2011

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Recommended Citation

Publisher Version: Schedlbauer, J., S. Oberbauer, G. Starr, K.L. Jimenez. 2011. Controls on sensible heat and latent energy fluxes from a short-hydroperiod Florida Everglades marsh. Journal of Hydrology 411: 331-341.

This material is based upon work supported by the National Science Foundation through the Florida Coastal Everglades Long-Term Ecological Research program under Cooperative Agreements #DBI-0620409 and #DEB-9910514. Any opinions, findings, conclusions, or recommendations expressed in the material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Controls on sensible heat and latent energy fluxes from a short-hydroperiod Florida Everglades marsh

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Abstract

Little is known of energy balance in low latitude wetlands where there is a year-round growing season and a climate best defined by wet and dry seasons. The Florida Everglades is a highly managed and extensive subtropical wetland that exerts a substantial influence on the hydrology and climate of the south Florida region. However, the effects of seasonality and active water management on energy balance in the Everglades ecosystem are poorly understood. An eddy covariance and micrometeorological tower was established in a short-hydroperiod Everglades marsh to examine the dominant environmental controls on sensible heat (H) and latent energy (LE) fluxes, as well as the effects of seasonality on these parameters. Seasonality differentially affected H and LE fluxes in this marsh, such that H was principally dominant in the dry season and LE was strongly dominant in the wet season. The Bowen ratio was high for much of the dry season (1.5 to 2.4), but relatively low (< 0.7) in the wet season. Net radiation strongly influenced H and LE fluxes across nearly all seasons and years (R^2_{adj} = 0.48-0.79). However, the 2009 dry season LE data were not consistent with this relationship (R^2_{adj} = 0.08) because of low seasonal variation in LE following a prolonged end to the previous wet season. In addition to net radiation, H and LE fluxes were significantly related to soil volumetric water content (VWC), water depth, air temperature, and occasionally vapor pressure deficit. Given that VWC and water depth were determined in part by water management decisions, it is clear that human actions have the ability to influence the mode of energy dissipation from this ecosystem. Impending modifications to water management under the Comprehensive Everglades Restoration Plan may shift the dominant turbulent flux from this ecosystem further toward LE, and this change will likely affect local hydrology and climate.

Keywords

eddy covariance; Everglades; latent energy; sensible heat; water management; wetland

1. Introduction

Wetlands cover 5-8% of the Earth's land surface area and play central roles in ecosystem energy balance (Keddy, 2000; Mitsch and Gosselink, 2007). Energy exchange in wetlands includes sensible heat (H) and latent energy (LE) fluxes to the atmosphere and is important in determining local hydrology, climate, and biogeochemical cycling (Chapin et al., 2002; Shukla and Mintz, 1982). Turbulent energy fluxes have been examined in a number of wetland ecosystems at mid- to high-latitude, and data indicate predictable environmental drivers of LE and H. Solar radiation (R_s) and plant phenology are often cited as important drivers of both fluxes, while LE flux is also frequently related to vapor pressure deficit (D) (Lafleur et al., 2005; Parmentier et al., 2009; Rocha and Goulden, 2008; Shimoyama et al., 2003). However, the thermal mass and horizontal movement of water through wetlands may complicate relationships between environmental drivers and energy balance in these ecosystems.

At present, the majority of our knowledge regarding wetland ecosystem energy balance is confined to the temperate, boreal, and arctic zones, with data principally collected only during the growing season. Little is known about energy exchange in wetlands of the subtropics and tropics where seasonality is best characterized by wet and dry seasons. The potential for year-round plant growth at low latitudes is likely to affect wetland energy balance differently during wet and dry periods of the year, as has been observed in some tropical terrestrial ecosystems (Malhi et al., 2002; von Randow et al., 2004).

The Florida Everglades is a large (>6000 km^2) subtropical wetland (Davis et al., 1994) that exerts significant influence over local hydrology and climate (Duever et al., 1994; Light and Dineen, 1994). Past efforts to examine components of ecosystem energy balance in

Everglades wetlands have focused principally on measuring and estimating LE as evapotranspiration (ET) (e.g. Abtew, 2004; German, 2000; Shoemaker and Sumner, 2006). No comprehensive assessments of environmental controls on LE and H have been performed, thus limiting our ability to understand and predict seasonal changes in these parameters.

Landscape modification to manage water in the Everglades began more than a century ago, and much of the Everglades is now impounded, with water levels and flows controlled by a system of canals, levees, and flow control structures (Light and Dineen, 1994; USACE and SFWMD, 1999). Prior to extensive human intervention in the south Florida landscape, water moved through the Everglades via continuous, slow sheet flow (Light and Dineen, 1994). Water levels and flows in the Everglades ecosystem will soon be altered under the Comprehensive Everglades Restoration Plan (CERP), a nearly $12 billion project authorized by the U.S. Congress in 2000. One of the objectives of CERP is to restore historical sheet flow within portions of the Everglades (Lodge, 2005), providing increased water flows, deeper water, and longer hydroperiods (i.e., duration of inundation). Construction associated with CERP is currently underway.

In light of limited data and imminent changes in Everglades water management as CERP is implemented, it is important to understand controls on LE and H in these wetlands. An eddy covariance and micrometeorological tower was established in the Everglades prior to any CERP-related changes in water management. The tower is located in a short-hydroperiod (seasonally inundated) marsh and two years of data collected at the site were used to address the following questions: (1) How does seasonality (i.e., dry vs. wet season) affect energy balance parameters? (2) What are the dominant environmental controls on

LE and H fluxes? (3) What changes in energy balance parameters can be anticipated with future alterations of Everglades water management?

2. Material and Methods

2.1 Study site

The study site is located within the short-hydroperiod Taylor Slough region of Everglades National Park (ENP) at 25°26'16.5" N, 80°35'40.68" W (Fig. 1a). The site is a freshwater marsh with a short-statured canopy (~0.73 m) dominated by sawgrass (*Cladium jamaicense*) and muhly grass (*Muhlenbergia capillaris*). Periphyton mats, comprised of algae, fungi, and bacteria, are also present at the site. Leaf area index is ~1.8 $m^2\ m^{-2}$ and does not vary seasonally (Schedlbauer et al., 2010). Soils are shallow (approx. 0.14 m) and composed of marl (calcium carbonate) sediments. The soil surface is gently undulating, though the site can be characterized as flat (Fig. 1b). The marsh extends for several kilometers in all directions around the study site but to the east where there is a canal and levee at a distance of 450 m. This area of ENP is typically flooded for ~5 months per year under the current regional water management program (Schedlbauer et al., 2010).

[Figure 1 approximately here]

The climate of south Florida is best characterized as tropical, with a winter dry season and summer wet season (Beck et al., 2006; Kottek et al., 2006). The mean annual temperature is 23.9°C and rainfall averages 143 cm per year (NCDC, 2009). The majority of annual precipitation falls during the wet season between May and October when regular convective storms form throughout the region (Duever et al., 1994). Significant wet season precipitation also comes from the passage of tropical storms and hurricanes. Precipitation during the dry season typically coincides with the passage of cold fronts over the Florida peninsula.

Hydroperiod at the Taylor Slough study site is a function of both precipitation and active water management by the South Florida Water Management District (Armentano et al., 2006; J.P. Sah, unpublished manuscript). The landscape of south Florida has been extensively managed for over a century, and water flow is largely controlled by an extensive system of canals, levees, and flow control structures. Water is actively pumped into Taylor Slough in a manner intended to coincide with the timing of historical hydroperiod (i.e., during south Florida's climatic wet season) and individual rainfall events (Abtew et al., 2009; Light and Dineen, 1994). For the present study, the wet season was defined as the time period during which the site was continually inundated, rather than by the climatically-defined south Florida wet season.

2.2 Eddy covariance and micrometeorological data

Data from an eddy covariance and micrometeorological tower, part of the AmeriFlux network, operating continuously in Taylor Slough from January 2008 to December 2009 are the subject of the present study. An open-path infrared gas analyzer (IRGA, LI-7500, LI-COR Inc., Lincoln, NE) was used to measure water vapor concentration and a sonic anemometer (CSAT3, Campbell Scientific, Logan, UT) was used to measure air temperature and windspeed in three directions. These sensors were installed 3.30 m above the soil surface and were 0.09 m apart. Data were logged at 10 Hz on a CR1000 datalogger (Campbell Scientific, Logan, UT) and stored on 2 GB CompactFlash cards. The IRGA was calibrated monthly using dry N_2 gas and a dewpoint generator (LI-610, LI-COR Inc., Lincoln, NE). Footprint analyses indicated that 90% of measured fluxes were from within 125 m of the tower (*see* Schedlbauer et al., 2010).

