

RESEARCH ARTICLE

10.1002/2014JG002700

Key Points:

- Patterns in energy partitioning covaried with hydroperiods and climate
- There were seasonal differences in the ratio of ET:precipitation
- Energy balance closure was within the range found at other wetland sites

Correspondence to:

S. L. Malone,
slmalone@crimson.ua.edu

Citation:

Malone, S. L., C. L. Staudhammer, H. W. Loescher, P. Olivas, S. F. Oberbauer, M. G. Ryan, J. Schedlbauer, and G. Starr (2014), Seasonal patterns in energy partitioning of two freshwater marsh ecosystems in the Florida Everglades, *J. Geophys. Res. Biogeosci.*, 119, 1487–1505, doi:10.1002/2014JG002700.

Received 29 APR 2014

Accepted 5 JUL 2014

Accepted article online 7 JUL 2014

Published online 5 AUG 2014

Seasonal patterns in energy partitioning of two freshwater marsh ecosystems in the Florida Everglades

Sparkle L. Malone^{1,2}, Christina L. Staudhammer¹, Henry W. Loescher^{3,4}, Paulo Olivas⁵, Steven F. Oberbauer⁵, Michael G. Ryan^{2,6}, Jessica Schedlbauer^{5,7}, and Gregory Starr¹

¹Department of Biological Sciences, University of Alabama, Tuscaloosa, Alabama, USA, ²Rocky Mountain Research Station, U.S. Forest Service, Fort Collins, Colorado, USA, ³National Ecological Observatory Network Inc., Boulder, Colorado, USA, ⁴Institute of Arctic and Alpine Research, University of Colorado Boulder, Boulder, Colorado, USA, ⁵Department of Biological Sciences, Florida International University, Miami, Florida, USA, ⁶Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado, USA, ⁷Department of Biology, West Chester University of Pennsylvania, West Chester, Pennsylvania, USA

Abstract We analyzed energy partitioning in short- and long-hydroperiod freshwater marsh ecosystems in the Florida Everglades by examining energy balance components (eddy covariance derived latent energy (LE) and sensible heat (H) flux). The study period included several wet and dry seasons and variable water levels, allowing us to gain better mechanistic information about the control of and changes in marsh hydroperiods. The annual length of inundation is ~5 months at the short-hydroperiod site (25°26'16.5"N, 80°35'40.68"W), whereas the long-hydroperiod site (25°33'6.72"N, 80°46'57.36"W) is inundated for ~12 months annually due to differences in elevation and exposure to surface flow. In the Everglades, surface fluxes feed back to wet season precipitation and affect the magnitude of seasonal change in water levels through water loss as LE (evapotranspiration (ET)). At both sites, annual precipitation was higher than ET (1304 versus 1008 at the short-hydroperiod site and 1207 versus 1115 mm yr⁻¹ at the long-hydroperiod site), though there were seasonal differences in the ratio of ET:precipitation. Results also show that energy balance closure was within the range found at other wetland sites (60 to 80%) and was lower when sites were inundated (60 to 70%). Patterns in energy partitioning covaried with hydroperiods and climate, suggesting that shifts in any of these components could disrupt current water and biogeochemical cycles throughout the Everglades region. These results suggest that the complex relationships between hydroperiods, energy exchange, and climate are important for creating conditions sufficient to maintain Everglades ecosystems.

1. Introduction

Land use change has led to substantial wetland loss (50% globally) [Mitsch and Gosselink, 2007] and has modified terrestrial energy and water budgets enough to alter climate patterns [Pielke et al., 1999; Chapin et al., 2002]. Energy dynamics are key to ecosystem analysis [Odum, 1968] because of their influence on the hydrologic cycle, which regulates other biogeochemical processes [Chapin et al., 2002]. In wetland ecosystems where hydroperiods strongly influence ecosystem structure and function [Davis and Ogden, 1994; Childers et al., 2006; Mitsch and Gosselink, 2007], the energy balance has a direct impact on climate and ecosystem processes. Given the vital role of energy and hydrologic cycles on wetland ecosystem function, it is critical that we understand their controls and the extent to which they have been modified by human actions.

Extensive land cover change has occurred in the Florida Everglades [Pielke et al., 1999; Marshall et al., 2004] where 53% of the original extent has been lost to drainage [Reddy and Delaune, 2008], development, and agriculture [Davis and Ogden, 1994]. These ecologically important systems have distinct wet and dry seasons that produce considerable variation in the hydrologic cycle, affecting nutrient delivery, ecosystem primary production, and ecosystem structure, which ultimately feeds back to contribute to the water cycle [Davis and Ogden, 1994]. While seasonal patterns in water cycling are heavily influenced by anthropogenic pressures (i.e., water control structures), implementation of the Comprehensive Everglades Restoration Plan (CERP) and future climate projections are predicted to have appreciable impacts on hydrologic patterns. To date the links between energy partitioning, climate, and hydrologic dynamics in short- and long-hydroperiod Everglades ecosystems have not been fully explored, making it important to develop an understanding of

these interactions and what they mean for Everglades hydrology prior to critical changes in water management and climate. Here hydroperiod refers to the seasonal pattern of water level [Mitsch and Gosselink, 2007] and duration of inundation [Schedlbauer et al., 2011].

Patterns in energy partitioning, among different ecosystems, can result from changes in environmental conditions [Lafleur, 2008; Twine et al., 2000; Wilson et al., 2002; da Rocha et al., 2004]. In wetland ecosystems energy is stored in the soil and/or water column (G) and is also partitioned as sensible heat flux (H) and latent energy flux (LE) [Lafleur, 2008; Piccolo, 2009; Schedlbauer et al., 2011]. Seasonality influences H and LE partitioning, which covary with fluctuations in hydroperiods [Schedlbauer et al., 2011]. Surface fluxes (H and LE) drive seasonal patterns in water level through their influence on water loss as LE (evapotranspiration (ET)) and convective rain, the main source of wet season precipitation [Myers and Ewel, 1992]. During the dry season, the Bermuda High pressure cell prevents convective clouds from forming thunderstorms, making continental fronts the main source of precipitation [Chen and Gerber, 1992]. This switch from wet season tropical climate to dry season temperate climate causes distinct changes in the amount of precipitation in the region [Chen and Gerber, 1992] and combined with constant water loss as LE produces seasonal fluctuations in water levels [Davis and Ogden, 1994; Myers and Ewel, 1992].

Driving and responding to changes in hydroperiods, H , and LE are important for describing seasonal changes in water and energy in the Everglades region. Schedlbauer et al. [2011] examined how the components of the energy balance changed seasonally in short-hydroperiod freshwater marsh ecosystems, showing that during the dry season more available energy was partitioned as H , and LE was the dominant flux during the wet season when water levels were typically above the soil surface. In addition to seasonal changes in R_n , soil volumetric water content (VWC), water depth, air temperature (T_{air}), and occasionally vapor pressure deficit (VPD) exhibited strong relationships with H and LE [Schedlbauer et al., 2011]. Although previous research has evaluated energy balance in Everglades freshwater marsh, no study has quantified the links between climate, energy exchanges, and hydroperiods or determined how these factors interact to influence seasonal hydrologic dynamics in marshes with different hydroperiods and over multiple years of study.

At the landscape scale, Everglades hydrologic dynamics are a complex function of weather patterns, topography, and water management [Davis and Ogden, 1994; Richardson, 2008]. Historical hydroperiods were determined by the combined effects of precipitation and runoff (inputs) and evapotranspiration (ET) and drainage (outputs). Small variations in elevation throughout the landscape regulate the degree of exposure to surface flow that originated in the north from Lake Okeechobee and moved south as sheet flow. Presently, the system is subject to substantial anthropogenic control through a complex system of canals, levees, and pumping stations [Loveless, 1959; Davis and Ogden, 1994]. As a result of water management activities, reduced water flow from Lake Okeechobee changed the natural characteristics of the Everglades wetland ecosystems [Davis and Ogden, 1994; Richardson, 2008]. Position within the landscape is important in understanding the seasonal patterns in water levels, the effects of anthropogenic water management on hydrologic dynamics, and ultimately the system's energy balance [Davis and Ogden, 1994; Richardson, 2008].

Evaluating links between hydroperiods and Everglades energy balance is especially important in light of imminent changes in water management and climate change. Current water management practices will be modified under the CERP, with the goal to reestablish the hydroperiods closer to natural seasonal regimes and to ameliorate areas that suffer from chronically low water levels [Perry, 2004]. This could increase the amount of available energy partitioned into LE and potentially affect the current (albeit altered) ecosystem structure, hydrologic dynamics, and local climate. What is not known is: how will changes in hydroperiod and water depth affect the controls on H and LE ? What are the pace, pattern, and potential feedbacks of this action? The complex interactions between environmental conditions and energy drive changes in ecosystem function (e.g., higher LE reduces ecosystem water levels thereby increasing the amount of exposed leaf area), making it important to understand the links between hydroperiods and surface fluxes in the Everglades region.

The goal of this research is to develop a quantitative understanding of how energy partitioning interacts with climate and hydrologic dynamics in short- and long-hydroperiod wetlands of Everglades National Park and explore if these ecosystems respond similarly to these changes. We hypothesize that (1) variations in the extent and timings of peak surface fluxes will indicate the magnitude of seasonal response in hydroperiods and (2) T_{air} , VPD , and VWC will exhibit significant positive relationships with H and LE that will vary by site as a result of dissimilarities in hydroperiods. Although changes in surface flow in response to precipitation patterns

produce seasonal differences in water levels, the magnitude of difference is controlled by interactions between surface flow (inputs) and the loss of water as LE (ET) to the atmosphere. At the short-hydroperiod site, where surface water inputs are much less than at the long-hydroperiod site, we expect that patterns (magnitude and timing of the peak) in H and LE will reflect the seasonal differences in water levels. Additionally, we expect differences in the magnitude of H and LE will be the result of dissimilarities in environmental controls at the sites. Both H and LE should exhibit positive relationships with T_{air} , VPD, and VWC. H is the amount of energy needed to change T_{air} , which influences atmospheric water holding capacity and therefore VPD and VWC.

2. Materials and Methods

2.1. Study Site

The Everglades are classified as subtropical wetlands with distinct wet and dry seasons during the summer and winter months respectively. Long-term (1963 to 2012) mean maximum and minimum daily temperatures were 29°C and 18°C, respectively (National Climatic Data Center, Royal Palm Ranger Station; 25°23'N/80°36'W), with the lowest daily temperatures in January and highest daily temperatures in August [Davis and Ogden, 1994]. The Everglades receive approximately 1380 mm of precipitation annually [Davis and Ogden, 1994]. The majority of rainfall (~70%) occurs during the wet season (May to October) as convective thunderstorms and tropical depressions, e.g., storms and hurricanes [Davis and Ogden, 1994]. During the dry season (November to April), general circulations switch from the summer Bermuda High [Wang et al., 2010; Li et al., 2011] to a continental-based high, causing cold fronts to contribute toward seasonal precipitation [Davis and Ogden, 1994].

The study sites are two oligotrophic freshwater marsh ecosystems that are part of the Florida Coastal Everglades (FCE) Long-Term Ecological Research (LTER; TS-1 and SRS-2). Although just 24 km apart, small variations in elevation influence the degree of exposure to surface flow resulting in contrasting hydroperiods at Taylor Slough (TS) and Shark River Slough (SRS). Taylor Slough (25°26'16.5"N, 80°35'40.68"W) is a short-hydroperiod marsh that is flooded for 4 to 6 months each year (June to November) and is characterized by shallow marl soils (~0.14 m) overlying limestone bedrock (FCE-LTER, <http://fcelter.fiu.edu/research/sites/>). Taylor Slough has a continuous canopy dominated by short-statured (height, $Z = 0.73 \text{ m} \pm 0.01 \text{ SE}$), emergent species, *Cladium jamaicense* (Crantz) and *Muhlenbergia capillaris* (Lam.). Microalgae that live on submerged substrates form periphyton [Davis and Ogden, 1994] and when the site is dry, the periphyton exists as a desiccated mat between individual plants and covering the soil surface. Shark River Slough (25°33'6.72"N, 80°46'57.36"W) is a long-hydroperiod marsh that is inundated ~12 months each year and is characterized by peat soils (~1 m thick) overlying limestone bedrock with ridge and slough microtopography [Duever et al., 1978]. For this site, average Z is 1.02 m ($\pm 0.03 \text{ SE}$). In ridge areas, SRS is dominated by tall, dense emergent species, *Cladium jamaicense*, *Eleocharis* sp., and *Panicum* sp., while short-statured, submerged species (*Utricularia* sp.) dominate the sloughs. Periphyton also exists on submerged structures as floating mats at SRS.

