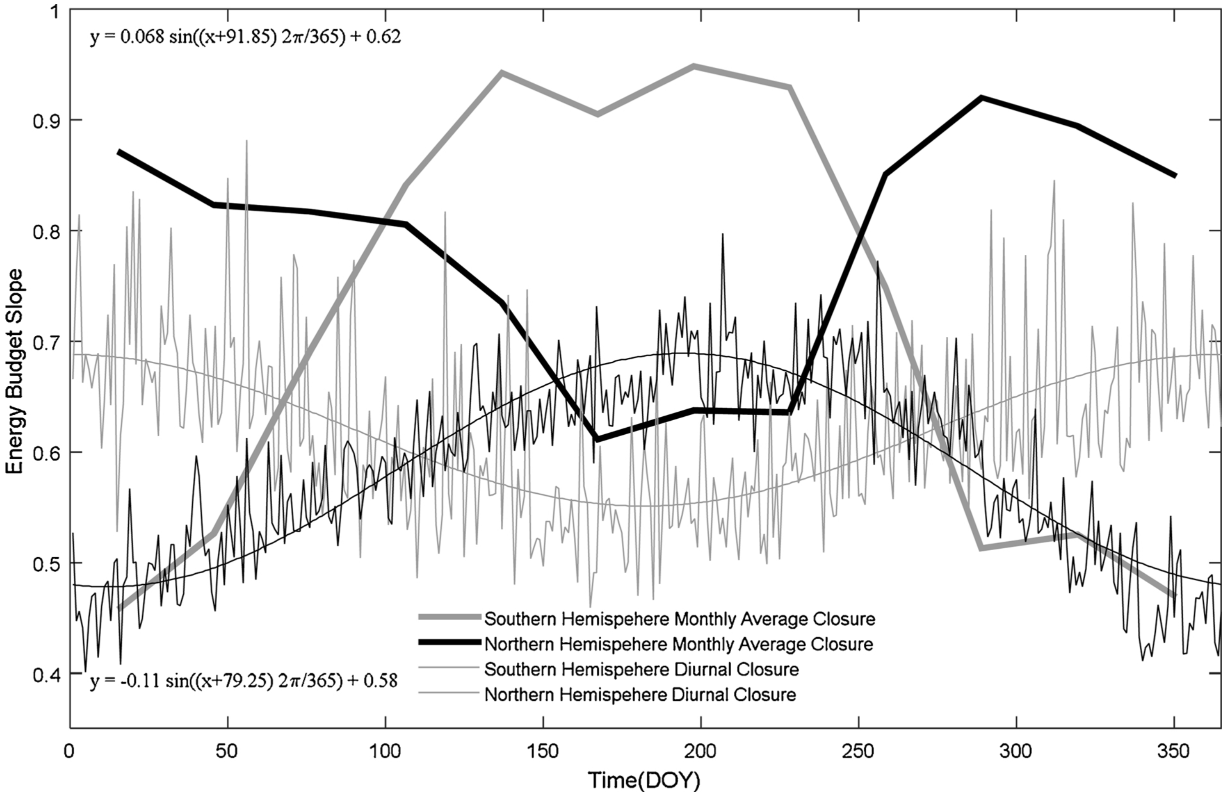

Fig. 7. Variation over an average year in FLUXNET2015 site energy closure, based on regression slope. Site separated by northern hemisphere (black, n = 132) and southern hemisphere (grey, n = 27). Bold lines shows monthly average regression energy closure at northern (bold black) and southern (bold grey) hemisphere sites.

site as this (Sulman Desai et al., 2009), show that annual water fluxes are correlated with water table depth over a seven year period, with higher latent heat fluxes during high water table periods. Results from a Western Canadian fen shows variation in water fluxes being only minority attributed (33%) to water table, with the majority (67%) of explanation coming from site radiation (Sonnentag et al., 2010) while 80% of the variance in water flux is attributed to net radiation in boreal peatlands (Wu et al., 2010). Furthermore, during the growing season only, Moore et al. (2013) shows no simple univariate relationship between water table depth and water fluxes during a water table manipulation experiment. Throughout the literature there is no clear relationship between water table levels and energy partitioning across sites.