Other variables measured on a half-hourly basis by the CR1000 included aspirated (43502, R.M. Young, Traverse City, MI) air temperature (T_{air}) and relative humidity (HMP45C, Vaisala, Helsinki, Finland), as well as barometric pressure (PTB110, Vaisala, Helsinki, Finland). The T_{air}/relative humidity sensor was installed 2.5 m above the soil surface.

Additional meteorological data were recorded every 30 min with a CR10X datalogger and AM16/32A Relay Multiplexer (Campbell Scientific, Logan, UT). Photosynthetically active radiation (PAR, PAR Lite, Kipp and Zonen, Delft, Netherlands), solar radiation (R_s, LI-200SZ, LI-COR Inc., Lincoln, NE), and net radiation (R_n, CNR2-L, Kipp and Zonen, Delft, Netherlands) were measured every 15 s and averaged every 30 min. Measurements of precipitation were made with a tipping bucket rain gage (TE525, Texas Electronics, Dallas, TX). Soil heat flux (G) was determined by two heat flux plates (HFP01, Hukseflux, Delft, Netherlands) buried in the soil at 5 cm depth. The multiplier for the average half-hourly millivolt signals recorded for each plate was determined once every three hours with a separate self-calibrating heat flux plate (HFP01SC, Hukseflux, Delft, Netherlands), also buried at 5 cm depth. Soil volumetric water content was calculated from a site-specific equation for marl soils (Velkamp and O'Brien, 2000) and the period output of two soil moisture sensors (CS616, Campbell Scientific, Logan, UT) buried between 0 and 20 cm soil depth.

A set of insulated thermocouples (Type-T, Omega Engineering, Inc., Stamford, CT) were used to measure average water temperature at the site every 30 min in the wet season. A pair of thermocouples was located at a fixed height 5 cm above the soil surface and another pair was attached to shielded floats that held the thermocouples in place 5 cm below the water surface. Data from all four thermocouples were averaged and used to calculate total water heat storage (W) during the wet season with the equation,

$$W = V/A * \rho_w * c_w * (dT/dt)$$

where V is water volume (m^3), A is surface area (m^2), ρ_w is water density (kg m^{-3}, allowed to vary at 1°C intervals), c_w is the specific heat of water (J kg^{-1} $°C^{-1}$), dT is the change in average water temperature over a 30 minute period (°C), and dt is the time interval (s) (Campbell and Norman, 1998). Water level was recorded every half-hour with a water level logger (HOBO U20-001-01, Onset, Bourne, MA) installed in a solution hole well adjacent to the tower.

2.3 Data processing and gap filling

Raw H and LE data were processed with EdiRe (v. 1.4.3.1184, Clement, 1999) following standard protocols including coordinate rotation, despiking, and air density corrections (Aubinet et al., 2000; Baldocchi et al., 1988; Webb et al., 1980). Processed data yielded half-hourly raw values of H (W m^{-2}) and LE (W m^{-2}) that were filtered to remove periods with (1) evidence of condensation or precipitation on the IRGA or sonic anemometer, (2) wind vectors with a standard deviation (SD) >4, (3) IRGA and sonic anemometer flags, (4) implausible H (>600 or <-50 W m^{-2}) or LE (>700 or <-50 W m^{-2}) values, and (5) friction velocity (u*) <0.15 m s^{-1} (*see* Schedlbauer et al., 2010). Fifty-one percent of the data during the two-year study period were filtered out using these criteria, comprising 29% of daytime data and 79% of nighttime data.

Data were gap filled using the look-up table method as described by Falge et al. (2001) with the programming language R (v. 2.10.0, R Core Development Team, 2009). Briefly, the two years of processed, filtered flux data were divided into twelve bi-monthly periods. To accurately capture seasonal changes within these two-month periods, breaks between months were allowed to vary if conditions at the site changed from dry to inundated or vice-versa. Within each bi-monthly period, PAR data and vapor pressure deficit (D) data were binned in increments of 100 μmol m^{-2} s^{-1} and 0.15 kPa, respectively. A separate PAR bin was established for nighttime data. Mean values of H and LE were computed for each PAR by D bin combination and missing values within PAR classes were linearly interpolated (R function na.approx, 'zoo' Package v. 1.6-4, Zeileis et al., 2010). Linear extrapolation within PAR classes was performed by hand in a spreadsheet. Once tables were complete, filtered data were gap filled from the appropriate bi-monthly look-up table.

The performance of the look-up tables as a gap filling method were evaluated by comparing observed half-hourly H and LE data with the look-up table estimates for that half hour. Mean absolute error and root mean square error were computed for H and LE in each of the bi-monthly periods described above (Table 1). Additionally, linear regressions of observed vs. predicted values (Piñeiro et al. 2008) were used to assess look-up table performance. Regression slopes were equal to one, with a single exception (slope = 1.001), and y-intercept values ranged from -0.103 to 0.011, though most (n = 18) were equal to zero (data not shown). The R^2_{adj} values of these regressions varied from 0.77 to 0.96 (Table 1), indicating that LE and H were adequately represented during gap filled periods.

[Table 1 approximately here]

2.4 Data analyses

Half-hourly values representing components of the energy balance, R_n, G, W, H, and LE were converted to units of MJ m^{-2} s^{-1} and summed daily. These data were used to evaluate energy balance closure at the site rather than half-hourly data because of the lags in energy storage inherent in this ecosystem (i.e., in standing water and/or soil). Energy balance was evaluated seasonally (dry vs. wet season) for both 2008 and 2009 by plotting the daily sum of H and LE vs. the difference, $R_n - G$ (dry season) or $R_n - G - W$ (wet season). Linear regression was used to assess the percentage of energy balance closure during each of the four time periods.

For further analyses, the energy balance was forced closed on a daily basis by maintaining the Bowen ratio (β) and increasing H and LE to reach closure (Twine et al., 2000). These data were then used to compute seven day running means of R_n, G, W, H, and LE to examine seasonal variation within and among these variables. Mean monthly β values ± one standard error (SE) were computed from daily values. Two months, August 2008 and January 2009, straddled seasonal changes in water level and were divided into dry and wet season periods to compute β values.

The role of various environmental drivers in determining H and LE, thus β, was examined through regression and residuals analyses. Daily H and LE data were divided by season and year and analyzed with linear regression in relation to R_n, often the principle driver of variation in these terms. To examine potential secondary influences on H and LE, the residuals of these regression equations were examined in relation to soil VWC (dry season), water depth (wet season), T_{air}, and D.

Evapotranspiration was calculated from daily LE data with the equation,

$$ET = LE / \rho_w \lambda$$

where LE is daily latent energy flux (J m^{-2}), ρ_w is the density of water (kg m^{-3}), and λ is the latent heat of vaporization of water (J kg^{-1}). Daily ET values were summed monthly and annually and examined in relation to rainfall.

3. Results

3.1 Seasonality and meteorological conditions

Seasonality at this short-hydroperiod Everglades marsh was defined by the presence of water above the soil surface (grey shaded area, Fig. 2). Site-specific seasonality did not always coincide with the climatic wet season in south Florida. This was particularly apparent in 2008 when the climatic wet season began with significant rainfall in June, but the site's water level did not remain above the soil surface until mid-August (Fig. 2a, c). Although seasonal rainfall ceased in mid-October 2008, the site remained inundated until mid-January 2009. The onset of the 2009 climatic wet season more closely coincided with site-specific seasonality, though the duration of inundation was again prolonged through the end of 2009 (Fig. 2a, c).

[Figure 2 approximately here]

Soil VWC closely tracked changes in water level at the site, with saturated conditions during the wet season of 0.74 m^3 m^{-3} (Fig. 2a, b). During the dry season, substantial increases in subsurface water level were tied to spikes in VWC (Fig. 2a, b). The climatic dry season of 2009 was characterized by few rainfall events, resulting in a precipitous drop in VWC to 0.35 m^3 m^{-3} in May 2009.

Seasonal variation in R_n and T_{air} followed anticipated patterns, with maximum values during summer months and minimum values in winter months (Fig. 2d, e). Little variation in T_{air} was observed during summer/wet season months, while winter/dry season months were characterized by frequent drops in T_{air} as cold fronts passed over south Florida (Fig. 2e).

Daytime D was variable throughout the year, though annual maximum D typically coincided with the end of the dry season when T_{air} was high (Fig. 2f). The lowest D values were recorded while the site was inundated, and D tended to decline steadily throughout the wet season (Fig. 2f).

3.2 Seasonal variation in energy balance

Energy balance closure calculated with daily data indicated partial closure with the sum of H and LE equal to 71 and 76% of the available energy in the 2008 and 2009 dry seasons, respectively (Fig. 3a). The degree of energy balance closure was somewhat lower in the 2008 wet season, at 60%, and was similar in the 2009 wet season, at 75% (Fig. 3b). In both years and seasons, the turbulent fluxes of H and LE underestimated total available energy (Fig. 3a, b).