Both marsh systems extend for several kilometers in all directions around the study sites except to the east at TS where there is a canal and levee at a distance of 450 m (outside of the flux tower footprint). Everglades freshwater marshes have a year-round growing season, though seasonal changes in average monthly leaf area have been observed [Jimenez et al., 2012]. At TS average monthly leaf area index (LAI) ranges from 0.2 to 0.4 and at SRS LAI ranges from 0.2 to 0.9 [Jimenez et al., 2012]. At both sites LAI is higher in the dry season when water levels are lower and decline in the wet season when water levels rise [Jimenez et al., 2012]. At both sites canopy height was measured at plot center in 100 plots along a transect. Canopy height and roughness were consistent throughout the wet and dry season at TS and SRS. Zeroplane displacement and the roughness length were estimated to be 65% (0.5 and 0.6 m at TS and SRS, respectively) and 10% (0.1 m at TS and SRS) of the canopy height, respectively (for a more detailed description of the vegetation, see Davis and Ogden [1994]).

2.2. Eddy Covariance and Micrometeorology

At TS and SRS, LE and H were measured from 1 January 2009 to 31 December 2012 using open-path eddy covariance methods [Moncrieff et al., 1996; Ocheltree and Loescher, 2007]. Open-path infrared gas analyzers (IRGAs; LI-7500, LI-COR Inc., Lincoln, NE) were used to measure water vapor molar density (ρ_w ; mg mol^{-1}), and sonic anemometers (CSAT3, Campbell Scientific Inc, Logan, UT) were employed to measure sonic temperature (T_s ; K) and three-dimensional wind speed (u , v , and w , respectively; m s^{-1}). These sensors were 0.09 m apart and installed 3.30 and 3.24 m above ground level at TS and SRS, respectively. Data were logged

at 10 Hz on a data logger (CR1000, Campbell Scientific Inc.) and stored on 2 GB CompactFlash cards. Both IRGAs were calibrated monthly using dry N₂ gas and a portable dew point generator (LI-610, LI-COR Inc.). Footprint analyses [Kljun *et al.*, 2002, 2004] indicated that 80% of measured fluxes were from within 100 m of the tower during near-neutral conditions. During unstable conditions most (70%) of the fluxes were from within 50 m of the tower, and under stable conditions the flux footprint ranged from 10 to 250 m at both sites. Other meteorological variables measured at 1 s and collected as half-hourly averages and acquired by the same data logger included: air temperature (T_{air} ; °C) and relative humidity (Rh; %) (HMP45C, Vaisala, Helsinki, Finland) mounted within an aspirated shield (43502, R. M. Young Co., Traverse City, MI) and barometric pressure (P ; atm) (PTB110, Vaisala). The T_{air} /Rh sensors were installed at the same height as the IRGA and sonic anemometer.

At each site, additional meteorological data were measured at 15 s and collected as 30 min averages through a multiplexer (AM16/32A Campbell Scientific Inc.) with another data logger (CR10X Campbell Scientific Inc.). This included photosynthetically active radiation (PAR; $\mu\text{mol m}^{-2} \text{s}^{-1}$) (PAR Lite, Kipp and Zonen Inc., Delft, Netherlands), incident solar radiation (R_s ; W m^{-2}) (LI-200SZ, LI-COR Inc.), and R_n (W m^{-2}) (CNR2-L, Kipp and Zonen). Precipitation measurements were made with tipping bucket rain gages (mm) (TE525, Texas Electronics Inc., Dallas, TX). Soil volumetric water content (VWC; %) was calculated following Veldkamp and O'Brien [2000] with equations developed for peat and marl soils which utilize the dielectric constant using two soil moisture sensors (CS616, Campbell Scientific Inc.) installed at a 45° angle at the soil surface. Thus, measurements are an integration from 0 to 15 cm depth at each site. Soil temperature (T_{soil} ; °C) was measured at 5 cm, 10 cm, and 20 cm depths at two locations within each site using insulated thermocouples (Type-T, Omega Engineering Inc., Stamford, CT). When inundated at SRS, water temperature (T_w ; °C) was measured using two pairs of insulated thermocouples located at a fixed height (5 cm) above the soil surface and another attached to shielded floats that held the thermocouples 5 cm below the water surface. At TS, T_w was measured using insulated thermocouples located at a fixed height 2 cm below the water surface when water levels were above the soil surface. Water level (m) at both sites was recorded every half hour with a water level logger (HOB0 U20-001-01, Onset, Bourne, MA).

2.3. Governing Equations

The energy budget is illustrated in Figure 1 and defined in (1). Each term represents an average energy flux over a half-hour period,

$$R_n = H + LE + G_w + G_{w+s} \quad (1)$$

where, R_n is the net radiation (W m^{-2}), H is the sensible heat flux (W m^{-2}), LE is the latent heat flux in the change of phase of water, i.e., vaporization or condensation (W m^{-2}), G_w is the change in energy storage associated with the water above the soil surface (W m^{-2}), and G_{w+s} is the change in energy storage in the matrix of both the water and the soil below the soil surface (W m^{-2}).

Vertical windspeed (w) was first estimated mean to streamline using a 2-D rotation in a Cartesian coordinate framework [Loescher *et al.*, 2006]. The H was then determined using the covariance of the turbulent fluctuations (noted as primes) of w and T_s [Loescher *et al.*, 2006] and the block average, $\overline{w'T'_s}$, estimated over a 30 min averaging period (noted as overbar), such that,

$$H = \rho_{air} C_p (\overline{w'T'_s} - (0.000321 T_k \overline{w'q'})) \quad (2)$$

where ρ_{air} is the air density (kg m^{-3}), C_p is the specific heat of air at constant pressure ($\text{J kg}^{-1} \text{°C}^{-1}$), $\overline{w'q'}$ is the covariance of the turbulent fluctuations in w and the molar fraction of water vapor calculated by unit conversion of ρ_v . Corrections for the effect of water vapor on the speed of sound were applied [Schotanus *et al.*, 1983]. Here actual air temperature is estimated from the sonic temperature, T_k (K),

$$T_k = \frac{T_s + 273.15}{1 + 0.000321q} \quad (3)$$

Simialry, LE (W m^{-2}) was calculated from the covariance of the turbulent fluctuations of w and ρ_v (mg mol^{-1}) and averaged over 30 min,

$$LE = \frac{P}{RT_s} \frac{M_{air}}{M_w \cdot 10^3} \lambda \overline{w'\rho_v'} \quad (4)$$

where R is the ideal gas constant ($0.082 \text{ L atm K}^{-1} \text{ mol}^{-1}$), λ is the heat of vaporation (J g^{-1}), M_{air} and M_w are the molecular weights of air ($28.965 \text{ g mol}^{-1}$) and water (18.01 g mol^{-1}), respectively, and 10^3 is a conversion

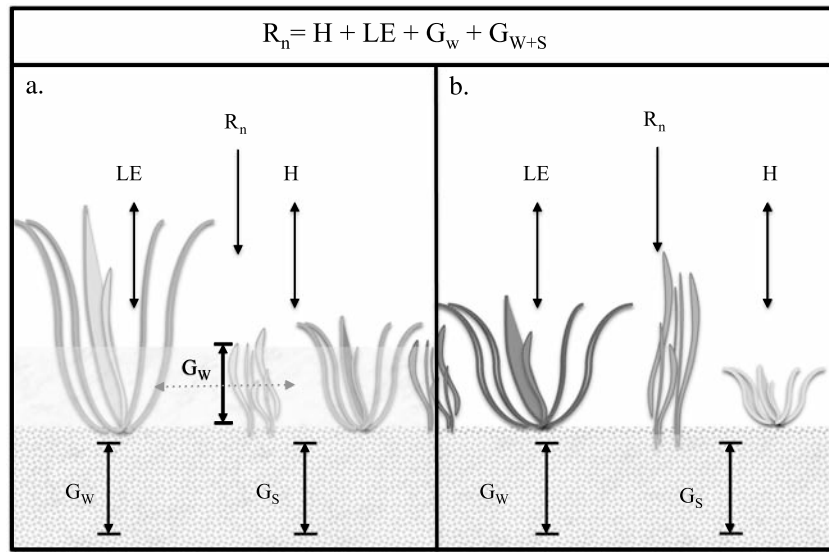


Figure 1. Energy budget for wetland ecosystems with distinct (a) wet and (b) dry seasons. LE is the dominant flux component in wetland ecosystems. Energy partitioned to H increases during the dry season as shown in Figure 1b when water levels are below the soil surface. Energy fluxes in the water column (G_w) and in the soil (G_s) are important in these systems, as the storage potential is great and energy stored in the standing water and soil is partitioned as H and LE flux. Energy in the water column also flows horizontally (grey dotted line); due to homogeneity in the landscape the horizontal flux is assumed negligible at TS and SRS.

factor (g to mg). Corrections for thermal and pressure related expansion and/or contraction, and water dilution were applied [Webb *et al.*, 1980].

Data (H and LE) were processed with EdiRe (v. 1.4.3.1184, [Clement, 1999]) following standard protocols, including despiking [Aubinet *et al.*, 2000], and both measurements were filtered when systematic errors in either H or LE were indicated, such as (1) evidence of rainfall, condensation, or bird fouling in the sampling path of the IRGA or sonic anemometer, (2) incomplete half-hour data sets during system calibration or maintenance, (3) poor coupling of the canopy with the external atmospheric conditions, as defined by the friction velocity, u^* , using a threshold $<0.15 \text{ m s}^{-1}$ [Goulden *et al.*, 1996; Clark *et al.*, 1999], or (4) excessive variation from the half-hourly mean based on analysis of standard deviations for u , v , and w winds and CO_2 statistics. Quality assurance of flux data was also maintained by examining plausibility tests of H and LE values (<-100 or $>800 \text{ W m}^{-2}$), stationarity criteria, and integral turbulent statistics [Foken and Wichura, 1996]. At TS 38% and 77% of the daytime and nighttime data were filtered, respectively. At SRS, 34% of daytime data and 70% of nighttime data were filtered. Missing H and LE values were then gap filled using the linear relationship between H or LE and R_n on a monthly basis. When R^2 values were less than 70%, annual relationships between R_n and H or LE were used to gap fill data in that month. Less than 5% of filtered data were filled with annual equations.

Heat flux (G_w) stored within the water column was determined by measuring temperature differences between the surface and the bottom of the water column (above the soil surface). As a result of site hydrological characteristics, thermocouple placement within the water column differed at SRS and TS. At SRS thermocouples measured water temperature at the surface and at the bottom of the water column. The linear relationship between surface water temperature and water temperature at the bottom of the water column was determined via linear regression at SRS ($R^2 > 90\%$). At TS thermocouples were only present at the water surface, and thus, a linear relationship established at SRS was used to estimate the temperature at the bottom of the water column at TS. The change in vertical temperature profile from the 30 min averaging period to the next ($\partial T_w / \partial t$) was used to determine the energy flux in the water column [Campbell and Norman, 1998]:

$$G_w = C_{pw} \rho_w \int_{z_0}^z \frac{\partial T_w}{\partial t} \partial z \quad (5)$$

where C_{pw} is the specific heat of liquid water ($\text{J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$), ρ_w is water density (kg m^{-3}), z is the water depth (m), and z_0 is the bottom of the water column.

Using the temperature profile for the soil, and the fraction of mineral, organic matter, and water in the soil, G_{s+w} was determined from the matrix of water and soil, below the soil surface, using a two-component approach:

$$G_{s+w} = aC_{pw}\rho_w \int_{z_0}^z \frac{\partial T_w}{\partial t} dz + bC_{ps}\rho_s \int_{z_0}^z \frac{\partial T_{soil}}{\partial t} dz \quad (6)$$

where a and b are the fractions of water and soil, respectively, below the soil surface, C_{ps} is the specific heat of the soil ($J\ kg^{-1}\ ^\circ C^{-1}$), ρ_s is the soil bulk density ($kg\ m^{-3}$), $\partial T_{soil}/\partial t$ is the change in vertical temperature profile of the soil, and z is the soil depth (0.10 m).

Evapotranspiration (mm) was calculated from LE data using the heat of vaporization (λ) and water density (ρ_w). For equations (5) and (6), ρ_w was calculated as a nonlinear function of temperature using known water density values at specified temperatures following *Campbell and Norman* [1998].