However, a site's energy balance is more than just how surface fluxes are partitioned as the soil heat flux, storage and transport of heat are also components of overall energy balance. When comparing bog ecosystems to fens, Noormets et al. (2004) show that differences in soil heat flux can be attributed to the longwave emissivity of the plant species present. Noormets et al. (2004) also concludes that soil heat storage is dependent on both soil properties and site water table depth. Another reason soil heat flux and soil heat storage should be a function of water table depth is because heat capacity and thermal conductivity are a function of the soil's volume fraction of water (Hillel, 2005). In this work we highlight the lateral transport of heat as a function of water discharge from the ecosystem, but heat flux, storage and transport are, in part, controlled by a site's biological and physical processes, such as ecosystem phenology, plant community dynamics, and water discharge rates.

While site-dependent and complex, results from this study and the literature show the possibility of a connection between variation in site energy budget and underlying ecosystem processes. In the case of wetlands, changes in water discharge can drive changes in water flux and heat storage, and hence can drive changes in energy partitioning. However, the relationship between water table depth and water fluxes is linear at some sites (Ewers et al., 2007; Sulman Desai et al., 2009) and non-linear at others (Kim and Verma, 1996; Moore et al., 2013; Wu et al., 2010). While water flux response to water table depth is divergent, the relationship between water table depth and both soil heat flux and storage is less explored (Hillel, 2005; Noormets et al., 2004). Previous work in Canadian wetlands as part of the Boreal Ecosystem-Atmosphere Study shows annual trends in water fluxes, Bowen ratio, albedo and energy storage over the course of a single year (Lafleur et al., 1997), highlighting how soil water dynamics interact with all energy balance terms throughout the year. However, across all Tier 1 Fluxnet sites, site energy closure varies in time.

4.2. Improving site energy closure

Finally, question three sought to determine if the incorporation of temporal change in energy balance terms improved a site's energy closure. There has been abundant research on potential causes of energy closure, with some notable causes of energy balances not reaching closure including but not limited to landscape level heterogeneity (Stoy et al., 2013), landscape scale atmospheric circulation patterns and standing waves (Foken, 2008; Gao et al., 2017), the importance of energy storage terms (Meyers and Hollinger, 2004), periods of low turbulence (Wilson et al., 2002), footprint and time-averaging mismatches (Metzger et al., in review; Xu et al., in review), and instrument biases (Frank et al., 2016; Horst et al., 2016). Energy closure varies between sites, both in terms of the numerical amount of closure and the potential reasons. However, in the FLUXNET2015 dataset, there is an increased diurnal variation in surface fluxes relative to net radiation, particularly in the afternoon. Without the addition of storage terms to the surface energy balance equation, time-lagged surface fluxes can be used as an approximation of these missing storage terms, and results from this work show it can be a non-trivial factor in energy closure. In the FLUXNET2015 dataset, nearly 20% of site-days showed improvement of energy closure when flux terms were lagged 30 min from R_n,