[Figure 3 approximately here]

Following forced energy balance closure, seven day running means of daily energy balance components revealed strong seasonal variation in these variables (Fig. 4a, b). Seasonal variation in energy inputs to the ecosystem was driven by variation in R_n with peaks in the late dry season to early wet season and troughs in the late wet season to early dry season (Fig. 4a). Both G and W made small seasonal contributions (≤5%) to the site's energy budget (Fig. 4a, Table 2). However, when examined on a daily basis, W fluxes were sometimes large (-4 to -9.8 MJ m^{-2} day^{-1}) during the passage of cold fronts over south

Florida (data not shown). These events were observed four times during the two-year study period.

[Figure 4, Table 2 approximately here]

During the early 2008 dry season, H and LE fluxes were of similar magnitude and exhibited gradually increasing daily values as R_n increased (Fig. 4b, Table 2). Bowen ratio values were high throughout this period with monthly mean values >1.5, indicating that fluxes were dominated by H (Fig. 5). With the onset of regular summer precipitation associated with the south Florida wet season (Fig. 2c), daily LE fluxes continued to increase while H fluxes decreased (Fig. 4b). These trends resulted in a steady decline in β (Fig. 5), as LE became the dominant flux (Table 2). In the early 2009 dry season, H and LE fluxes were again of similar magnitude, though β indicated that H again dominated over LE (Fig. 4b, 5, Table 2). A divergence in these fluxes occurred beginning in March 2009 when H fluxes began to increase to a two-year peak while LE fluxes remained roughly constant (Fig. 4b). By April 2009, β reached 2.3. Despite variation in dry season flux dynamics, the evaporative fraction (EF), calculated as the daily ratio of LE to R_n and averaged seasonally was the same for both dry seasons with a mean ± one SE of 0.52 ± 0.02.

[Figure 5 approximately here]

In the 2008 and 2009 wet seasons, turbulent fluxes were dominated by LE, a flux that varied in congruence with increases and decreases in R_n (Fig. 4a, b). Fluxes of H during the 2008 wet season were relatively steady, but declined over the course of the 2009 wet season (Fig. 4b). The wet season was consistently characterized by the lowest monthly β of the year with values from 0.3 to 0.8 (Fig. 5). Latent energy fluxes accounted for the dissipation of a substantial portion of R_n entering the ecosystem during the wet season. Evaporative fraction averaged 0.90 ± 0.03 in 2008 and 0.81 ± 0.06 in 2009.

3.3 Environmental controls on sensible and latent heat fluxes

Variation in daily values of H during the dry season was principally explained by variation in the daily sum of R_n (Fig. 6a). Residuals analyses indicated that additional variation was explained by soil VWC (27% in 2008, 6% in 2009, $p < 0.001$, data not shown) and T_{air} (19% in 2008, 22% in 2009, $p \leq 0.003$, data not shown). In the wet season, H was more weakly related to R_n than in the dry season (Fig. 6c). Because soils were saturated during the wet season, residuals analyses included water depth rather than VWC as a potential predictor variable. Water depth was significantly related to wet season H residuals, explaining 21 and 14% of the variation in residuals during 2008 and 2009, respectively ($p < 0.001$, data not shown). Wet season H residuals were also significantly related to T_{air} with 17% of the variation explained in 2008 and 3% in 2009 ($p \leq 0.006$, data not shown).

[Figure 6 approximately here]

In the 2008 dry season, variation in LE was highly related to R_n, but this relationship was weak in the 2009 dry season (Fig. 6b). Further analyses indicated that no environmental variable was strongly related to the residuals of the LE vs. R_n relationship in 2009, with only 11% and 3% of the variance explained by VWC and D ($p \leq 0.025$, data not shown). In contrast, VWC explained 27% of the residual variation in 2008 ($p < 0.001$, data not shown) and T_{air} explained 8% ($p < 0.001$, data not shown). During the wet season, the relationship between LE and R_n was strong (Fig. 6d). However, residual variation was only weakly related to other environmental variables in the wet season. Seven percent was explained by water depth in 2008, and this value dropped to 2% in 2009 ($p \leq 0.020$, data not shown). Residual variation was also slightly related to T_{air} in 2009 (4%, $p = 0.001$, data not shown).

3.4 Evapotranspiration

Daily rates of ET varied widely from a minimum of 0.2 mm day^{-1} to a maximum of 7.5 mm day^{-1} over the two-year study period. Dry season ET averaged 2.5 ± 0.04 mm day^{-1}. The highest rates of ET were recorded during wet season months, with a mean ET of 3.5 ± 0.05 mm day^{-1}. Annually, ET was 1038 mm in 2008 and 1168 mm 2009. Evapotranspiration accounted for 86% of rainfall in 2008 and 91% in 2009.

Monthly patterns of ET follow annual cycles, with lowest monthly rates occurring in the dry season and highest rates in the wet season (Table 3). Because south Florida experiences extended periods during the dry season in which little to no rain falls (Fig. 2c), ET exceeded precipitation for several months of the study period. This was most notable in the 2009 climatic dry season (i.e., following the cessation of wet season rainfall) when ET was more than seven times greater than precipitation for five of the six months from November 2008 to April 2009 (Table 3).

[Table 3 approximately here]

4. Discussion

4.1 Seasonal variation in energy balance

The dominant turbulent flux at this short-hydroperiod Everglades marsh varied seasonally, with H principally dominant in the dry season and LE clearly dominant in the wet season. The onset of seasonal rains in the early summer clearly shifted the ecosystem's dominant flux from H to LE, a pattern that became more strongly pronounced once the site was fully inundated. Within low latitude ecosystems, strong seasonal shifts in the dominant turbulent flux from H to LE are uncommon, though they have been reported in a savanna ecosystem (Giambelluca et al., 2009). Throughout much of the tropics, LE fluxes strongly dominate energy losses from terrestrial ecosystems year-round (da Rocha et al., 2004; Hutyra et al., 2007; Malhi et al., 2002; von Randow et al., 2004; Vourlitis et al., 2008). This annual pattern has also been reported in a subtropical rice paddy with a 10-month period of inundation (Hossen et al., in press). Comparisons of current data from the Everglades with other non-agricultural, subtropical or tropical wetlands are not possible because, to our knowledge, no long-term data sets yet exist for these ecosystems.

The variation in seasonal dominance of LE and H was clearly reflected in other calculated parameters, specifically β and EF. Bowen ratio fluctuated from ≥ 1.5 at the height of the dry season to lows <0.7 in the wet season. While not exceptional among Everglades wetlands (German 2000), the magnitude of seasonal variation in β at Taylor Slough was larger than that reported for a range of ecosystems throughout subtropical Florida and across several tropical ecosystems (da Rocha et al., 2004; Douglas et al., 2009; von Randow et al., 2004; Vourlitis et al., 2008). The high degree of variation in β within this Everglades marsh was due to the high dry season β values, something that may be an artifact of water management activities that have increased drought-like conditions in marl marshes (Davis et al., 2005). These dry season β data are unexpectedly similar to values associated with semi-arid environments and tropical savannas rather than subtropical rice paddies, subtropical wetlands, and tropical forests (Chapin et al., 2002; Douglas et al., 2009; Giambelluca et al., 2009; Hossen et al., in press).

The high dry season β values were clearly influenced by increased H fluxes as incoming radiation heated plant and soil surfaces typically submerged during the wet season. The substantial decreases observed in soil VWC during the dry seasons indicated that the high β values were also influenced by the limitation of ET. Leaf-level gas exchange measurements confirm that transpiration rates were reduced in the dry season relative to the wet season. The two dominant plant species at the site, *C. jamaicense* and *M. capillaris*, both had significantly lower dry season transpiration rates ($p < 0.03$, S.F. Oberbauer, unpublished data). In light of these data, it is likely that the high dry season β at Taylor Slough was driven by a combination of increased H fluxes, reduced evaporative water losses from the soil, and restricted transpiration rates as the soils dried.

Throughout the dry season, EF was moderate (52%) though substantially reduced from wet season highs of 81-90%. Similar seasonal shifts have been reported in other short-hydroperiod Everglades marshes and in a subtropical rice paddy (German and Sumner, 2002; Hossen et al., in press). The change in EF at Taylor Slough reflected the seasonal shifts in dominance between H and LE as modes of energy transport from the ecosystem. Wet season EF was most similar to values reported for open-water Everglades sites (>80%) rather than vegetated sites (62-79%) (German, 2000). Although leaf-level transpiration was significantly higher in the wet season, the majority of the ecosystem's leaf area was submerged during periods of inundation (Schedlbauer et al., 2010). This likely contributed to the functionality of this ecosystem as an open-water site rather than a vegetated site.