2.4. Data Analyses

Models were formulated to explore the complex relationships between R_n and surface fluxes (H and LE), with environmental variables (T_{air} , water depth, VPD, and VWC). Models for the Bowen ratio (β), which is the ratio of H to LE, were also estimated. The β is important to describe site hydrologic conditions. For example, when LE dominates surface fluxes ($\beta < 1$), water moves from the ecosystem to the atmosphere, lowering the amount of available free water for evaporation (i.e., water levels and soil moisture content).

As a result of autocorrelation, observations recorded at 30 min time intervals are not independent, violating the underlying assumptions of general linear modeling approaches [Brocklebank and Dickey, 2003]. To address the serial dependence inherent in data collected over time, a time series approach, utilizing autoregressive integrated moving average (ARIMA) models, to identify and describe the relationship between environmental variables and energy fluxes was used. In ARIMA models, autocorrelation in a data stream is explicitly accounted for by incorporating its past values. These models incorporate three types of components: autoregressive (AR) of order p , moving average (MA) of order q , and if necessary, differencing of degree d . ARIMA models fit to time series data use AR and MA terms to describe their serial dependence and can also use other time series data as independent variables to explain their dependence on outside factors.

First, both dependent and independent variables were tested for stationarity via the augmented Dickey-Fuller test [Dickey and Fuller, 1979] and differenced if necessary. Differencing was required when time series exhibited nonstationarity [Pankratz, 1983]. Stationary processes are those where the mean and standard deviation do not change over time. ARIMA models were then fit to time series for R_n , H , LE, and β using an iterative Box-Jenkins approach: (1) autocorrelation and partial autocorrelation analysis were used to determine if AR and/or MA terms were necessary for the given time series, (2) model coefficients were calculated using maximum likelihood techniques, and (3) autocorrelation plots of model residuals were examined to further determine the structure of the model [Brocklebank and Dickey, 2003].

Explanatory variables were selected for analysis based on the literature [Burba et al., 1999a; Schedlbauer et al., 2011; Jimenez et al., 2012] and included the following: T_{air} , VPD, water level, and soil VWC. A temporary intervention to examine the effect of season was also included by incorporating an indicator series into the model. Because the presence of autocorrelation in the explanatory series can lead to misleading conclusions about the cross correlations between series, autocorrelation was removed from all input series via a process called prewhitening [Brocklebank and Dickey, 2003]. ARIMA models were then fit to the dependent variables using the prewhitened explanatory series as predictor variables. Plots of cross-correlation functions between each explanatory series and dependent variables were used to identify relationships at various lags or time shifts, and autocorrelation plots of the residuals verified that the residual series had characteristics of random error, or white noise (i.e., nonsignificant correlation coefficients at nonzero time lags).

Model selection was based on minimum Akaike's information criterion (AIC), and models were acceptable when residual white noise was minimized [Hintze, 2004]. A backward selection method was used, removing the least significant parameter one at a time until all regression terms in the final model were significant at the $\alpha = 0.05$ level and/or no improvement was made in the AIC. Models of R_n , H , LE, and β were estimated separately by site, but model forms were kept the same to aid in site comparisons. Nonsignificant parameters remained in a particular site's model if they were significant in the other site and showed no effect on the final model of the subject site. ARIMA model assumptions of normality and independence of residuals were

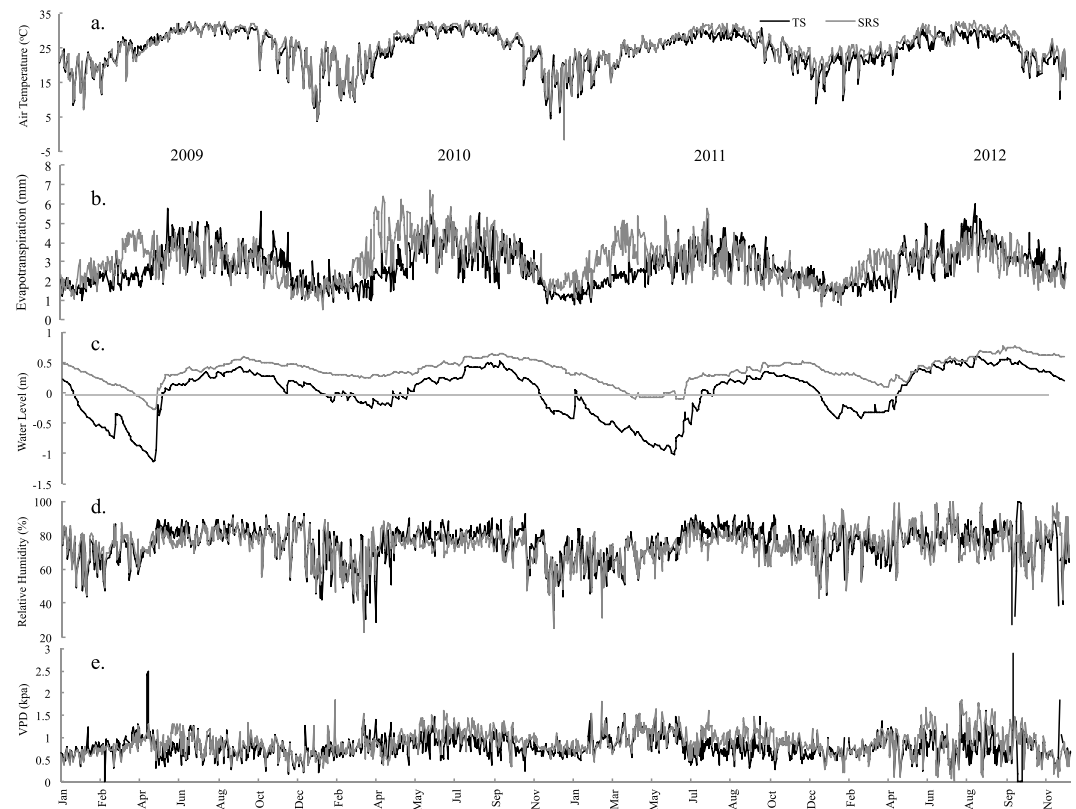


Figure 2. (a) T_{air} , (b) ET, (c) water level, (d) Rh, and (e) VPD at TS and SRS from 2009 to 2012. Patterns in T_{air} , ET, Rh, and VPD were similar by site.

evaluated by examining residual plots. Multicollinearity between explanatory variables was also explored to ensure models did not contain input series that were highly correlated.

2.5. Energy Balance

Energy balance closure was analyzed daily due to lags in storage terms where energy stored earlier in the day was released in the afternoon [Leuning *et al.*, 2012; Gao *et al.*, 2010]. Half-hourly values for each component of the energy balance, R_n , H , LE, G_w , and G_s were converted to units of MJ m^{-2} and summed over each day. Energy balance was evaluated by plotting the daily sum of H and LE versus the difference, $R_n - G_s$ (water level < 0) or $R_n - G_s - G_w + s$ (water level > 0). Linear regression was used to assess the percentage of energy balance closure for each site. Closure was examined separately when water levels were above the soil surface and when water levels were below the soil surface.

3. Results

3.1. Environmental Conditions

Over the study period, the magnitude and seasonal patterns in Rh, T_{air} and VPD were similar for both sites (Figure 2); however, the average annual rainfall was slightly higher for TS (1304 mm yr^{-1}) than for SRS (1207 mm yr^{-1}). At both sites, 2009 and 2011 reflect drought conditions as measured by Palmer Drought Severity Index [Palmer, 1965] values of -3 or lower. Over the study period, on average TS was inundated 211 days a year compared to 335 days at SRS. However, drought conditions resulted in 133 and 207 dry days at TS and 34 and 81 dry days at SRS, in 2009 and 2011, respectively. In nondrought years, days of inundation annually averaged 228 days at TS while at SRS, water levels were continuously above the soil surface. The amount of precipitation received in drought years was not substantially less over the entire calendar year; however, during drought years, there were fewer rainfall events during the 4 months leading up to the wet season. During normal years (nondrought), total rainfall in the first 4 months of the year averaged 276 mm at TS and 246 mm at SRS while in drought years, TS received 107 mm and SRS received 82 mm.

Table 1. Annual and Seasonal ET and Precipitation at Taylor Slough and Shark River Slough (2009 to 2012)

Season/Year	Taylor Slough		Shark River Slough	
	ET (mm m ⁻² yr ⁻¹)	Precipitation (mm m ⁻² yr ⁻¹)	ET (mm m ⁻² yr ⁻¹)	Precipitation (mm m ⁻² yr ⁻¹)
Wet	622.3	1042.2	612.3	934.7
Dry	396.3	242.5	449.5	155.5
2009	1018.6	1284.5	1061.8	1090.2
Wet	655.3	1095.8	766.5	760.2
Dry	347.9	294.6	470.2	327.9
2010	1003.2	1390.4	1236.6	1088.1
Wet	593.6	929.6	587.5	1140.2
Dry	374.7	164.8	515.1	151.9
2011	968.3	1094.5	1102.7	1292.1
Wet	660.8	1089.0	636.5	1098.0
Dry	383.1	361.0	424.1	262.0
2012	1043.9	1450.0	1060.6	1360.0
Average	1008.5	1304.8	1115.4	1207.6

3.1.1. Evapotranspiration and Rainfall

Annual and seasonal patterns in rainfall and ET were similar at both sites (Table 1), although ET rates were higher at SRS than at TS (averages 1115 and 1008 mm yr⁻¹, respectively). Precipitation peaked in July which was ~2 weeks prior to peak LE (ET) except, in 2011 when the peak in precipitation occurred much later in wet season (late July, early August) and resulted in less wet season LE compared to other years. In all years, annual rainfall was greater than annual ET, though this pattern was not observed seasonally. Dry season ET rates surpassed rainfall while wet season precipitation was much greater than ET (Table 1). Over the study period, 80% of annual precipitation fell during the wet season while just 60% of annual ET occurred during the same period. The resulting ratio of ET to precipitation was 0.61 and 1.53 during the wet and dry season, respectively, at TS. At SRS, the ratio of ET to precipitation was 0.69 in the wet season and 2.33 in the dry season. Although precipitation rates were lower in the dry season during drought years, there was no change in ET rates at either site. As a result of lower precipitation, the ratio of ET to precipitation in the dry season was higher (TS: 1.95; SRS: 3.14) compared to the dry season of nondrought years (TS: 1.12; SRS: 1.52). Comparing ET rates at TS while dry and SRS while inundated shows that although sites were experiencing similar environmental conditions (T_{air} , VPD), differences in inundation resulted in ~6% difference between ET rates.

3.2. Seasonality in Everglades Freshwater Marshes

Seasonal oscillations in water availability followed patterns in energy partitioning (Figure 3). At both sites, rates of daily H ranged from -2 to 13 MJ m⁻² d⁻¹ and increased with increasing R_n . At both TS and SRS, H peaked at the end of the dry season (approximately 4 May) and was followed by the peak in R_n ~5 weeks later. Sensible heat flux accounted for just 26% of R_n at TS and 11% at SRS annually, and the majority of energy was partitioned in the form of LE (TS: 53%; SRS: 56%). At the start of the wet season, rates of LE increased with rising R_n and estimates ranged from -1 to 15 MJ m⁻² d⁻¹ at TS and SRS (Figures 3c and 3d). At TS the peak in LE occurred in early August although the peak in water level was ~1 month later. At SRS the peak in LE was within 2 weeks of the peak in R_n and occurred 1 month (approximately 27 June) prior to the peak in water levels (approximately 11 November). Although storage fluxes were large on a half-hour time scale, fluxes were small on a daily (Figure 3), seasonal, and annual basis at both TS and SRS. On a daily time scale, fluxes were less than 5% of R_n . Seasonally, energy stored in the water column and soil accounted for less than 1% of R_n , and annually, storage fluxes approached 0 MJ m⁻². At SRS energy stored in the water column (3.5 MJ m⁻² yr⁻¹) was 2 times greater than at TS (1.66 MJ m⁻² yr⁻¹), and during the dry season energy stored in the water column (average 1.2 MJ m⁻² dry season⁻¹) was half that of the wet season (average 2.24 MJ m⁻² season⁻¹).