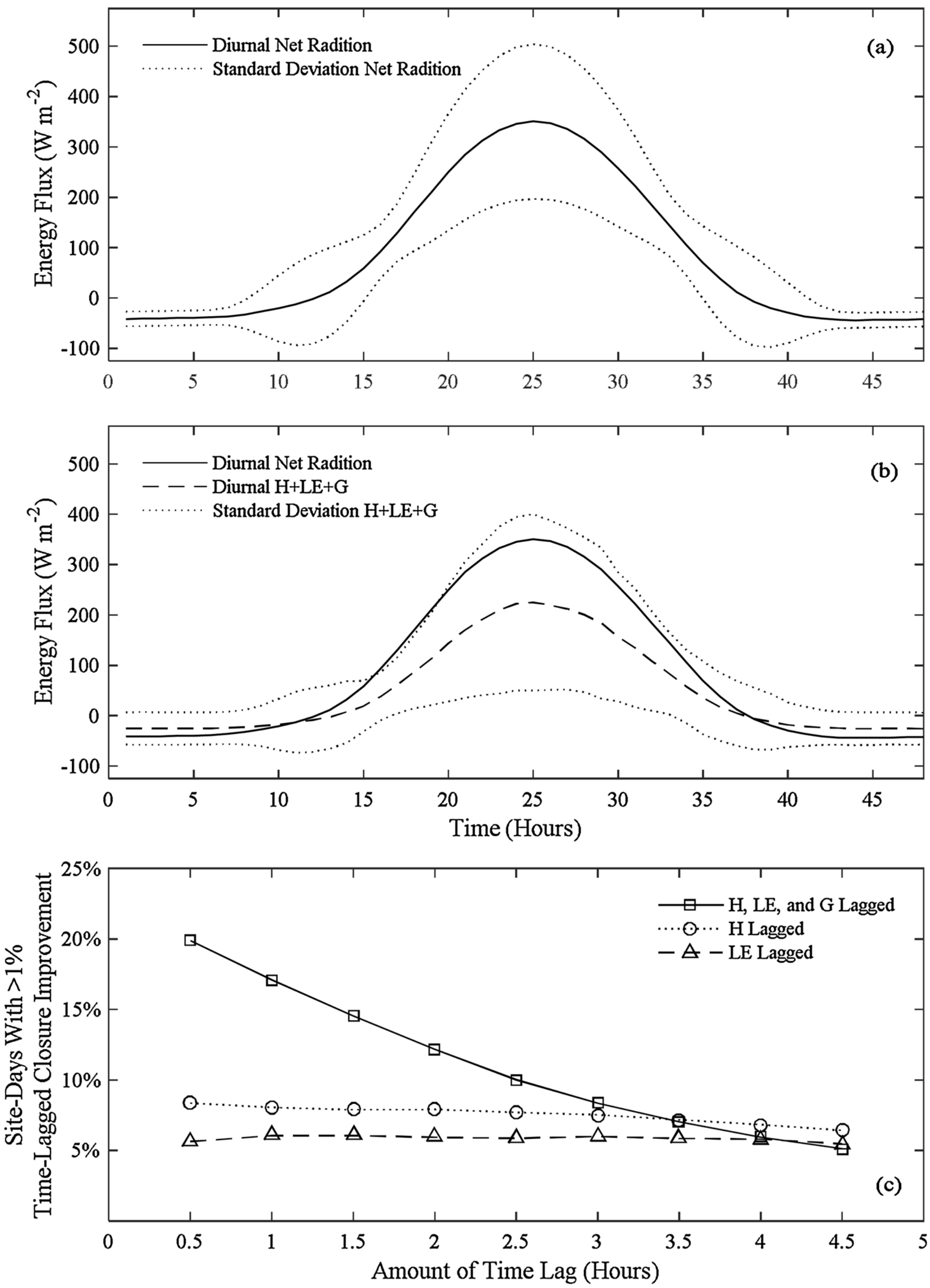

Fig. 8. Diurnal net radiation and its standard deviation (a) and diurnal sum of surface heat fluxes (H + LE + G) and its standard deviation (b), with diurnal net radiation plotted as a reference, across the entire FLUXNET2015 dataset. Percent of FLUXNET2015 site-days that show a 1% or better improvement in energy closure with all energy fluxes, sensible and latent heat fluxes lagged in time (c).

which we assume is because this lagging takes into account the unmeasured temporal effects of biomass and soil heat and moisture storage, which are then imprinted subsequent turbulent fluxes.