4.2 Energy balance closure

Energy balance closure at this site was typically >70%, though the 2008 wet season proved to be an exception with closure at 60%. Available energy was consistently underestimated by the turbulent fluxes H and LE. The energy balance closure values at this short-hydroperiod marsh were within the range of values reported across terrestrial FLUXNET sites, though they were lower than the FLUXNET mean of 80% closure (Wilson et al., 2002). Among other wetland studies reporting energy balance data, closure at ~70% is not unusual (Hossen et al., in press; Li et al., 2009; Mackay et al., 2007).

The most likely explanation for the moderate energy balance closure at this short-statured site was that water vapor and heat carried by large eddies operating at a landscape scale were not captured by the eddy covariance system (Foken, 2008). This explanation applies best in heterogeneous landscapes (Foken et al., 2010) and, while the Taylor Slough site is relatively homogenous, the larger landscape includes levees, canals, and abandoned agricultural land. By forcing the Taylor Slough energy balance closed by preserving β (Twine et al., 2000), it was assumed that β was identical across small and large eddies. This assumption should be evaluated in future work at the site.

During the wet season, water slowly moves through the Taylor Slough study site at a rate of ~0.5 to 0.8 cm s^{-1} (Schaffranek and Ball, 2001). It is therefore possible that energy stored in the soil or water column is transported horizontally through the tower's footprint area. However, it is unlikely that this potential flow of energy affected the site's energy balance because of the homogeneity of the area immediately surrounding the tower. Any outflows of energy were likely balanced by inflows during the wet season.

4.3 Environmental controls on sensible and latent heat fluxes

In many low latitude and wetland ecosystems, seasonal variation in H and LE is often tied to variation in phenology, as well as a suite of environmental factors (Admiral et al., 2006; da Rocha et al., 2004; Giambelluca et al., 2009; Goulden et al., 2007). However, in this Everglades marsh, phenology is of little importance because total leaf area index and *C. jamaicense* aboveground biomass do not vary seasonally (Schedlbauer et al., 2010). Among environmental drivers of turbulent fluxes, R_n was highly related to H and LE across seasons and years, though the amount of variation explained by R_n varied. In particular, there was a substantial dry to wet season decline in the relationship between R_n and H. Inundation, which submerges the soil surface and majority of the site's leaf area, tempers the responsiveness of H to variation in R_n, in addition to reducing the magnitude of H fluxes. The relationship between LE and R_n was more consistent across seasons, with the exception of the 2009 dry season.

Beyond R_n, the influence of other environmental factors on turbulent fluxes varied within and across seasons, indicating that local variation in these factors can influence H and LE. Some of these variables, specifically water depth and VWC, fall partly under human control through water management decisions affecting Taylor Slough (Armentano et al., 2006; J.P. Sah, unpublished manuscript). In the wet season, increased water depth had a negative influence on H and a positive influence on LE. In the dry season, increased soil VWC, a factor that varied synchronously with water depth, had an identical influence on H and LE fluxes. In light of these relationships, it is clear that management decisions affecting water levels in Taylor Slough can influence the mode of energy dissipation from this ecosystem.

Albedo, a factor not measured in the present study, is an additional variable that may influence turbulent fluxes through its effect on R_n. Seasonal variation in albedo has been reported for other south Florida wetlands that fluctuate between dry and wet conditions (Sumner et al., 2011). In the dry season, the light-colored soil surface and exposed periphyton at the Taylor Slough site would likely have increased albedo over wet season conditions. Given that increased albedo is characterized by increased reflection of shortwave radiation, there is a subsequent decrease in available energy (R_n) that can have consequences for fluxes of H and LE. Independent measurements of incoming and outgoing short- and long-wave radiation will be required to resolve the role of albedo in determining energy fluxes at this site.

4.4 Evapotranspiration

Annual ET at Taylor Slough was comparable to values reported for nearby short-hydroperiod Everglades marshes (1077 and 1105 mm yr^{-1}), though the β-energy budget method was used for ET determination in these studies rather than EC (German, 2000; German and Sumner, 2002). In the present study, ET was 130 mm lower in 2008 than in 2009, a difference that was partly accounted for by the delayed onset of inundation in 2008. During this period (June, July, and August), ET was an average of 28.5 mm mo^{-1} lower than in 2009.

Despite similarities in annual ET across Everglades marshes, differences emerged when the data were examined on a seasonal basis. Average daily ET was comparable to rates reported for other Everglades marshes in the dry season, but was lower by ~1 mm day^{-1} in the wet season (Douglas et al., 2009). Annual ET rates in Everglades marshes increase in a linear fashion with increasing median annual water depth (German, 2000), and a positive wet season relationship between LE and water depth was observed in the present study. Therefore, the relatively shallow water depths at Taylor Slough may explain the low wet season ET values reported here.

4.5 Influence of water management on energy balance parameters

Human actions play a role in determining the duration of the wet and dry seasons within Taylor Slough (Armentano et al., 2006; J.P. Sah, unpublished manuscript). Prolonging or shortening seasons by altering the initiation and termination of each season through water management can affect the magnitude of LE and H fluxes. These alterations, as well as mismatches between South Florida's climatic seasonality and site-specific seasonality (i.e., inundated vs. non-inundated periods) can alter fluxes in unexpected ways.

The influence of water management on turbulent fluxes was particularly clear in the 2009 dry season, during which LE remained fairly steady and increased notably only after seasonal rainfall began in mid-May. The 2008 wet season lasted for ~3 months after seasonal rains ceased, as water was continually pumped into Taylor Slough (J.L. Schedlbauer, personal observation). As a result, the site was inundated until mid-January 2009 and there was ample soil water available for ET in the early 2009 dry season. Although R_n was close to its annual minimum in January 2009, it had little effect on LE. Water management activities leading to high soil water availability during a typically dry period of the year altered the usually highly predictable relationship between R_n and LE.

The implications of water management decisions on hydrologic cycling in short-hydroperiod Everglades marshes should be considered as Everglades restoration activities under CERP proceed. As CERP is implemented, Everglades freshwater marshes will be subject to longer hydroperiods and deeper water levels. These alterations are likely to increase LE fluxes from short-hydroperiod marshes and may reduce the duration of time in which H fluxes dominate energy dissipation. Considered relative to the land area occupied by Everglades marl prairie (1900 km^2, Davis et al., 2005), anthropogenic changes in hydrologic patterns have the potential to affect factors such as convective storm formation, thus delivery of precipitation, to parts of the Everglades ecosystem and surrounding agricultural and urban centers.

4.6 Conclusions

The two years of energy balance data presented here provide a first look at the dynamics of H and LE in a low-latitude, non-agricultural wetland where seasonality is defined by dry and wet seasons. One of the most striking findings is the fluctuation in the dominant turbulent flux in this ecosystem from H in the dry season to LE in the wet season. This fluctuation, reflected in terms such as β, highlights the environmental extremes of this ecosystem. Plants exhibit significantly reduced transpiration rates, but survive under drought-like conditions, likely to have been exacerbated by water management activities (Davis et al., 2005), in the dry season. In contrast, the same vegetation persists through extended periods of total inundation during the wet season.

Despite these environmental extremes, fluxes of H and LE from this short-hydroperiod marsh are relatively predictable and highly related to variation in R_n, provided that the site's hydroperiod mirrors south Florida's climatic seasonality. Other environmental factors influencing H and LE vary seasonally and are at least partly under human control. Efforts to restore historical patterns of water flow to Everglades marshes may shift energy dissipation from this ecosystem to favor LE over H, a change that will likely affect local hydrology and climate.

Acknowledgements

This research was funded by the Department of Energy's National Institute for Climate Change Research through grant number 07-SC-NICCR-1059. Research was conducted under permit EVER-2007-SCI-0065 from Everglades National Park. Thanks to Javier Arenas, Jay Munyon, Benjamin Wilson, and Elizabeth Ortiz for field and lab assistance and to John Beneski for help with image editing. Thanks also to W. Barclay Shoemaker and one anonymous reviewer for valuable comments that greatly improved this manuscript.

References

Abtew, W., 2004. Evapotranspiration in the Everglades; Comparison of Bowen Ratio Measurements and Model Estimations. Technical Paper EMA #417, South Florida Water Management District, West Palm Beach.

Abtew, W., Pathak, C., Huebner, R.S., Ciuca, V., 2009. Hydrology of the south Florida environment, in: South Florida Environmental Report, Vol. I, The South Florida Environment. South Florida Water Management District, West Palm Beach. pp. 2.1-2.53.

Admiral, S.W., Lafleur, P.M., Roulet, N.T., 2006. Controls on latent heat flux and energy partitioning at a peat bog in eastern Canada. Agricultural and Forest Meteorology 140, 308-321.