Stronger seasonal patterns in energy partitioning (Figure 3c) were observed at TS, where LE dominated H fluxes during the wet season and H dominated LE fluxes during the dry season. H fluxes were higher at TS throughout both the wet and dry season as compared to SRS (Figures 3c and 3d). At TS higher β (Figure 4), larger ranges

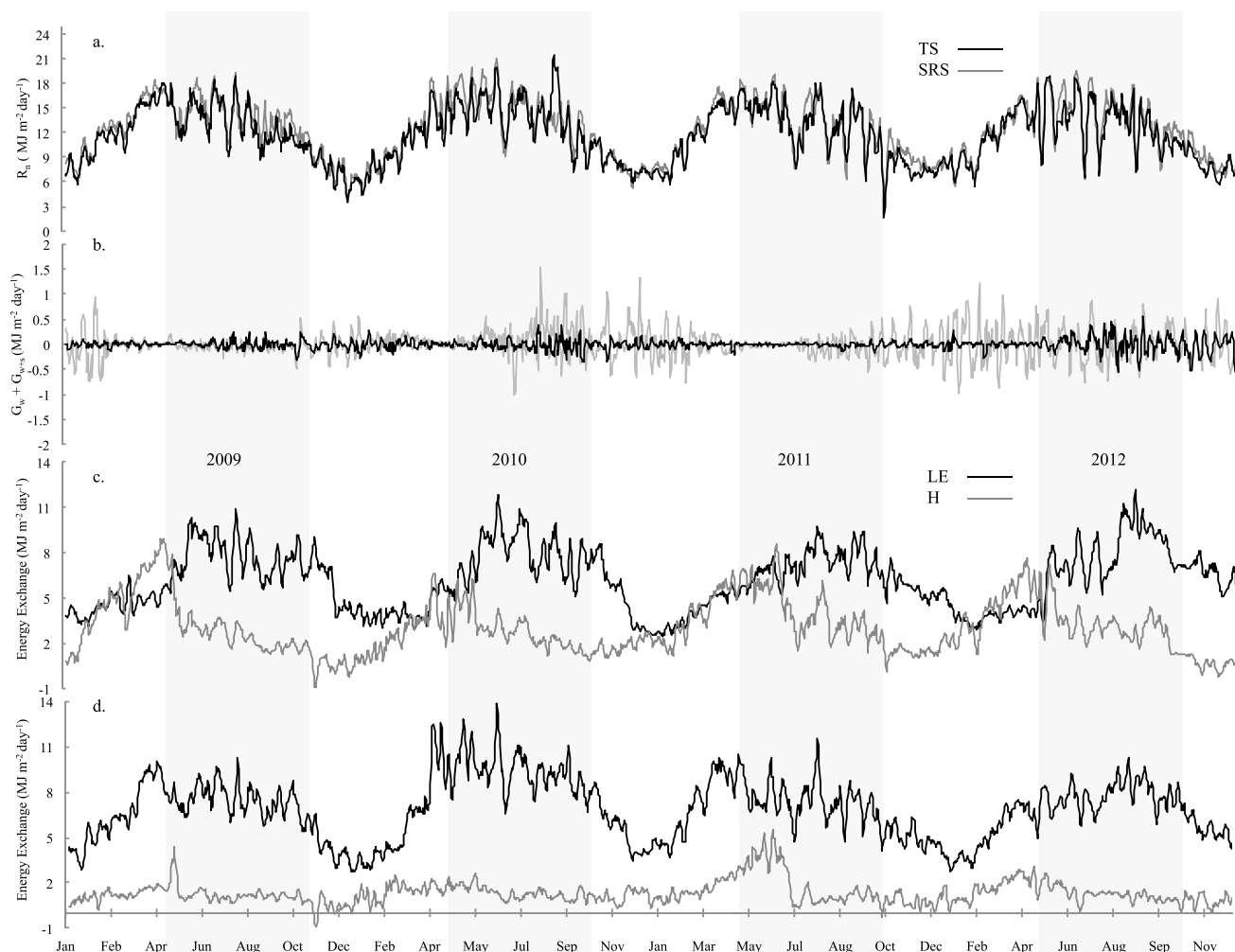


Figure 3. Annual patterns in (a) R_n and (b) storage fluxes at TS (TS) and SRS (SRS) and H and LE exchanges at (c) TS and (d) SRS, from 1 January 2009 to 31 December 2012 (5 day moving average). Changes in H and LE exchanges followed patterns in R_n . The shaded region highlights the wet season that extends from May to October.

in surface fluxes (Figure 3c), and greater seasonal changes in water depth were observed (Figure 2c); during the dry season the β was much higher (0.64) than during the wet season (0.40). Although strong patterns were observed in LE at both sites, seasonal changes in the magnitude of H exchange were limited at SRS (Figure 3d), where energy partitioned as H was just 12% and 10% of R_n in the dry and wet seasons, respectively. The seasonal patterns in β were also reduced at SRS (Figure 5) and the difference between H and LE gradually expanded as R_n increased (Figure 3d).

Annual fluctuations in the timing of peak water level, H , and LE suggest there may be discernable changes in the wet and dry season onset at TS and SRS. Shifts in water level peaks were quite variable at both TS and SRS (standard deviation = 76 and 59 days, respectively), indicating that seasons can shift substantially from 1 year to the next and the calendar-delineated season (wet season from May to October) might not capture seasonal variability (i.e., timing and length). Additionally, the distance between peaks in H and LE at each site differed substantially (94 and 55 days at TS and SRS, respectively) and reflected differences in hydroperiod.

3.3. Environmental Drivers of Energy Fluxes

Despite parallel patterns and similar magnitudes in environmental variables (T_{air} , VPD, soil WVC, and R_h) observed for the two sites (Figure 2), the estimated parameters from R_n , H , LE, and the β models differed by site. After prewhitening, some small (<0.05) but statistically significant autocorrelation remained in prewhitened series. However, this sensitivity resulted from the large number of observations available and was judged to

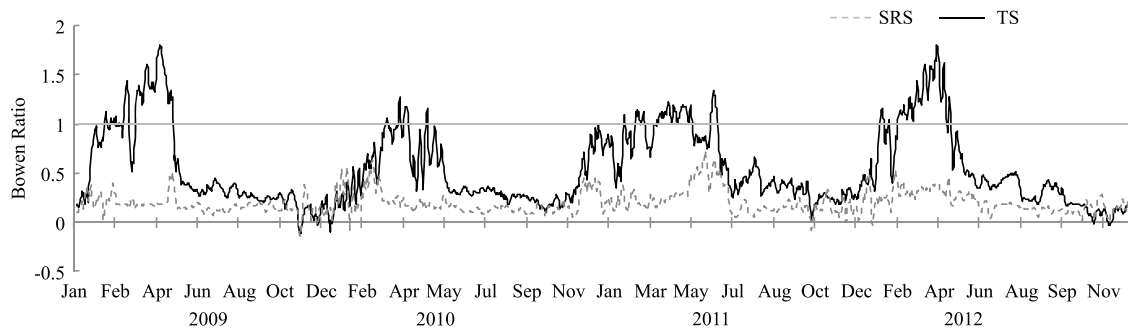


Figure 4. Weekly moving average Bowen ratios (β) at TS and SRS from 2009 to 2012. The β was higher during the dry season when the amount of energy partitioned to the H flux increased. Seasonal fluctuations in the β were greater at TS, where a greater range of water level was observed.

be biologically insignificant (Starr et al., unpublished data, 2014). Differencing was required for water level and soil VWC time series due to the lack of stationarity at both sites. The lack of stationarity indicates a lack of stability in the mean of these variables over time, further suggesting that there were considerable changes in hydroperiods at both sites. By including differenced variables in models (Δ water level, Δ VWC) we evaluated how changes in water level and soil VWC were correlated with R_n , H , ET, and β .

Models for R_n at both sites included a significant 24 h lagged MA component (MA(48)), as well as significant AR components at 0.5, 24, and 24.5 h, reflecting daily and half-hourly self-similarity in observations. At both sites, T_{air} and VPD with its half-hour lag were significantly and positively related to R_n ($p < 0.001$; Table 2). Net radiation was negatively correlated with Δ water level ($p = 0.008$) at SRS, while no significant correlation was detected at TS (Table 2). At both sites, VPD had the strongest correlation with R_n , and the effect of VPD lagged by one half hour was significantly greater at TS than at SRS. When water level, VPD, and T_{air} were accounted for, season was not significantly correlated with R_n at either site.

Models for H at both sites included the same significant daily MA component (MA(48)) as R_n , and had the same significant AR components at 0.5, 24, and 24.5, as well as an additional AR component at 48 h. VPD, Δ water level, and Δ VWC were important indicators of H exchange (Table 3). At both sites, VPD and its half-hour lag were significant positive predictors ($p < 0.001$) of H , and its effect was stronger at TS. At SRS, the change in water level was negatively correlated with H ($p < 0.001$), while this effect was not significant at TS ($p = 0.4686$). The strongest driver of H was Δ VWC, which was significantly more negative at TS than at SRS ($p < 0.001$). Like R_n , when Δ water level, VPD, and Δ VWC were accounted for, season was not significantly correlated with H at either site.

Models for LE at both sites included the same significant MA components as those of H and R_n but indicated a more complex AR structure with significant components at 0.5, 1, 23.5, 24, and 24.5. Unlike models of R_n and H ,

Table 2. Parameter Estimates From ARIMA Models of R_n by Site^a

Parameter	Taylor Slough				Shark River Slough			
	Estimate	Standard Error	<i>t</i> Value	Approx Pr > <i>t</i>	Estimate	Standard Error	<i>t</i> Value	Approx Pr > <i>t</i>
MA(48)	0.9656	0.0011	872.81	<0.0001	0.9615	0.0011	837.80	<0.0001
AR(1)	0.7268	0.0026	276.71	<0.0001	0.7163	0.0027	265.81	<0.0001
AR(48)	0.9973	0.0003	3418.72	<0.0001	0.9975	0.0003	3582.36	<0.0001
AR(49)	−0.7241	0.0027	−272.86	<0.0001	−0.7138	0.0027	−262.44	<0.0001
Δ Water Level	0.0005	0.0050	0.10	0.9184	−0.2130	0.0791	−2.69	0.0071
T_{air}	0.0108	0.0004	30.62	<0.0001	0.0092	0.0004	25.70	<0.0001
VPD	0.1626	0.0026	63.46	<0.0001	0.1521	0.0027	56.26	<0.0001
VPD(1)	0.0532	0.0025	20.93	<0.0001	0.0260	0.0027	9.78	<0.0001

^aMA(48) is the estimated moving average term at a lag of 48 time periods (24 h), and AR(1), AR(48), and AR(49) are estimated autoregressive terms at 1, 48, and 49 period lags (0.5 h, 24 h, and 24.5 h, respectively). Lagged values of independent variables are denoted similarly. The averaging period for R_n and all explanatory series is 0.5 h. Δ Water Level is the change in water level (mm) between half-hourly measurements, T_{air} is air temperature (°C), and VPD is vapor pressure deficit.

^bSignificant difference between sites.

Table 3. Parameter Estimates From ARIMA Models of H by Site^a

Parameter	Taylor Slough					Shark River Slough			
	Estimate	Standard Error	t Value	Approx Pr > t		Estimate	Standard Error	t Value	Approx Pr > t
MA(48)	0.9527	0.0020	481.67	<0.0001		0.9458	0.0017	559.99	<0.0001
AR(1)	0.1168	0.0037	31.13	<0.0001	b	0.7420	0.0026	289.31	<0.0001
AR(48)	1.0074	0.0043	234.65	<0.0001	b	1.0566	0.0029	364.51	<0.0001
AR(49)	−0.0950	0.0039	−24.53	<0.0001	b	−0.7337	0.0027	−275.78	<0.0001
AR(96)	−0.0315	0.0039	−8.11	<0.0001	b	−0.0650	0.0027	−24.04	<0.0001
ΔWater Level	0.0131	0.0180	0.72	0.4686		−0.0598	0.0150	−3.99	<0.0001
VPD	0.1039	0.0075	13.77	<0.0001	b	0.0107	0.0005	20.92	<0.0001
VPD(1)	0.0376	0.0075	4.98	<0.0001	b	0.0014	0.0005	2.83	0.0047
ΔVWC	−3.3745	0.5133	−6.57	<0.0001	b	−0.75669	0.09981	−7.58	<0.0001

^aMA(48) is the estimated moving average term at a lag of 48 time periods (24 h), and AR(1), AR(48), AR(49), and AR(96) are estimated autoregressive terms at 1, 48, 49, and 96 period lags (0.5 h, 24 h, 24.5 h, and 48 h respectively). Lagged values of independent variables are denoted similarly. The averaging period for H and all explanatory series is 0.5 h. ΔWater Level and ΔVWC are the change in water level (mm) and change in volumetric water content (%), respectively, between half-hourly measurements, and VPD is vapor pressure deficit.