When calculated using hourly, multi-hour or daily values, reported energy closure at sites have been reported to vary (Gerken et al., 2017), pointing to energy closure having an important temporal aspect. As part of the review on the topic, Leuning et al. (2012) presented data from Glacier Lakes Ecosystem Experiments Site (GLEES) and Virginia Park that shows the energy slope balance was 0.72 and 0.92 respectively when calculated at hourly timescales, but decreased to 0.69 and 0.84 respectively when calculated on daily timescales. The decrease in energy closure slope when averaging from hourly to daily time scales at select sites implies that the common assumption that energy storage terms are required to balance over a 24 h period could not hold true at some sites and that energy storage can be more complex than previously thought because the energy coming into a storage term does not leave within 24 h. The rational in Leuning et al. (2012) is that, for the GLEES site in particular, complex terrain and advective flux divergences due to drainage flows may be high at the site, which would add further complexity to energy storage. In this work, we show energy slope balance can be more complex than even just calculated from hourly or daily values and that when choosing hourly or daily averaging timescales as well as examining closure over annual or seasonal time periods, one must consider the multiple included assumptions.

When energy storage terms are lagged in time at the Chimney Park site, an optimal time-lag that changed by year can be found. Reed et al. (2016) shows the amount of energy storage at this site is connected to declines in canopy LAI and water flux from the ongoing bark beetle disturbance. This has the mechanistic effect of increasing the amount of soil water, and hence the total soil energy storage while decreasing the total amount of canopy biomass energy storage as tree boles dry out after mortality. While there are changes to the net amount of energy storage due to the increasing ecosystem mortality, there is also an increase in the effect time-lags have on energy closure. This time-lag changing between years can not only be used to improve the site's energy closure, but can also be connected to biophysical processes responding to the ecosystem disturbance. This increases trust in the turbulent flux measurements as energy closure improves and at the same time, provides supporting evidence of ecological results (Reed et al., 2016). We do not assume all sites to exhibit similar interannual variation in energy closure, but this work shows that further examination of energy terms at disturbance or successional studies would be justified.

It has been shown that surface heterogeneity at the sub-footprint scale is important for soil heat flux (Kustas et al., 2000; Shao et al., 2008) and also that soil heat flux measurements have a time dependency as a component of the measurement (Ochsner et al., 2007). Due to the spatial location of a soil heat flux plate several cm below the surface, there is an intrinsic time delay between thermal energy being absorbed at the soil-atmosphere surface and moving to depth (Hillel, 2005) and accounting for the time dependency of soil heat capacity is an accepted method for incorporating the time-lag within the soil profile (Ochsner et al., 2007). However, heat diffusion formulations can numerically dampen soil heat flux by not capturing rapid fluctuations in soil heat flux (≤ 30 min) which therefore introduce errors in energy partitioning. (Gentine et al., 2011). Without the required soil heat capacity and soil water content information needed to calculate the time derivative of soil heat capacity from Ochsner et al. (2007), preforming a best-fit time-lag analysis of soil energy terms as presented here would incorporate the time dependent phase shift of the temperature wave propagating through the soil, although potentially not the temperature damping.

5. Conclusions

While the spatial aspect of eddy covariance observations and energy balance has been well studied, the temporal considerations and assumptions of observations are often disregarded. This study demonstrates that energy closure at a site is not a static value, but varies in time and is reflective of the state of the ecosystem. This variability at a wetland study site is connected to the monthly and interannual amount of water flowing through the wetlands. While previous work at a site undergoing bark beetle disturbance demonstrates the impact of increasing mortality on energy budget terms, this work shows how the addition of time-lags to energy storage can increase energy closure at a site. Throughout all sites in the FLUXNET2015 dataset, when energy balance terms have time lags applied, site energy closure improves at 20% of site-days.

The implications of considering the temporal aspect of energy balance terms is twofold. First, when applying time-lags of energy balance terms at unique study sites, site energy balance can be incrementally improved. With this improvement comes increased confidence in both energy and mass flux observations. Secondly, at select sites where ecosystem processes such as heat advection, horizontal energy flow or physical canopy changes are important factors, examining variation in energy balance can provide an indirect and independent estimation of these processes. While every site is unique, further investigation of variations in energy balance could help address the lack of energy-balance conservation across eddy covariance field sites.

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