Armentano, T.V., Sah, J.P., Ross, M.S., Jones, D.T., Cooley, H.C., Smith, C.S., 2006. Rapid responses of vegetation to hydrological changes in Taylor Slough, Everglades National Park, Florida, USA. Hydrobiologia 569, 293-309.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A.S., Martin, P.H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grünwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., Vesala, T., 2000. Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology, in: Fitter, A.H., Raffaelli, D.G. (Eds.), Advances in Ecological Research. Academic Press, New York, pp. 113-175.

Baldocchi, D.D., Hicks, B.B., Meyers, T.P., 1988. Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods. Ecology 69, 1331-1340.

Beck, C., Grieser, M., Kottek, M., Rubel, F., Rudolf, B., 2006. Characterizing global climate change by means of Köppen Climate Classification. Klimastatusbericht 2005, 139-149.

Campbell, G.S., Norman, J.M., 1998. An Introduction to Environmental Biophysics, second ed., Springer, New York.

Chapin, F.S., Matson, P.A., Mooney, H.A., 2002. Principles of Terrestrial Ecosystem Ecology, first ed., Springer, New York.

da Rocha, H.R., Goulden, M.L., Miller, S.D., Menton, M.C., Pinto, L.D.V.O., de Freitas, H.C., e Silva Figueira, A.M., 2004. Seasonality of water and heat fluxes over a tropical forest in eastern Amazonia. Ecological Applications 14, S22-S32.

Davis, S.M., Gaiser, E.E., Loftus, W.F., Huffman, A.E., 2005. Southern marl prairies conceptual ecological model. Wetlands 25, 821-831.

Davis, S.M., Gunderson, L.H., Park, W.A., Richardson, J.R., Mattson, J.E., 1994. Landscape dimension, composition, and function in a changing Everglades ecosystem, in: Davis, S.M., Ogden, J.C. (Eds.), Everglades: the Ecosystem and its Restoration. St. Lucie Press, Delray Beach, pp. 419-444.

Douglas, E.M., Jacobs, J.M., Sumner, D.M., Ray, R.L., 2009. A comparison of models for estimating potential evapotranspiration for Florida land cover types. Journal of Hydrology 373, 366-376.

Duever, M.J., Meeder, J.F., Meeder, L.C., McCollom, J.M., 1994. The climate of south Florida and its role in shaping the Everglades ecosystem, in: Davis, S.M., Ogden, J.C. (Eds.), Everglades: the Ecosystem and its Restoration. St. Lucie Press, Delray Beach, pp. 225-248.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grünwald, T., Hollinger, D., Jensen, N.-O., Katul, G., Keronen, P., Kowalski, A., Lai, C.T., Law, B.E., Meyers, T., Moncrieff, J., Moors, E., Munger, J.W., Pilegaard, K., Rannik, Ü., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agricultural and Forest Meteorology 107, 43-69.

Foken, T., 2008. The energy balance closure problem: an overview. Ecological Applications 18, 1351-1367.

Foken, T., Mauder, M., Liebethal, C., Wimmer, F., Beyrich, F., Leps, J.-P., Raasch, S., DeBruin, H.A.R., Meijninger, W.M.L., Bange, J., 2010. Energy balance closure for the LITFASS-2003 experiment. Theoretical and Applied Climatology 101, 149-160.

German, E.R., 2000. Regional Evaluation of Evapotranspiration in the Everglades, Water-Resources Investigations Report 00-4217. United States Geological Survey, Tallahassee.

German, E.R., Sumner, D.M., 2002. Evapotranspiration rates from two different sawgrass communities in south Florida during drought conditions, in Proceedings of the Second

Federal Interagency Hydrologic Modeling Conference, Advisory Committee on Water Information, Las Vegas.

Giambelluca, T.W., Scholz, F.G., Bucci, S.J., Meinzer, F.C., Goldstein, G., Hoffmann, W.A., Franco, A.C., Buchert, M.P., 2009. Evapotranspiration and energy balance of Brazilian savannas with contrasting tree density. Agricultural and Forest Meteorology 149, 1365-1376.

Goulden, M.L., Litvak, M., Miller, S.D., 2007. Factors that control Typha marsh evapotranspiration. Aquatic Botany 86, 97-106.

Hossen, M.S., Mano, M., Miyata, A., Baten, M.A., Hiyama, T., In Press. Surface energy partitioning and evapotranspiration over a double-cropping paddy field in Bangladesh. Hydrological Processes

Hutyra, L.R., Munger, J.W., Saleska, S.R., Gottlieb, E., Daube, B.C., Dunn, A.L., Amaral, D.F., de Camargo, P.B., Wofsy, S.C., 2007. Seasonal controls on the exchange of carbon and water in an Amazonian rain forest. Journal of Geophysical Research 112, G03008.

Keddy, P.A., 2000. Wetland Ecology Principles and Conservation, first ed. Cambridge University Press, New York.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift 15, 259-263.

Lafleur, P.M., Hember, R.A., Admiral, S.W. , Roulet, N.T., 2005. Annual and seasonal variability in evapotranspiration and water table at a shrub-covered bog in southern Ontario, Canada. Hydrological Processes 19, 3533-3550.

Li, Y., Zhou, L., Xu, Z., Zhou, G., 2009. Comparison of water vapor, heat and energy exchanges over agricultural and wetland ecosystems. Hydrological Processes 23, 2069-2080.

Light, S.S., Dineen, J.W., 1994. Water control in the Everglades: a historical perspective, in: Davis, S.M., Ogden, J.C. (Eds.), Everglades: the Ecosystem and its Restoration. St. Lucie Press, Delray Beach, pp. 47-84.

Lodge, T.E., 2005. The Everglades Handbook: Understanding the Ecosystem, second ed. CRC Press, Boca Raton.

Mackay, D.S., Ewers, B.E., Cook, B.D., Davis, K.J., 2007. Environmental drivers of evapotranspiration in a shrub wetland and an upland forest in northern Wisconsin. Water Resources Research 43, W03442.

Malhi, Y., Pegoraro, E., Nobre, A.D., Pereira, M.G.P., Grace, J., Culf, A.D., Clement, R., 2002. The energy and water dynamics of a central Amazonian rain forest. Journal of Geophysical Research 107, LBA 45-1.

Mitsch, W.J., Gosselink, J.G., 2007. Wetlands, fourth ed. John Wiley and Sons, Hoboken.

National Climatic Data Center (NCDC), 2009. Royal Palm Rs daily surface data. http://www.ncdc.noaa.gov/oa/ncdc.html, NCDC, Asheville, accessed 4/10/09.

Parmentier, F.J.W., van der Molen, M.K., de Jeu, R.A.M., Hendriks, D.M.D., Dolman, A.J., 2009. CO_2 fluxes and evaporation on a peatland in the Netherlands appear not affected by water table fluctuations. Agricultural and Forest Meteorology 149, 1201-1208.

Piñeiro, G., Perelman, S., Guerschman, J.P., Paruelo, J.M., 2008. How to evaluate models: Observed vs. predicted or predicted vs. observed? Ecological Modeling 216, 316-322.

Rocha, A.V., Goulden, M.L., 2008. Large interannual CO_2 and energy exchange variability in a freshwater marsh under consistent environmental conditions. Journal of Geophysical Research 113, G04019.

Schaffranek, R.W., Ball, M.H., 2001. Flow velocities in wetlands adjacent to canal C-111 in south Florida, in: Eggleston, J.R., Embry, T.L., Mooney, R.H., Wedderbum, L., Goodwin, C.R., Henkel, H.S., Pegram, K.M.H., Enright, T.J. (Eds.), U.S. Geological Survey Program on the South Florida Ecosystem: 2000 Proceedings. USGS, Tallahassee, pp. 43-45.

Schedlbauer, J.L., Oberbauer, S.F., Starr, G., Jimenez, K.L., 2010. Seasonal differences in the CO_2 exchange of a short-hydroperiod Florida Everglades marsh. Agricultural and Forest Meteorology 150, 994-1006.

Shimoyama, K., Hiyama, T., Fukushima, Y., Inoue, G., 2003. Seasonal and interannual variation in water vapor and heat fluxes in a West Siberian continental bog. Journal of Geophysical Research 108, ACL 14.

Shoemaker, W.B., Sumner, D.M., 2006. Alternate corrections for estimating actual wetland evapotranspiration from potential evapotranspiration. Wetlands 26, 528-543.

Shukla, J., Mintz, Y., 1982. Influence of land-surface evapotranspiration on the Earth's climate. Science 215, 1498-1501.

Sumner, D.M., Wu, Q., Pathak, C.S., 2011. Variability of albedo and utility of the MODIS albedo product in forested wetlands. Wetlands 31, 229-237.

Twine, T.E., Kustas, W.P., Norman, J.M., Cook, D.R., Houser, P.R., Meyers, T.P., Prueger, J.H., Starks, P.J., Wesely, M.L., 2000. Correcting eddy-covariance flux underestimates over a grassland. Agricultural and Forest Meteorology 103, 279-300.