^bSignificant difference between sites.

the model of LE included a significant seasonal effect, which significantly differed between sites. LE was higher during the wet season at TS ($p = 0.0004$), a pattern not observed at SRS where water was readily available year round. At both sites, LE was positively correlated with T_{air} and synchronous VPD ($p < 0.001$; Table 4), but these effects were significantly stronger at TS (Table 4). The half-hour lag in VPD was also significant; at SRS and positively correlated with LE ($p < 0.001$), whereas this effect was negative at TS ($p < 0.0001$). Like R_n , VPD had the strongest correlation with LE at both sites, and this effect was significantly greater at TS.

Models for β included a significant MA component at 24 h (MA(48)) and significant AR components at 0.5 h, 1 h, and 24 h. T_{air} ($p < 0.001$) was significantly positively related to the β at both sites, with significantly larger effects at TS (Table 5). At both sites, β was significantly lower during the wet season; however, the effect of season was only detectable at SRS ($p < 0.001$; Table 5).

3.4. Energy Balance

Energy balance closure was determined using daily summations of available energy inputs and losses (1). At both sites, the turbulent fluxes of H and LE underestimated total available energy. Closure decreased when sites were inundated and closure was lower overall at SRS than at TS. Closure at SRS was 61% ($R^2 = 0.77$) and 66% ($R^2 = 0.87$) when inundated and dry, respectively (Figure 5). At TS, energy closure was 70% ($R^2 = 0.85$) when water levels were above the soil surface and 81% ($R^2 = 0.91$) when dry. Although the relationships between closure rates and β and wind direction were explored, no quantifiable patterns were found.

Table 4. Parameter Estimates From ARIMA Models of LE by Site^a

Parameter	Taylor Slough					Shark River Slough			
	Estimate	Standard Error	t Value	Approx Pr > t		Estimate	Standard Error	t Value	Approx Pr > t
MA(48)	0.9355	0.0029	327.19	<0.0001	b	0.8566	0.0040	216.37	<0.0001
AR(1)	0.1121	0.0038	29.8	<0.0001	b	0.6351	0.0031	202.16	<0.0001
AR(2)	0.0128	0.0011	11.16	<0.0001		0.0072	0.0014	5.28	<0.0001
AR(47)	0.0185	0.0013	14.69	<0.0001	b	0.0471	0.0018	26.1	<0.0001
AR(48)	0.9520	0.0025	378.28	<0.0001	b	0.8886	0.0039	227.78	<0.0001
AR(49)	−0.0964	0.0039	−25.02	<0.0001	b	−0.5781	0.0039	−149.54	<0.0001
T_{air}	0.0025	0.0005	5.46	<0.0001		0.0028	0.0001	21.01	<0.0001
Season	0.0269	0.0075	3.57	0.0004	b	−0.0004	0.0034	−0.13	0.8947
VPD	0.1116	0.0076	14.64	<0.0001	b	0.0341	0.0010	34.29	<0.0001
VPD(1)	0.0374	0.0076	4.91	<0.0001	b	−0.0083	0.0010	−8.44	<0.0001

^aMA(48) is the estimated moving average term at a lag of 48 time periods (24 h), and AR(1), AR(2), AR(47), AR(48), and AR(49) are estimated autoregressive terms at 1, 2, 47, 48, 49, and 50 period lags (0.5 h, 1 h, 23.5 h, 24 h, 24.5, and 25 h, respectively). Lagged values of independent variables are denoted similarly. The averaging period for LE and all explanatory series is 0.5 h. T_{air} is air temperature (°C), season is an indicator for the dry (0) and wet (1) seasons, and VPD is vapor pressure deficit.

^bSignificant difference between sites.

Table 5. Parameter Estimates From ARIMA Models of the Bowen Ratio, β , by Site^a

Parameter	Taylor Slough					Shark River Slough			
	Estimate	Standard Error	t Value	Approx Pr > t		Estimate	Standard Error	t Value	Approx Pr > t
Intercept	−2.1272	0.1210	−17.58	<0.0001	b	−0.4571	0.0620	−7.37	<0.0001
MA(48)	0.8802	0.0045	195.25	<0.0001	b	0.9101	0.0039	233.61	<0.0001
AR(1)	0.0488	0.0021	23.59	<0.0001	b	0.0367	0.0018	20.02	<0.0001
AR(2)	0.0212	0.0017	12.14	<0.0001		0.0221	0.0016	13.84	<0.0001
AR(48)	0.9072	0.0039	235.32	<0.0001	b	0.9270	0.0034	275.13	<0.0001
T _{air}	0.0829	0.0042	19.55	<0.0001	b	0.0149	0.0020	7.41	<0.0001
Season	−0.0618	0.0777	−0.79	0.4268		0.0699	0.0346	2.02	0.0435

^aMA(48) is the estimated moving average term at a lag of 48 time periods (24 h), and AR(1), AR(2), and AR(48) are estimated autoregressive terms at 1, 2, and 48 period lags (0.5 h, 1 h, and 24 h, respectively). The averaging period for β and all explanatory series is 0.5 h. T_{air} is air temperature (°C) and season is an indicator for the dry (0) and wet (1) seasons.

^bSignificant difference between sites.

4. Discussion

The unique and contrasting hydrologic attributes of Everglades freshwater ecosystems [Davis and Ogden, 1994] lead to differences in rates and drivers of energy exchange [Schedlbauer et al., 2010]. Wetland formation is related to the controls on water inputs (precipitation, sheet flow) and outputs (ET, runoff) [Mitsch and Gosselink, 2007], making water levels a key determinant governing this ecosystem's functions for the Greater Everglades ecosystem [Rouse, 2000; Davis and Ogden, 1994]. Here the variance in precipitation, seasonality, and controls on LE (ET) and H in two contrasting wetlands across years that included droughts was examined. Differences in hydrologic patterns between sites were reflected in the magnitude and timing of the peak in surface fluxes and the effect of environmental controls. Although season was not significant in models of LE and H , climatic variables with distinctive seasonal patterns were important and strong predictors of LE and H . The results presented here add insight into the complicated relationships and feedbacks between energy dynamics, hydroperiods, and environment controls.

4.1. Seasonality in Everglades Freshwater Marshes

In the Everglades, ET is an important source of water loss [Davis and Ogden, 1994; Obeysekera et al., 1999], making LE a major driver of both water and energy cycles [Chapin et al., 2002]. The timing and extent of water level oscillations, which are controlled by precipitation and ET, affect the colonization and survival of marsh vegetation (i.e., submergence) [Myers and Ewel, 1992]. Seasonal patterns in water levels resulted from the

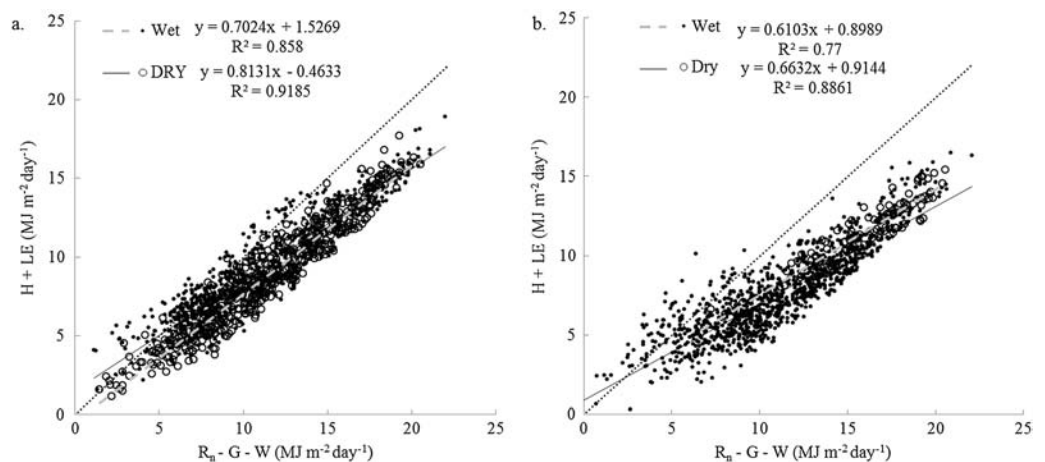


Figure 5. Energy balance closure at (a) TS and (b) SRS, under inundated conditions (black circles) and dry conditions (hollow circles). Wet conditions are defined by water levels above the soil surface while dry conditions are defined by water levels below the soil surface. The dotted line is a one-to-one line showing that both TS and SRS underestimate available energy, and this lack of closure increased when sites were inundated.

difference between ET and precipitation and changes in surface flows [Davis and Ogden, 1994] at the study sites. Although precipitation surpassed ET annually, dry season ET surpassed rainfall and wet season precipitation was much greater than ET (Table 1). The positive water balance is important for providing surface flow to wetlands downstream [Harvey et al., 2013; Sutula et al., 2013], the quantity of freshwater and organic matter flowing into Florida Bay [Davis and Ogden, 1994; Reddy and DeLaune, 2008], and for ground water recharge [Fennema et al., 1994; Harvey et al., 2013; Sutula et al., 2013].

While precipitation is driven by climate, ET is driven by both climate and wetland characteristics [Lafleur, 2008]. The dominant control on ET is available energy [Piccolo, 2009; Soucha et al., 1998], followed by surface and vegetative resistance [Piccolo, 2009]. Less seasonality in ET suggests that like other wetlands dominated by vascular plants, the water availability is not substantially reduced until the water table drops below the rooting zone [Soucha et al., 1998]. Comparing ET under similar environmental conditions and when TS was dry and SRS inundated showed that there was only a 6% difference in ET rates on average. At SRS, hydrologic implications of ET are similar to those of regional coastal systems [Harvey and Nuttle, 1995] where water loss through ET is minor because it is replaced by surface runoff. Here ET rates were not limited by water availability but driven largely by available energy. At TS, steady rates of ET suggest that while it is driven by energy availability, the role of transpiration increases as water levels fall below the soil surface [Lafleur, 1990; Campbell and Williamson, 1997; Soucha et al., 1998].

Most wetlands have lower ET rates than would be expected from open water under the same conditions [Idso and Anderson, 1988; Lafleur, 1990; Linacre, 1976; Lafleur, 2008], suggesting that transpiration is a very important component of ET. Similar to wetland ecosystems with tall reed vegetation [Goulden et al., 2007; Soucha et al., 1998; Lafleur, 2008], ET from Everglades marshes seems to be insensitive to changes in water level due to persistently high water availability. The low sensitivity in ET when water levels drop below the soil surface suggests that transpiration is a major source of ET that is less affected by the presence or absence of standing water [Lafleur, 2008]. Wetland plants have evolved in such a way that there is an upper limit to ET regardless of water supply and atmospheric demand [Lafleur, 2008], and the vascular vegetation of the wetlands limit ET by sheltering the underlying surface from turbulence and reducing the amount of radiant energy reaching the substrate.

It has been suggested that feedbacks between wetland ET and local precipitation perpetuate the existence of wetland areas [Lafleur, 2008]. In the Everglades region, precipitation patterns throughout the Kissimmee-Okeechobee-Everglades region [Davis and Ogden, 1994; Redfield, 2000] are important for the greater Everglades hydrologic dynamics. Wet season ET feedbacks to precipitation [Douglas and Rothchild, 1987; Pielke et al., 1999], which accounted for 80% of the annual precipitation during the study period. These patterns suggest that the Everglades itself is important for perpetuating the hydrologic patterns in the region [Myers and Ewel, 1992].

4.2. Energy Balance

In wetland ecosystems, LE (ET) is the most important energy flux [Jacobs et al., 2002; Piccolo, 2009], accounting for up to 100% of precipitation losses [Linacre, 1976; Lafleur, 1990; Soucha et al., 1998]. When standing water is present, there is very similar flux partitioning among wetland ecosystems [Soucha et al., 1998]. The LE accounts for approximately 50% of the R_n , and 20% of the R_n go to H [Soucha et al., 1998; Piccolo, 2009]. At both Everglades sites, energy partitioned for H and LE were within the ranges found in other wetlands [Teal and Kanwisher, 1970; Vugts and Zimmerman, 1985; Rouse, 2000; Beigt et al., 2008], where annual average β was < 1 [Burba et al., 1999a, 1999b; Heilman et al., 2000] (Table 5). Unique to this system was the seasonal shift in surface fluxes (Figure 3) and how they feedback to the regional climate and hydroperiods [Chen and Gerber, 1992].