U.S. Army Corps of Engineers (USACE) and South Florida Water Management District (SFWMD), 1999. Central and Southern Florida Project Comprehensive Review Study, Final Integrated Feasibility Report and Programmatic Environmental Impact Statement. USACE, Jacksonville District, Jacksonville and SFWMD, West Palm Beach.

Veldkamp, E., O'Brien, J.J., 2000. Calibration of a frequency domain reflectometry sensor for humid tropical soils of volcanic origin. Soil Science Society of America Journal 64, 1549-1553.

von Randow, C., Manzi, A.O., Kruijt, B., de Oliveira, P.J., Zanchi, F.B., Silva, R.L., Hodnett, M.G., Gash, J.H.C., Elbers, J.A., Waterloo, M.J., Cardoso, F.L., Kabat, P., 2004. Comparative measurements and seasonal variations in energy and carbon exchange over forest and pasture in South West Amazonia. Theoretical and Applied Climatology 78, 5-26.

Vourlitis, G.L., Nogueira, J.d.S., Lobo, F.d.A., Sendall, K.M., de Paulo, S.R., Dias, C.A.A., Pinto, O.B.P., de Andrade, N.L.R., 2008. Energy balance and canopy conductance of a tropical semi-deciduous forest of the southern Amazon Basin. Water Resources Research 44, W03412.

Webb, E.K., Pearman, G.I., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Quarterly Journal of the Royal Meteorological Society 106, 85-100.

Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., Dolman, H. , Field, C., Grelle, A., Ibrom, A., Law, B.E., Kowalski, A., Meyers, T., Moncrieff, J., Monson, R., Oechel, W., Tenhunen, J., Valentini, R., Verma, S., 2002. Energy balance closure at FLUXNET sites. Agricultural and Forest Meteorology 113, 223-243.

Table 1. Mean absolute error (MAE), root mean square error (RMSE), and R^2_{adj} calculated to compare observed half-hourly values of sensible heat flux and latent energy flux with values determined using the look-up table gap filling method. Data are reported for the 12 bi-monthly periods for which different look-up tables were generated.

	Sensible heat flux ($W m^{-2}$)			Latent energy flux ($W m^{-2}$)		
Period	**MAE**	**RMSE**	**R^2_{adj}**	**MAE**	**RMSE**	**R^2_{adj}**
2008						
Jan-Feb	11.7	16.9	0.96	10.0	14.2	0.89
Mar-Apr	17.5	27.1	0.93	14.4	21.2	0.86
May-Jun	19.1	27.7	0.94	20.0	28.3	0.80
Jul-Aug	25.3	36.7	0.84	23.4	32.8	0.81
Sep-Oct	10.5	15.2	0.79	17.6	23.9	0.81
Nov-Dec	11.9	16.6	0.80	13.3	17.2	0.77
2009						
Jan-Feb	13.0	19.0	0.96	11.7	16.6	0.88
Mar-Apr	18.3	26.8	0.95	18.8	28.4	0.79
May-Jun	11.6	17.9	0.92	20.0	29.3	0.83
Jul-Aug	9.9	14.5	0.85	20.1	28.0	0.81
Sep-Oct	9.3	12.7	0.83	19.9	26.9	0.77
Nov-Dec	10.2	14.1	0.90	16.8	22.7	0.83

Table 2. Mean values ± one SE of daily net radiation (R_n, MJ m^{-2} day^{-1}), sensible heat flux (H), latent energy flux (LE), soil heat flux (G), and water heat flux (W) for each season at Taylor Slough.

	Energy flux (MJ m^{-2} day^{-1})				
Season	**R_n**	**H**	**LE**	**G**	**W**
2008 Dry	13.00 ± 0.28	6.16 ± 0.18	6.25 ± 0.13	0.59 ± 0.07	--
2008 Wet	9.49 ± 0.31	1.77 ± 0.09	7.83 ± 0.21	-0.03 ± 0.08	-0.09 ± 0.17
2009 Dry	12.74 ± 0.31	6.79 ± 0.26	6.06 ± 0.11	-0.11 ± 0.10	--
2008 Wet	11.46 ± 0.30	2.26 ± 0.10	8.95 ± 0.16	0.34 ± 0.10	-0.10 ± 0.11

Table 3. Monthly sums of evapotranspiration (ET, mm mo^{-1}) and monthly ET expressed as a percentage of monthly rainfall.

	ET (mm mo^{-1})	ET % of Rainfall
2008		
Jan	47.0	343
Feb	60.6	69
Mar	70.9	60
Apr	86.7	89
May	86.0	458
June	88.0	52
July	101.3	71
Aug	104.6	38
Sept	108.3	72
Oct	121.6	105
Nov	85.5	748
Dec	77.8	900
2009		
Jan	75.6	4963
Feb	64.8	982
Mar	73.8	118
Apr	73.9	2910
May	90.8	37
June	119.2	57
July	126.7	61
Aug	133.4	63
Sept	108.4	72
Oct	113.9	712
Nov	110.7	98
Dec	76.4	135

Figure Captions

Figure 1. Map of south Florida with the study site indicated (star, A) and image of the eddy covariance tower located in Taylor Slough (B).

Figure 2. Mean daily water depth, relative to the soil surface (m, A), mean daily soil volumetric water content (VWC, m^3 m^{-3}, B), summed daily rainfall (mm, C), total daily net radiation (R_n, MJ m^{-2} day^{-1}, D), mean daily air temperature (T_{air}, °C, E), and mean daytime vapor pressure deficit (D, kPa, F) at the Taylor Slough study site. Grey shaded areas are time periods when the site was inundated.

Figure 3. Summed daily sensible heat (H) and latent energy (LE) fluxes plotted as a function of the daily sum of net radiation (R_n) less soil heat flux (G) and water heat flux (W). Dry season (A) and wet season (B) data are plotted separately for the years 2008 (black circles) and 2009 (grey circles). The black (2008) and grey (2009) lines are derived from linear regressions for each season by year combination. The dotted line on each panel represents the 1:1 line.

Figure 4. Seven-day running means of daily net radiation (R_n), soil heat flux (G), water heat flux (W) (A), sensible heat flux (H), and latent energy flux (LE) (B). Grey shaded areas are time periods when the site was inundated.

Figure 5. The monthly mean ± one SE Bowen ratio (β) calculated from mid-day mean values. Months that were split between dry and wet periods were divided and β was calculated independently for each period. Grey shaded areas are time periods when the site was inundated.

Figure 6. Summed daily sensible heat (H) flux and latent energy (LE) flux plotted as a function of daily net radiation (R_n) for the dry (A, B) and wet (C, D) seasons. Data from

2008 and 2009 are plotted separately. The black (2008) and grey (2009) lines are derived from linear regressions for each season by year combination.

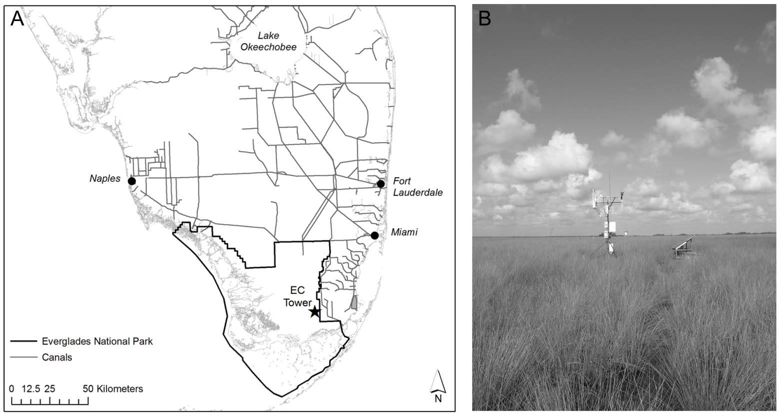

A
Lake Okeechobee
Naples
Fort Lauderdale
Miami
EC Tower
Everglades National Park
Canals
0 12.5 25 50 Kilometers
N
B

Fig. 1

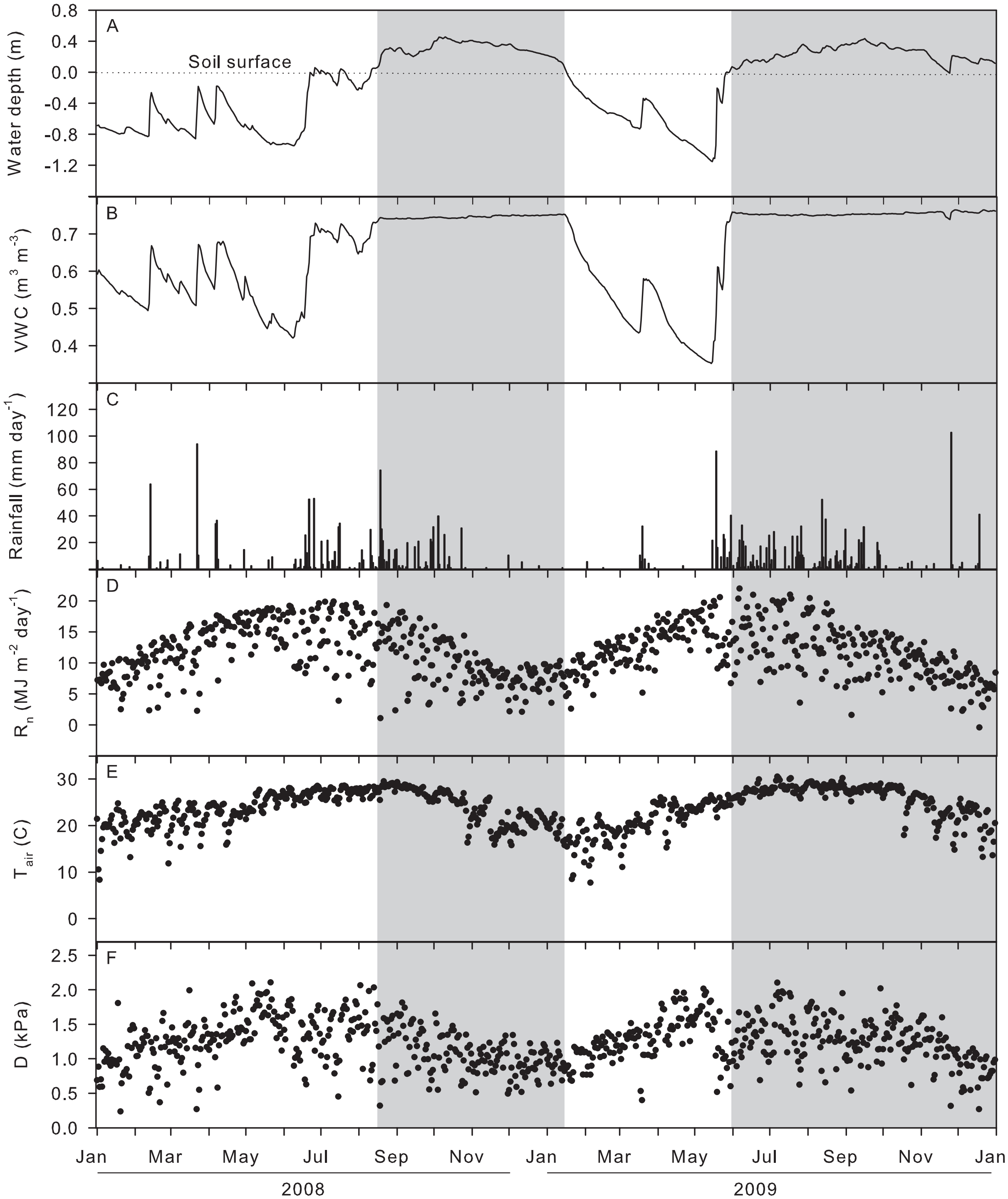

A
Soil surface
Water depth (m)
0.8
0.4
0.0
-0.4
-0.8
-1.2
B
VWC (m3 m-3)
0.7
0.6
0.5
0.4
C
Rainfall (mm day-1)
120
100
80
60
40
20
D
Rn (MJ m-2 day-1)
20
15
10
5
0
E
Tair (C)
30
20
10
0
F
D (kPa)
2.5
2.0
1.5
1.0
0.5
0.0
Jan
Mar
May
Jul
Sep
Nov
Jan
Mar
May
Jul
Sep
Nov
Jan
2008
2009

Fig. 2

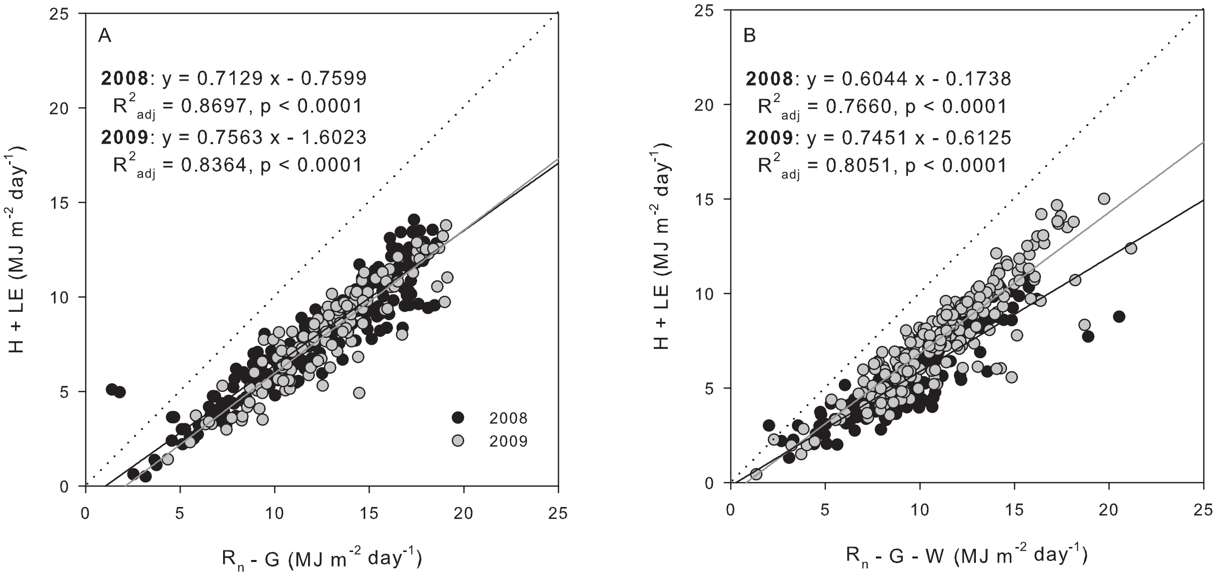

A
2008: y = 0.7129 x - 0.7599
R2adj = 0.8697, p < 0.0001
2009: y = 0.7563 x - 1.6023
R2adj = 0.8364, p < 0.0001
2008
2009
H + LE (MJ m-2 day-1)
Rn - G (MJ m-2 day-1)
B
2008: y = 0.6044 x - 0.1738
R2adj = 0.7660, p < 0.0001
2009: y = 0.7451 x - 0.6125
R2adj = 0.8051, p < 0.0001
H + LE (MJ m-2 day-1)
Rn - G - W (MJ m-2 day-1)