In the Everglades, seasonal fluctuations are driven by precipitation patterns [Davis and Ogden, 1994], and results suggest that surface fluxes influence the magnitude of the seasonal effect (Figure 4). Seasonal shifts in precipitation led to offsets in peak in H and LE and as hypothesized, differences in the timing of the peak in H and LE specified the magnitude of the seasonal response. In the Everglades, wet season LE feedbacks to precipitation through thunderstorm formation and the disruption of this pattern in the fall and winter months by the Bermuda High pressure cell [Chen and Gerber, 1992] leads to a decline in surface flow and water levels. At TS where the exposure to surface flows is lower than at SRS [Davis and Ogden, 1994], water loss as LE caused a greater decline in water levels and generated larger seasonal differences

Table 6. Energy Flux Partitioning in Wetland Ecosystems

Site	LE/ R_n	H/R_n	Storage/ R_n	β	Source
Everglades short-hydroperiod marsh, Florida	0.53	0.26	>0.05	0.49	This study
Everglades long-hydroperiod marsh, Florida	0.56	0.11	>0.05	0.19	This study
Nueces River Delta, Texas	0.67 (wet), 0.27 (dry)	0.30 (wet), 0.65 (dry)	-	-	Heilman et al. [2000]
Prairie Wetland, Nebraska	0.8–0.9	-	-	-	Burba et al. [1999a]
Paynes Prairie Preserve, Florida	0.7	0.26	0.04	0.42	Jacobs et al. [2002]
Boreal fen, Manitoba	0.53–0.76	0.24–0.47			Lafleur et al. [1997] and Baldocchi et al. [2000]
Churchill sedge fen	0.64	0.25–0.30	0.5–0.11	0.39	Eaton et al. [2001]
Schefferville, Quebec	0.63	0.25	0.1		Moore et al. [1994] and Eaton et al. [2001]
Hudson Bay Coast, Ontario	0.68	0.3	0.06		Rouse et al. [1977] and Eaton et al. [2001]

in surface fluxes. As a result, the distance between peak H and peak LE was ~ 3.1 months apart. At SRS, where surface flow exposure is greater [Davis and Ogden, 1994], water level declined less and peak H and LE were just ~ 1.8 months apart. Seasonal changes in H and LE indicate that the β should reveal changes in wet and dry season strength.

The β is a useful indicator of ecosystem energy and water dynamics, where larger H indicates a dryer climate and larger LE rates suggest a more humid climate [Lafleur, 2008]. Both freshwater marsh ecosystems fall within the range of wetland β (-0.11 to 1) and fall on either side of the mean growing season β for wetland ecosystems (0.32) [Soucha et al., 1996; Price, 1994; Goulden et al., 2007; Burba et al., 1999a, 1999b; Rijks, 1969; Linacre et al., 1970]. At TS, we expected and observed higher β and larger ranges in surface fluxes as a result of greater seasonal changes in H and LE, and therefore water levels. As a result of the strength of the seasonal patterns at TS, the annual average β was higher than other wetland ecosystems (Table 6). Seasonality in the β was reduced at SRS as a result of the year-round dominance of LE. At TS, β resembled those of grassland [Twine et al., 2000] and Mediterranean [Wilson et al., 2002] ecosystems, where large seasonal differences in water availability resulted in a larger disparity between wet and dry season β . Because SRS remained inundated throughout most normal years, β resembled those of tropical ecosystems and energy partitioned as LE dominated H year round [da Rocha et al., 2004].

Shifts in peak precipitation, H , and LE suggest that the timing and length of seasons may fluctuate in the Everglades region [Chen and Gerber, 1992], and the use of the calendar-based seasonality does not capture changes in the wet and dry season. Future studies should take this into consideration when determining seasonal patterns in ecosystem function in Everglades freshwater ecosystems. The β captured the unique features of the subtropical Everglades, displaying both seasonal and annual patterns in energy and water fluxes. In the future, the β should be explored as an indicator of season onset and length.

4.3. Environmental Drivers of Energy Fluxes

Wetland functioning is intimately tied to the atmosphere by energy and mass exchanges, which are controlled by many factors whose interactions are unique to every wetland ecosystem [Lafleur, 2008]. Like R_n , H and LE are controlled by surface and atmospheric properties [Lafleur, 2008]. Seasonal sinusoidal patterns of H and LE in subtropical wetland ecosystems followed those in R_n although their peaks were offset. At the end of the dry season H peaked and LE peaked soon after the peak in precipitation. In the subtropical Everglades region, T_{air} and precipitation also tracked patterns in R_n , which increased in the wet summer months and declined in the dry winter months. As found by other studies [Rouse, 2000], results show that environmental controls exerted by the atmosphere, water levels, and wetland plants interact with available energy, influencing annual and seasonal patterns in H and LE. As hypothesized, changes in water level, T_{air} , VPD, and ΔWWC had strong correlations with available energy and energy partitioning, which differed by site.

The sensible heat flux varied with changes in T_{air} and water and energy availability. These results and other studies have found that rising H increases T_{air} and VPD [Halliwell and Rouse, 1987; Soucha et al., 1998], which provides a positive feedback to LE. In the Everglades, H was also negatively correlated with an increase in water levels and soil volumetric water content. Soil properties, which play an important role in plant composition and productivity [Adams, 1963; Pennings et al., 2005; Wang and Harwell, 2007; Piccolo, 2009] are significantly

affected by H , and this effect was higher at TS than at SRS. These results suggest that a higher H is correlated with decreases in soil water content, which is a result of the relationship between H , T_{air} , and VPD.

Like other wetland ecosystems, the dominant outgoing flux component, LE, is especially important because it represents the loss of water from the ecosystem and contributes to atmospheric moisture. Similar to the results presented here, previous research has identified two dominating meteorological influences on LE (ET), R_n , and VPD [Lafleur, 2008; Kellner, 2001; Kim and Verma, 1996; Soucha et al., 1996]. Despite physiological differences among wetland species, the response in stomatal conductance to atmospheric VPD has been reported throughout the literature [Admiral and Lafleur, 2007; Johnson and Caldwell, 1976; Lafleur and Rouse, 1988; Munro, 1989; Tagaki et al., 1998; Lafleur, 2008], though the nature and magnitude of the response may vary [Lafleur, 2008]. The VPD is known to have a positive relationship with LE [Lafleur, 2008] until a threshold is reached [Admiral and Lafleur, 2007]. Such behavior is an important negative feedback that limits the upper rates of ET from wetlands [Admiral and Lafleur, 2007]. Time series analysis identified VPD as a very important indicator of water and energy exchange with the atmosphere. Extremely important for ecosystem productivity through its effect on gas exchange and on water availability [Burba et al., 1999a; Schedlbauer et al., 2011], VPD links energy partitioning to ecosystem productivity [Lafleur, 2008], showing that water levels are responding to fluctuations in both.

4.4. Energy Budget Closure

Energy budget closure provides a measure of how well we understand and can measure component fluxes (R_n , H , LE), and storage fluxes ($G_w + s$ and G_w). Using daily summations of available energy ($R_n - G_w + s - G_w$) and surface fluxes (H and LE) from 2009 to 2012, surface fluxes underestimated available energy at both sites and energy budget closure was lower at SRS than at TS (Figure 5). Independent measurements of the major energy balance flux components are not often consistent with the principle of conservation of energy [Twine et al., 2000], resulting in the failure to close the energy budget as seen across many different FLUXNET sites [Wilson et al., 2002]. Closure in this study was within the range of values reported across FLUXNET sites and provided a qualitative understanding, such that rates for SRS and when inundated at TS were lower than the FLUXNET mean of 80% closure [Wilson et al., 2002]. However, closure rates were consistent with other wetland studies that report energy balance closure at ~70% [Mackay et al., 2007; Li et al., 2009; Schedlbauer et al., 2010]. Possible explanations for the lack of closure include (1) sampling errors associated with differences in measurement source areas, (2) a systematic bias in instrumentation (e.g., sonic anemometry [Frank et al., 2013; Kochendorfer et al., 2012] and condensation on net radiometers), (3) neglected energy sinks, e.g., heat transported horizontally in the water column, (4) neglected advection of scalars [Wilson et al., 2002; Loescher et al., 2006], and (5) the loss of low- and/or high-frequency contributions to the turbulent flux. This latter explanation applies best in heterogeneous landscapes [Foken et al., 2010], and while TS and SRS have relatively homogenous source areas, the larger landscape at TS includes levees, canals, and agricultural lands that are outside the flux source area.

The underestimation of total available energy was higher when water levels were above the soil surface (Figure 2). The greater lack of closure when sites are inundated suggests storage fluxes are being underestimated [Lafleur et al., 1997]. However, on annual time scales, energy storage cancels out and errors in the small contributions made by storage terms (G_w and $G_w + s$) to the energy budget on the daily basis would not account for a 20 to 30% lack of closure. The previous suggested instrumentation biases may be systematically manifest in the accumulation of condensation on net radiometers. Condensation on net radiometers causes an underestimation of outgoing long-wave radiation leading to an overestimation of net radiation which may explain the lower closure rates when sites were inundated. No correlations between the lack of closure and the β were found, negating the notion of underestimation of LE independent of H . The lack of closure at both sites may be an indication that both H and LE are being underestimated, which is important for the water balance of Everglades. A 10 to 15% increase in LE at TS and SRS would suggest that less water would flow into downstream ecosystems, which have already been identified as suffering from chronically low water levels [Davis and Ogden, 1994]. Additional research on the source of error, whether it is underestimation of the storage components or surface fluxes, is required prior to making any modifications to the Everglade energy balance to account for the lack of energy balance closure. It is becoming extremely important to determine the water balance of these systems as the CERP implementation has reached a point of increasing water flows in the northern section of the park and determination of the effects of this increased flow on hydrologic dynamics will be used as a measure of ecosystem restoration.

4.5. Hydroperiods and Climate Change

Patterns in R_n , H , and LE fluctuate with climate and water levels, indicating that hydroperiod drives ecosystem function and energy partitioning in the Everglades. Considering the effect of water depth on vegetation function and composition, changes in vegetation associated with altered hydroperiods can also stimulate changes in the climate system through fluctuations in albedo, surface roughness, soil moisture, and plant resistance to evaporation [Dickinson, 1992; Thomas and Rowntree, 1992; Betts et al., 1996; Baldocchi et al., 2000].

Climate change is emerging as an important challenge for natural resource managers and decision makers. In the southeastern United States, shifts in precipitation patterns and higher temperatures are projected by climate models [Christensen et al., 2007; Allan and Soden, 2008; Li et al., 2011; Intergovernmental Panel on Climate Change, 2013] and could have a substantial effect on the timing and length of wet and dry seasons. With the implementation of the CERP, shifts in climate that result in increases in drought frequency and intensity [Stanton and Ackerman, 2007] may be moderated by restored hydrologic conditions. The CERP could reestablish the seasonal patterns of water depth closer to natural levels, thereby increasing the amount of available energy partitioned into LE and potentially affect current ecosystem structure, hydroperiods, and climate. Feedbacks to other ecological processes are also likely given this scenario, e.g., changes in species composition, primary productivity, ratio of anaerobic:aerobic metabolism, and organic matter accumulation. Patterns in energy partitioning covaried with hydroperiods and climate, suggesting that shifts in any of these components could disrupt current water and biogeochemical cycles throughout the Everglades region.

5. Conclusion

The hydrologic cycle is driven by energy exchanges, which feeds back into creating the climate sufficient for wetland maintenance. In the Everglades, R_n , H , and LE oscillate with climate and water levels, showing how hydroperiods drive and respond to energy partitioning. Hydroperiods define seasonality in this subtropical ecosystem through its control on VPD, which is important for both carbon and energy exchanges. Significant relationships between energy fluxes, VPD, water levels, and soil VWC were also observed and have also been identified in previous research as important indicators of C dynamics [Schedlbauer et al., 2012; Jimenez et al., 2012]. Considering the effect of water levels on vegetation function and composition [Mitsch and Gosselink, 2007], changes in vegetation associated with altered hydroperiods can also stimulate changes in the climate system through fluctuations in albedo, surface roughness, soil moisture, and plant resistance to evaporation [Thomas and Rowntree, 1992; Betts et al., 1996; Baldocchi et al., 2000]. This study linked environmental variables important for C dynamics and the energy balance in Everglades ecosystems, showing that there exist complex relationships between hydroperiods, energy exchange, and climate that is important for creating conditions sufficient to maintain wetland ecosystems.