Fig. 3

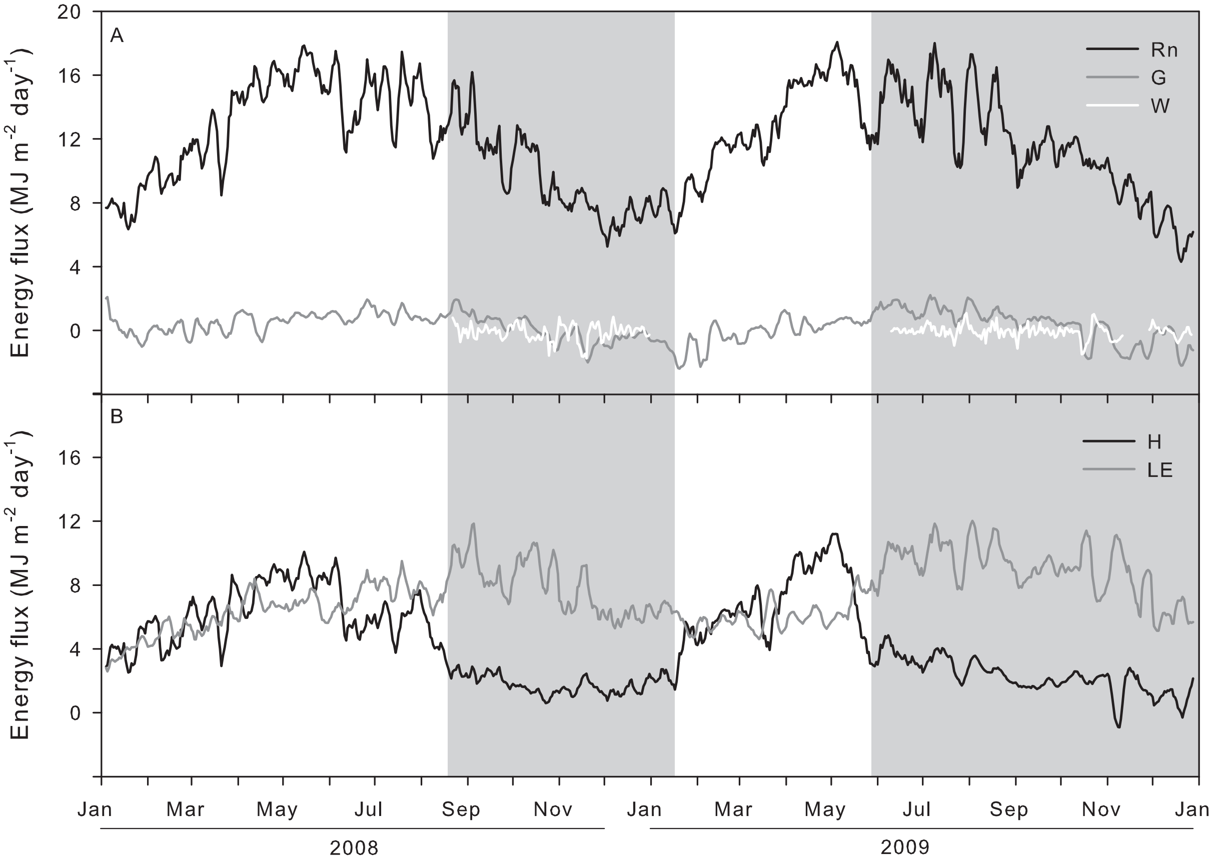
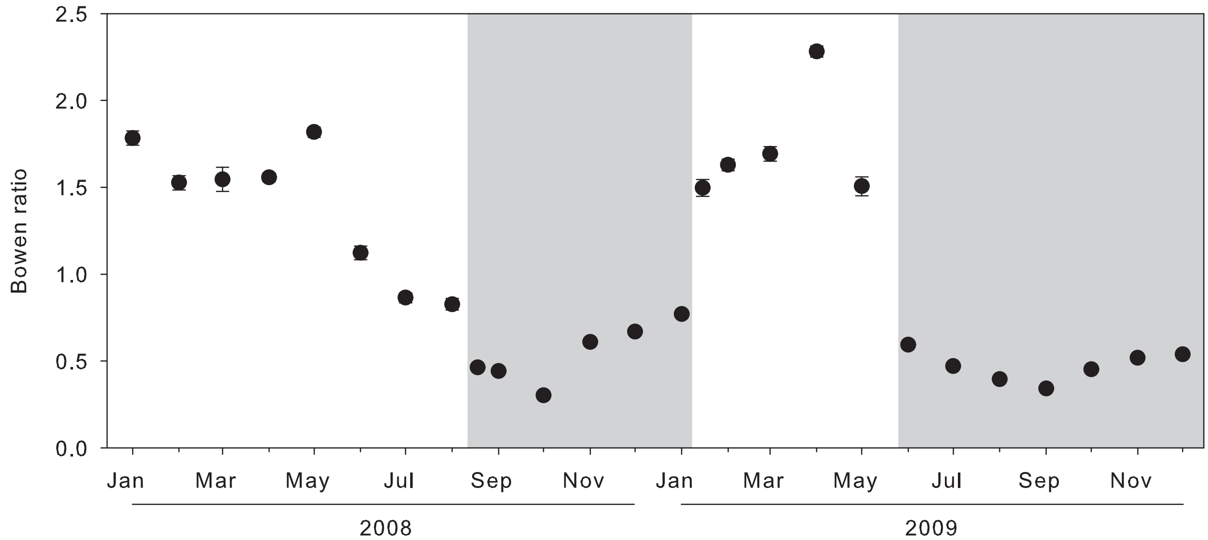

A
B
Energy flux (MJ m-2 day-1)
Rn
G
W
H
LE
Jan
Mar
May
Jul
Sep
Nov
2008
2009

Fig. 4



Bowen ratio
2.5
2.0
1.5
1.0
0.5
0.0
Jan
Mar
May
Jul
Sep
Nov
Jan
Mar
May
Jul
Sep
Nov
2008
2009

Fig. 5

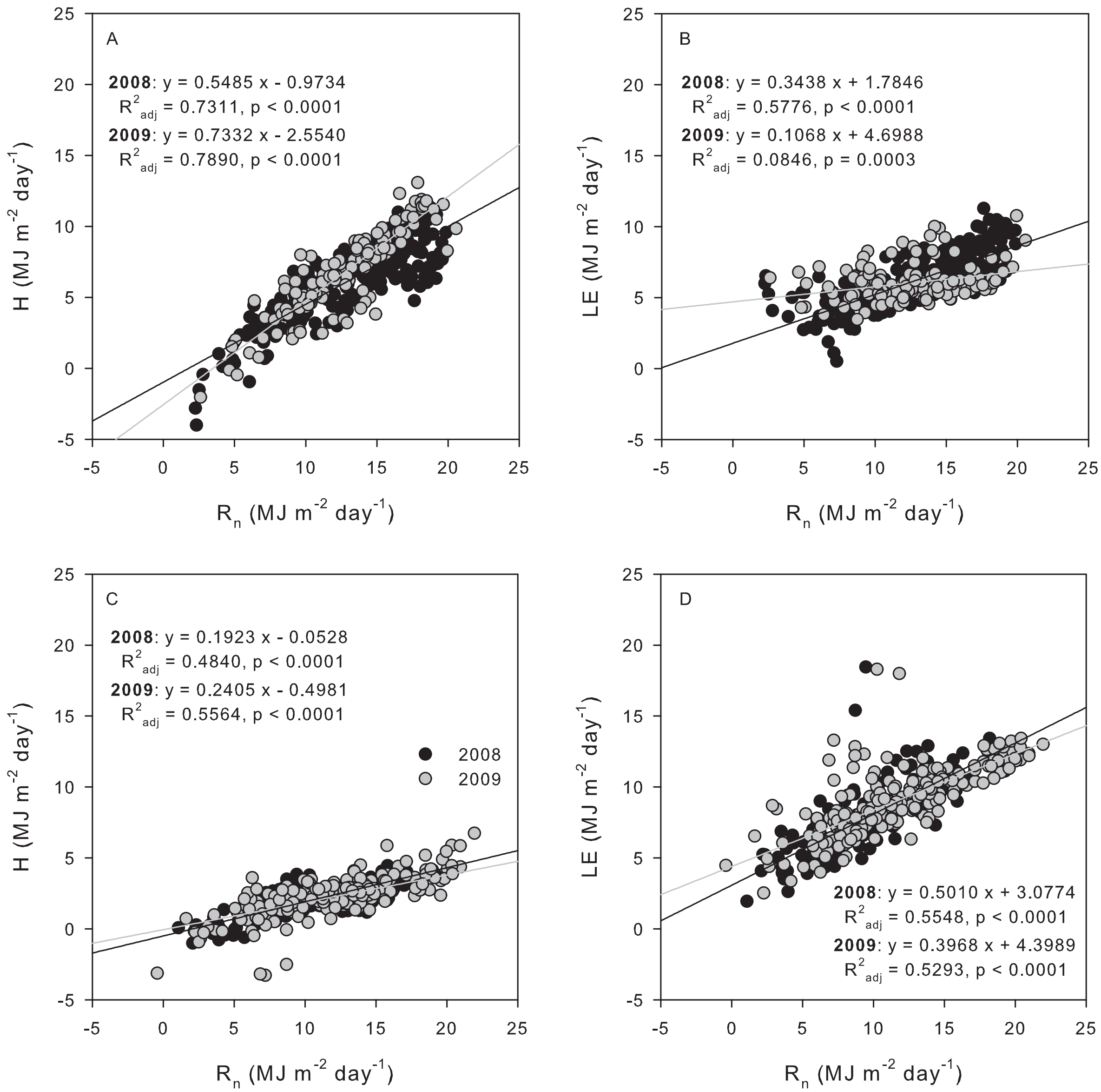

A
2008: y = 0.5485 x - 0.9734
R2adj = 0.7311, p < 0.0001
2009: y = 0.7332 x - 2.5540
R2adj = 0.7890, p < 0.0001
H (MJ m-2 day-1)
Rn (MJ m-2 day-1)
B
2008: y = 0.3438 x + 1.7846
R2adj = 0.5776, p < 0.0001
2009: y = 0.1068 x + 4.6988
R2adj = 0.0846, p = 0.0003
LE (MJ m-2 day-1)
Rn (MJ m-2 day-1)
C
2008: y = 0.1923 x - 0.0528
R2adj = 0.4840, p < 0.0001
2009: y = 0.2405 x - 0.4981
R2adj = 0.5564, p < 0.0001
2008
2009
H (MJ m-2 day-1)
Rn (MJ m-2 day-1)
D
2008: y = 0.5010 x + 3.0774
R2adj = 0.5548, p < 0.0001
2009: y = 0.3968 x + 4.3989
R2adj = 0.5293, p < 0.0001
LE (MJ m-2 day-1)
Rn (MJ m-2 day-1)

Fig. 6