References

- Adams, D. A. (1963), Factors influencing vascular plant zonation in North Carolina salt marshes, *Ecology*, 44(3), 445–456, doi:10.2307/1932523.
- Admiral, S. W., and P. M. Lafleur (2007), Partitioning of latent heat flux at a northern peatland, *Aquat. Bot.*, 86(2), 107–116, doi:10.1016/j.aquabot.2006.09.006.
- Allan, R. P. R., and B. J. B. Soden (2008), Atmospheric warming and the amplification of precipitation extremes, *Science*, 321(5895), 1481–1484, doi:10.1126/science.1160787.
- Aubinet, M., et al. (2000), Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology, *Adv. Ecol. Res.*, 30, 113–175, doi:10.1016/S0065-2504(08)60018-5.
- Baldocchi, D., F. M. Kelliher, T. A. Black, and P. Jarvis (2000), Climate and vegetation controls on boreal zone energy exchange, *Global Change Biol.*, 6(S1), 69–83, doi:10.1046/j.1365-2486.2000.06014.x.
- Beigt, D., M. C. Piccolo, and G. M. E. Perillo (2008), Surface heat budget of an estuarine tidal flat (Bahía Blanca Estuary, Argentina), *Cienc. Mar.*, 34(1), 1–15.
- Betts, A. K., J. H. Ball, A. C. M. Beljaars, M. J. Miller, and P. A. Viterbo (1996), The land surface-atmosphere interaction: A review based on observational and global modeling perspectives, *J. Geophys. Res.*, 101(D3), 7209–7225, doi:10.1029/95JD02135.
- Brocklebank, J. C., and D. A. Dickey (2003), *SAS System for Forecasting Time Series*, 1986 ed., SAS Institute Inc., Cary, North Carolina.
- Burba, G. G., S. B. Verma, and J. Kim (1999a), Surface energy fluxes of Phragmites australis in a prairie wetland, *Agric. For. Meteorol.*, 94(1), 31–51, doi:10.1016/S0168-1923(99)00007-6.
- Burba, G. G., S. B. Verma, and J. Kim (1999b), Energy fluxes of an open water area in a mid-latitude prairie wetland, *Boundary Layer Meteorol.*, 91(3), 495–504, doi:10.1023/A:1001802821846.
- Campbell, G. S., and J. M. Norman (1998), *An Introduction to Environmental Biophysics*, 2nd ed., Springer-Verlag New York, Inc., New York, ISBN:978-0-387-94937-6.
- Campbell, D. I., and J. L. Williamson (1997), Evaporation from a raised peat bog, *J. Hydrol.*, 193(1–4), 142–160, doi:10.1016/S0022-1694(96)03149-6.
- Chapin, F. S., III, M. C. Chapin, P. A. Matson, and P. Vitousek (2002), *Principles of Terrestrial Ecosystem Ecology*, Springer, New York.
- Chen, E., and J. F. Gerber (1992), Climate, in *Ecosystems of Florida*, edited by R. L. Myers and J. J. Ewel, University of Central Florida Press, Orlando, Fla.

Acknowledgments

All research was performed under permits issued by Everglades National Park (EVER-2009-SCI-0070 and EVER-2013-SCI-0058) and the flux data for TS and SRS are made available through AmeriFlux (<http://ameriflux.ornl.gov>). This research is based in part on support of the Department of Energy's (DOE) National Institute for Climate Change Research (NICCR) through grant 07-SC-NICCR-1059, the U.S. Department of Education Graduate Assistantships in Areas of National Need (GAANN) program, Florida International University, and the National Science Foundation (NSF) Division of Atmospheric and Geospace Sciences (AGS), Atmospheric Chemistry program through grant 1233006. This research was also supported by the NSF through the Florida Coastal Everglades Long-Term Ecological Research program under Cooperative Agreements DBI-0620409 and DEB-9910514 and by the United States Forest Service Rocky Mountain Research Station. H.W.L. acknowledges the NSF, EF-102980, for their ongoing support. The National Ecological Observatory Network (NEON) is a project sponsored by the NSF and managed under cooperative agreement by NEON, Inc. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF. Finally, the authors would like to recognize all those that have advanced our predictive understanding of ecology, past, present, and in the future.

- Childers, D. L., D. Iwaniec, D. Rondeau, G. Rubio, E. Verdon, and C. J. Madden (2006), Responses of sawgrass and spikerush to variation in hydrologic drivers and salinity in Southern Everglades marshes, *Hydrobiologia*, 569(1), 273–292, doi:10.1007/s10750-006-0137-9.
- Christensen, J. H., et al. (2007), Regional climate projections, in *Climate Change, 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 847–940, Cambridge Univ. Press, Cambridge, U. K., and New York.
- Clark, K. L., H. Gholz, J. B. Moncrieff, F. Cropley, and H. W. Loescher (1999), Environmental controls over net exchanges of carbon dioxide from contrasting Florida ecosystems, *Ecol. Appl.*, 9(3), 936–948, doi:10.1890/1051-0761(1999)009[0936:ECONEO]2.0.CO;2.
- Clement, R. (1999), EdiRe data software, v.1.5.0.32; University of Edinburgh, Edinburgh, U. K. [Available at <http://www.geos.ed.ac.uk/abs/research/micromet/EdiRe/>].
- da Rocha, H. R., M. L. Goulden, S. D. Miller, M. C. Menton, L. D. Pinto, H. C. de Freitas, and A. M. e Silva Figueira (2004), Seasonality of water and heat fluxes over a tropical forest in eastern Amazonia, *Ecol. Appl.*, 14(sp4), 22–32, doi:10.1890/02-6001.
- Davis, S. M., and J. C. Ogden Eds. (1994), *Everglades: The Ecosystem and Its Restoration*, St. Lucie Press, Boca Raton, Fla.
- Dickey, D. A., and W. A. Fuller (1979), Distribution of the estimators for autoregressive time series with a unit root, *J. Am. Stat. Assoc.*, 74(366), 427–431.
- Dickinson, R. E. (1992), Land surface, in *Climate System Modeling*, edited by K. E. Trenberth, pp. 149–172, Cambridge Univ. Press, Cambridge, Cambridge, Mass.
- Douglas, M. S., and J. Rothchild (1987), *Marjory Stoneman Douglas: Voice of the River*, Pineapple Press, Sarasota, Fla.
- Duever, M. J., J. E. Carlson, L. A. Riopelle, and L. C. Duever (1978), Ecosystem analysis at corkscrew swamp, in *Cypress Wetlands for Water Management, Recycling, and Conservation*, Annu. Rep. Natl. Sci. Found. Rockefeller Found. Cent. Wetlands, pp. 534–570, University of Florida, Gainesville, Fla.
- Eaton, A. K., W. R. Rouse, P. M. Lafleur, P. Marsh, and P. D. Blanken (2001), Surface energy balance of the western and central Canadian subarctic: Variations in the energy balance among five major terrain types, *J. Clim.*, 14(17), 3692–3703, doi:10.1175/15200442(2001)014<3692:SEBOTW>2.0.CO;2.
- Fennema, R. J., C. J. Neidrauer, R. A. Johnson, T. K. MacVicar, and W. A. Persins (1994), A computer model to simulate natural Everglades hydrology, in *Everglades, The Ecosystem and its Restoration*, edited by S. M. Davis and J. C. Ogden, pp. 249–289, St. Lucie Press, Delray Beach, Fla.
- Foken, T., and B. Wichura (1996), Tools for quality assessment of surface-based flux measurements, *Agric. For. Meteorol.*, 78(1–2), 83–105, doi:10.1016/0168-1923(95)02248-1.
- Foken, T., M. Mauder, C. Liebethal, F. Wimmer, F. Beyrich, J.-P. Leps, S. Raasch, H. A. R. DeBruin, W. M. L. Meijninger, and J. Bange (2010), Energy balance closure for the LITFASS-2003 experiment, *Theor. Appl. Climatol.*, 101(1–2), 149–160, doi:10.1007/s00704-009-0216-8.
- Frank, J. M., W. J. Massman, and B. E. Ewers (2013), Underestimates of sensible heat flux due to vertical velocity measurement errors in non-orthogonal sonic anemometers, *Agric. For. Meteorol.*, 171–172, 72–81, doi:10.1016/j.agrformet.2012.11.005.
- Gao, Z., R. Horton, and H. P. Liu (2010), Impact of wave phase difference between soil surface heat flux and soil surface temperature on soil surface energy balance closure, *J. Geophys. Res.*, 115, D16112, doi:10.1029/2009JD013278.
- Goulden, M. L., J. W. Munger, and S. M. Fan (1996), Measurements of carbon sequestration by long-term eddy covariance: Methods and a critical evaluation of accuracy, *Global Clim. Change Biol.*, 2, 169–182, doi:10.1111/j.1365-2486.1996.tb00070.x.
- Goulden, M. L., M. Litvak, and S. D. Miller (2007), Factors that control Typha marsh evapotranspiration, *Aquat. Bot.*, 86(2), 97–106, doi:10.1016/j.aquabot.2006.09.005.
- Halliwel, D. H., and W. R. Rouse (1987), Soil heat flux in permafrost: Characteristics and accuracy of measurement, *J. Climatol.*, 7(6), 571–584, doi:10.1002/joc.3370070605.
- Harvey, J. W., and W. K. Nuttle (1995), Fluxes of water and solute in a coastal wetland sediment. 2. Effect of macropores on solute exchange with surface water, *J. Hydrol.*, 164, 109–125, doi:10.1016/0022-1694(94)02562-P.
- Harvey, J. W., J. Choi, and R. H. Mooney (2013), Hydrologic interactions between surface water and ground water in Taylor Slough, Everglades National Park, *U.S. Geol. Surv. Open-File Rep.* 00–449, 24–26.
- Heilman, J. L., F. A. Heinsch, D. R. Cobos, and K. J. McInnes (2000), Energy balance of a high marsh on the Texas Gulf Coast: Effect of water availability, *J. Geophys. Res.*, 105(D17), 22,371–22,377, doi:10.1029/2000JD900334.
- Hintze, J. (2004), *Number Crunching Statistical System*, NCSS and PASS, Kaysville, Utah. [Available at <http://www.NCSS.com/>].
- Idso, S. B., and M. G. Anderson (1988), A comparison of two recent studies of transpirational water loss from emergent aquatic macrophytes, *Aquat. Bot.*, 31(1–2), 191–195, doi:10.1016/0304-3770(88)90049-6.
- Intergovernmental Panel on Climate Change (2013), *Climate Change 2013: The Physical Science Basis*, in *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Joussaume and J. Penner, pp. 1–2216, Cambridge Univ. Press, Cambridge, U. K., and New York.
- Jacobs, J. M., S. L. Mergelsberg, A. F. Lopera, and D. A. Myers (2002), Evapotranspiration from a wet prairie wetland under drought conditions: Paynes Prairie Preserve, Florida, USA, *Wetlands*, 22(2), 374–385, doi:10.1672/0277-5212(2002)022[0374:EFAWPW]2.0.CO;2.
- Jimenez, K. L., G. Starr, C. L. Staudhammer, J. L. Schedlbauer, H. W. Loescher, S. L. Malone, and S. F. Oberbauer (2012), Carbon dioxide exchange rates from short- and long-hydroperiod Everglades freshwater marsh, *J. Geophys. Res.*, 117, G04009, doi:10.1029/2012JG002117.
- Johnson, D., and M. Caldwell (1976), Water potential components, stomatal function and liquid phase water transport resistances of four arctic and alpine species in relation to moisture stress, *Plant Physiol.*, 36, 271–278, doi:10.1111/j.1399-3054.1976.tb04427.x.
- Kellner, E. (2001), Surface energy fluxes and control of evapotranspiration from a Swedish Sphagnum mire, *Agric. For. Meteorol.*, 110(2), 101–123, doi:10.1016/S0168-1923(01)00283-0.
- Kim, J., and S. B. Verma (1996), Surface exchange of water vapour between an open sphagnum fen and the atmosphere, *Boundary Layer Meteorol.*, 79(3), 243–264, doi:10.1007/BF00119440.
- Kljun, N., M. W. Rotach, and H. P. Schmid (2002), A three-dimensional backward Lagrangian footprint model for a wide range of boundary-layer stratifications, *Boundary Layer Meteorol.*, 103(2), 205–226, doi:10.1023/A:1014556300021.
- Kljun, N., P. Calanca, M. W. Rotach, and H. P. Schmid (2004), A simple parameterisation for flux footprint predictions, *Boundary Layer Meteorol.*, 112(3), 503–523, doi:10.1023/B:BOUN.0000030653.71031.96.
- Kochendorfer, J., T. P. Meyers, J. Frank, W. J. Massman, and M. W. Heuer (2012), How well can we measure the vertical wind speed? Implications for fluxes of energy and mass, *Boundary Layer Meteorol.*, 145(2), 383–398, doi:10.1007/s10546-012-9738-1.
- Lafleur, P. M. (1990), Evapotranspiration from sedge-dominated wetland surfaces, *Aquat. Bot.*, 37(4), 341–353, doi:10.1016/0304-3770(90)90020-L.
- Lafleur, P. M. (2008), Connecting atmosphere and wetland: Energy and water vapour exchange, *Geogr. Compass*, 2(4), 1027–1057, doi:10.1111/j.1749-8198.2007.00132.x.
- Lafleur, P. M., and W. R. Rouse (1988), The influence of surface cover and climate on energy partitioning and evaporation in a subarctic wetland, *Boundary Layer Meteorol.*, 44, 327–347, doi:10.1007/BF00123020.

- Lafleur, P. M., J. H. McCaughey, D. W. Joiner, P. A. Bartlett, and D. E. Jelinski (1997), Seasonal trends in energy, water, and carbon dioxide fluxes at a northern boreal wetland, *J. Geophys. Res.*, 102(D24), 29,009–29,020, doi:10.1029/96JD03326.
- Leuning, R., E. van Gorsel, W. J. Massman, and P. R. Isaac (2012), Reflections on the surface energy imbalance problem, *Agric. For. Meteorol.*, 156, 65–74, doi:10.1016/j.agrformet.2011.12.002.
- Li, Y., L. Zhou, Z. Xu, and G. Zhou (2009), Comparison of water vapour, heat and energy exchanges over agricultural and wetland ecosystems, *Hydrol. Processes*, 23(14), 2069–2080, doi:10.1002/hyp.7339.
- Li, W., L. Li, and Y. Kushnir (2011), Variation of the North Atlantic subtropical high western ridge and its implication to Southeastern US summer precipitation, *Clim. Dyn.*, 39(6), 1401–1412, doi:10.1007/s00382-011-1214-y.
- Linacre, E. T. (1976), Swamps, in *Vegetation and the Atmosphere*, edited by J. L. Monteith, pp. 329–350, Academic Press, Waltham, Mass.
- Linacre, E. T., B. B. Hicks, G. R. Saintry, and G. Grauze (1970), The evaporation from a swamp, *Agric. Meteorol.*, 7, 375–386, doi:10.1016/0002-1571(70)90033-6.
- Loescher, H. W., B. E. Law, L. Mahrt, and D. Y. Hollinger (2006), Uncertainties in, and interpretation of, carbon flux estimates using the eddy covariance technique, *J. Geophys. Res.*, 111, D21S90, doi:10.1029/2005JD006932.
- Loveless, C. M. (1959), A study of the vegetation in the Florida Everglades, *Ecology*, 40(1), 1–9, doi:10.2307/1929916.
- Mackay, D. S., B. E. Ewers, B. D. Cook, and K. J. Davis (2007), Environmental drivers of evapotranspiration in a shrub wetland and an upland forest in northern Wisconsin, *Water Resour. Res.*, 43, W03442, doi:10.1029/2006WR005149.
- Marshall, C. H., R. A. Pielke Sr., L. T. Steyaert, and D. A. Willard (2004), The impact of anthropogenic land-cover change on the Florida peninsula sea breezes and warm season sensible weather, *Mon. Weather Rev.*, 132(1), 28–52, doi:10.1175/1520-0493(2004)132<0028:TIOALC>2.0.CO;2.
- Mitsch, G., and J. G. Gosselink (2007), *Wetlands*, 4th ed., John Wiley, Hoboken, N. J.
- Moncrieff, J. B., Y. Malhi, and R. Leuning (1996), The propagation of errors in long-term measurements of land-atmosphere fluxes of carbon and water, *Global Change Biol.*, 2(3), 231–240, doi:10.1111/j.1365-2486.1996.tb00075.x.
- Moore, K. E., D. R. Fitzjarrald, S. C. Wofsy, B. C. Daube, J. W. Munger, P. S. Bakwin, and P. Crill (1994), A season of heat, water vapor, total hydrocarbon, and ozone fluxes at a subarctic fen, *J. Geophys. Res.*, 99(D1), 1937–1952, doi:10.1029/93JD01442.
- Munro, D. S. (1989), Stomatal conductances and surface conductance modelling in a mixed wetland forest, *Agric. For. Meteorol.*, 48, 235–249, doi:10.1016/0168-1923(89)90071-3.
- Myers, R. L., and J. J. Ewel (Eds) (1992), *Ecosystems of Florida*, University of Central Florida Press, Orlando, Fla.
- Obeyskera, J., J. Browder, L. Hornung, and M. A. Harwell (1999), The natural South Florida system I: Climate, geology, and hydrology, *Urban Ecosyst.*, 3(3), 223–244, doi:10.1023/A:1009552500448.
- Ocheltree, T. O., and H. W. Loescher (2007), Design of the AmeriFlux portable eddy-covariance system and uncertainty analysis of carbon measurements, *J. Atmos. Oceanic Technol.*, 24, 1389–1409, doi:10.1175/JTECH2064.1.
- Odum, E. P. (1968), Energy flow in ecosystems: A historical review, *Am. Zool.*, 8, 11–18.
- Palmer, W. (1965), *Meteorological Drought, Res. Pap.*, vol. 45, 58 pp., U.S. Department of Commerce Weather Bureau, Washington, D. C.
- Pankratz, A. (1983), *Forecasting With Univariate Box-Jenkins Models Concepts and Cases*, Wiley, New York.
- Pennings, S. C., M. B. Grant, and M. D. Bertness (2005), Plant zonation in low-latitude salt marshes: Disentangling the roles of flooding, salinity and competition, *J. Ecol.*, 93(1), 159–167, doi:10.1111/j.1365-2745.2004.00959.x.
- Perry, W. (2004), Elements of South Florida's comprehensive Everglades restoration plan, *Ecotoxicology*, 13(3), 185–193, doi:10.1023/B:ECTX.0000023564.10311.4a.
- Piccolo, M. C. (2009), Heat energy balance in coastal wetlands, in *Coastal Wetlands: An Integrated Ecosystem Approach*, 1st edn., edited by E. M. Gerardo et al., pp. 211–230, Elsevier, doi:10.1016/B978-0-444-53103-2.00007-7.
- Pielke, R. A., R. L. Walko Sr., L. T. Steyaert, P. L. Vidale, G. E. Liston, W. A. Lyons, and T. N. Chase (1999), The influence of anthropogenic landscape changes on weather in South Florida, *Mon. Weather Rev.*, 127(7), 1663–1673, doi:10.1175/1520-0493(1999)127<1663:TIOALC>2.0.CO;2.
- Price, J. S. (1994), Evapotranspiration from a lakeshore Typha marsh on Lake Ontario, *Aquat. Bot.*, 48(3–4), 261–272, doi:10.1016/0304-3770(94)90019-1.
- Reddy, K. R., and R. D. DeLaune (2008), *Biogeochemistry of Wetlands*, CRC Press, Boca Raton, Fla.
- Redfield, G. W. (2000), Ecological research for aquatic science and environmental restoration in South Florida, *Ecol. Appl.*, 10(4), 990–1005, doi:10.1890/1051-0761(2000)010[0990:ERFASA]2.0.CO;2.
- Richardson, C. (2008), *The Everglades Experiments: Lessons for Ecosystem Restoration*, p. 698, Springer-Verlag, New York, doi:10.1007/978-0-387-68923-4.
- Rijks, D. A. (1969), Evaporation from a papyrus swamp, *Q. J. R. Meteorol. Soc.*, 95(405), 643–649, doi:10.1002/qj.49709540515.
- Rouse, W. R. (2000), The energy and water balance of high-latitude wetlands: Controls and extrapolation, *Global Change Biol.*, 6(5), 59–68, doi:10.1046/j.1365-2486.2000.06013.x.
- Rouse, W. R., P. F. Mills, and R. B. Stewart (1977), Evaporation in high latitudes, *Water Resour. Res.*, 13(6), 909–914, doi:10.1029/WR013i006p00909.
- Schedlbauer, J. L., S. F. Oberbauer, G. Starr, and K. L. Jimenez (2010), Seasonal differences in the CO₂ exchange of a short-hydroperiod Florida Everglades marsh, *Agric. For. Meteorol.*, 150(2010), 994–1006, doi:10.1016/j.agrformet.2010.03.005.
- Schedlbauer, J. L., S. F. Oberbauer, G. Starr, and K. L. Jimenez (2011), Controls on sensible heat and latent energy fluxes from a short-hydroperiod Florida Everglades marsh, *J. Hydrol.*, 411(3–4), 331–341, doi:10.1016/j.jhydrol.2011.10.014.
- Schedlbauer, J. L., J. W. Munyon, S. F. Oberbauer, and E. E. Gaiser (2012), Controls on ecosystem carbon dioxide exchange in short- and long-hydroperiod Florida Everglades freshwater marshes, *Wetlands*, 32, 801–812, doi:10.1007/s13157-012-0311-y.
- Schotanus, P., F. T. M. Nieuwstadt, and H. A. R. De Bruin (1983), Temperature measurement with a sonic anemometer and its application to heat and moisture fluxes, *Boundary Layer Meteorol.*, 26(1), 81–93, doi:10.1007/BF00164332.
- Soucha, C., C. Susan, B. Grimmer, and C. P. Wolfe (1998), Evapotranspiration rates from wetlands with different disturbance histories: Indiana Dunes National Lakeshore, *Wetlands*, 18(2), 216–229, doi:10.1007/BF03161657.
- Soucha, C., C. P. Wolfe, and C. S. B. Grimmer (1996), Wetland evaporation and energy partitioning: Indiana Dunes National Lakeshore, *J. Hydrol.*, 184(3–4), 189–208, doi:10.1016/0022-1694(95)02989-3.
- Stanton, E. A., and F. Ackerman (2007), *Florida and climate change: The Costs of Inaction*, Global Development and Environment Institute, Tufts University, Medford, Mass.
- Sutula, M., J. W. Day, J. Cable, and D. Rudnick (2013), Hydrological and nutrient budgets of freshwater and estuarine wetlands of Taylor Slough in Southern Everglades, Florida (U.S.A.), *Biogeochemistry*, 56, 287–310, doi:10.1023/A:1013121111153.
- Tagaki, K., T. Tsuboya, and H. Takahashi (1998), Diurnal hysteresis of stomatal and bulk surface conductance in relation to vapor pressure deficit in a cool-temperate wetland, *Agric. For. Meteorol.*, 91, 177–191, doi:10.1016/0168-1923(89)90071-3.
- Teal, J. M., and J. W. Kanwisher (1970), Total energy balance in salt marsh grasses, *Ecology*, 51(4), 690–695, doi:10.2307/1934050.

- Thomas, G., and P. R. Rowntree (1992), The boreal forests and climate, *Q. J. R. Meteorol. Soc.*, *118*(505), 469–497, doi:10.1002/qj.49711850505.
- Twine, T. E., W. P. Kustas, J. M. Norman, D. R. Cook, P. R. Houser, T. P. Meyers, J. H. Prueger, P. J. Starks, and M. L. Wesely (2000), Correcting eddy-covariance flux underestimates over a grassland, *Agric. For. Meteorol.*, *103*(3), 279–300, doi:10.1016/S0168-1923(00)00123-4.
- Veldkamp, E., and J. J. O'Brien (2000), Calibration of a frequency domain reflectometry sensor for humid tropical soils of volcanic origin, *Soil Sci. Soc. Am. J.*, *64*(5), 1549–1553, doi:10.2136/sssaj2000.6451549x.
- Vugts, H. F., and J. T. F. Zimmerman (1985), The heat balance of a tidal flat area, *Neth. J. Sea Res.*, *19*(1), 1–14, doi:10.1016/0077-7579(85)90037-7.
- Wang, H., and H. Harwell (2007), Modeling soil salinity distribution along topographic gradients in tidal salt marshes in Atlantic and Gulf coastal regions, *Ecol. Modell.*, *201*(3–4), 11–11, doi:10.1016/j.ecolmodel.2006.10.013.
- Wang, H., R. Fu, A. Kumar, and W. Li (2010), Intensification of summer rainfall variability in the southeastern United States during recent decades, *J. Hydrometeorol.*, *11*(4), 1007–1018, doi:10.1175/2010JHM1229.1.
- Webb, E. K., G. I. Pearman, and R. Leuning (1980), Correction of flux measurements for density effects due to heat and water vapour transfer, *Q. J. R. Meteorol. Soc.*, *106*(447), 85–100, doi:10.1002/qj.49710644707.
- Wilson, K. B., et al. (2002), Energy partitioning between latent and sensible heat flux during the warm season at FLUXNET sites, *Water Resour. Res.*, *30*(12), 1294, doi:10.1029/2001WR000989.