**Spatial and temporal variability in spectral-based surface energy evapotranspiration measured from
Landsat 5TM across two mangrove ecotones**

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ABSTRACT

Coastal mangroves lose large amounts of water through evapotranspiration (ET) that can be equivalent to the amount of annual rainfall in certain years. Satellite remote sensing can play a crucial role in identifying regional ET trends and surface energy changes after disturbances in isolated and inaccessible areas of coastal mangrove wetlands, like those found in Everglades National Park in southern Florida. Using a combination of long-term datasets acquired from the NASA Landsat 5TM satellite database and the Florida Coastal Everglades Long-Term Ecological Research project, the present study investigates how ET as well as radiation and other energy balance parameters in the Everglades mangrove ecotone have responded to multiple hurricane events and restoration projects over the past two decades. An energy balance model using satellite data was used to estimate latent heat (λE) in tall and scrub mangrove environments. An eddy-covariance tower and weather tower supplied long-term data of multiple environmental and meteorological parameters that were used in calibrating and testing the modeled results from the Landsat images. Results identified significant differences in λE and soil heat flux measurements between the tall and scrub, and fringe and basin mangrove environments. The scrub mangrove site had the lowest λE rates, highest soil heat flux and lowest biophysical index (i.e., Fractional Vegetation Cover (*FVC*), Normalized Difference Vegetation Index (*NDVI*), and Soil-Adjusted Vegetation Index (*SAVI*) values. Mangrove damage and mortality associated with two strong hurricanes decreased *FVC*, *NDVI*, and *SAVI*, and increased soil heat flux at the tall mangrove site located in a basin-type environment. Recovery of the spectral characteristics, energy balance parameters and λE following hurricane disturbance was quicker in fringe mangroves than in basin mangroves. Latent heat fluxes (λE) were also relatively high after each storm and may have increased as a result of increasing vapor pressure deficits. Remote sensing of the surface energy balance and λE of mangrove forests can help our understanding of how these environments respond to disturbances to the landscape and the effect that these changes can have on the energy and water budget. Moreover, relationships between energy and

43 water balance components developed for the coastal mangroves of southern Florida could be
44 extrapolated to other mangrove systems in the Caribbean to measure changes caused by natural events
45 and human modifications.

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47 Keywords: Everglades, hydrology, disturbance, evapotranspiration, latent heat, soil heat flux, surface

48 energy balance

49

1. Introduction

Evapotranspiration (ET) is a large component of the water cycle in subtropical and tropical wetlands (Rockstrom et al., 1999) and can amount to 70-110% of the annual rainfall in these regions (Sumner, 1996). The strong coupling between rainfall and ET in these regions can be attributed to high levels of rainfall recycling from high rates of ET (Eltahir and Bras, 1994; Price et al., 2008). Many of the coastal subtropical and tropical wetlands are dominated by mangrove forests, which have some of the highest carbon storage among forest ecosystems, yet are disappearing at a rate of two percent per year. Changes in ET induced by natural processes such as climate change as well as anthropogenic alterations such as land-use change can lead to regional variability and significant changes to the water budget (Pielke et al., 2002).

Remote sensing has proved to be an effective tool for estimating ET rates and various other energy balance parameters across a variety of different ecosystems including: agricultural lands (Boegh et al., 2002), terrestrial forests (Chen et al., 2005), grasslands (Jiang and Islam, 2001) and wetlands (Chen et al., 2002; Jiang et al., 2009; Anderson et al., 2011). There have been few studies dedicated to modeling ET and surface energy balance in mangrove environments (Monji et al., 2002; Barr et al., 2013; Barr et al., 2014), despite a number of studies that have measured or calculated various biophysical parameters (i.e., leaf area index, water use efficiency, spectral indices) that are useful in estimating ET (see reviews by Green et al., 1998 and Kuenzer et al., 2011). Even fewer studies have investigated the role of satellite remote sensing in modeling surface energy balance and ET in mangroves (Jiang et al., 2009). In that study, Jiang et al (2009) used coarse resolution imagery to estimate ET across south Florida with little emphasis on vegetation community. There appears to be a gap in the literature in regard to detailed surface energy and ET mapping specifically in and among mangrove communities using higher resolution satellite remote sensing techniques. Measurements of ET over large areas are needed to support efforts

aimed at modeling climate variability at global scales, particularly in mangroves where carbon accumulation, ET, and water-use-efficiency are high (Ball et al., 1988; Barr et al., 2013).

Exhaustive research has investigated energy balance and ET in south Florida (German, 2000; Abtew, 2004; Douglas et al., 2009; Schedlbauer et al., 2011; Barr et al., 2013; Barr et al., 2014). Many of the referenced studies utilized expensive meteorological equipment in the form of eddy-covariance towers to measure changes to solar irradiance, temperature, wind velocity, and water vapor. Using the sophisticated equipment, surface energy balance models and ET models, the south Florida studies identified site-specific seasonal patterns with the greatest monthly average ET ($\sim 5\text{-}6\text{ mm day}^{-1}$) occurring during the early summer (May-July) and the lowest ET ($\sim 2\text{-}3\text{ mm day}^{-1}$) in early winter (German, 2000; Barr et al., 2013). Excluding the recent work by Barr et al. (2013 and 2014), the majority of the measurements originate from vegetated environments outside the mangrove zone. A regional-scale evaluation of the spatial variability of ET across a coastal mangrove community using satellite remote sensing will provide a better understanding of the variability in energy and water budgets associated with mangrove productivity and their response to damage and recovery from tropical storms.

The present study sought to investigate the spatial and temporal variability of ET along the Florida coastal Everglades mangrove ecotone region (EMER) using a multi-year dataset of optical satellite images. More specifically, the study estimates the variability in ET and energy balance components between tall, riverine mangrove and scrub mangrove forests over time and in response to strong tropical storm events. This study provides some of the first satellite-derived surface energy balance estimates in mangrove ecotones and expands upon earlier site-specific mangrove studies by introducing spatial and temporal variability in the mangrove forests.

2. Study area

The Florida Everglades once covered most of South Florida, extending from Lake Okeechobee south to Florida Bay and southwest to the Gulf of Mexico (Fig. 1). Most of the original Everglades has now been drained, channelized and converted to agricultural, urban, and water conservation areas to support the growing population and the subsequent water demand (Light and Dineen, 1994; Chimney and Goforth, 2001). Water flow into Everglades National Park (ENP) has been reduced to 15-25% of the original inflow, allowing seawater to propagate upstream in the surface water and intrude landward into the aquifer (Fennema et al., 1994; Price et al., 2006). More than two-thirds of the 1.2 m annual rainfall in south Florida occurs during the wet season between late May and November, with peak rainfall occurring in June and August (Duever et al., 1994; Childers et al., 2006). During the wet season, the Florida peninsula is prone to daily thunderstorms and tropical cyclones, whereas in the dry season infrequent frontal systems account for much of the precipitation (Obeysekera et al., 1999).

An extensive coastal mangrove environment covers a large portion of the southern Everglades (~1445 km²) (Simard et al., 2006; Rivera-Monroy et al., 2011) and recent models suggest a landward transgression of mangrove communities over the next century under various regimes of sea-level rise (Doyle et al., 2000). In fact, in some southeastern areas of the Everglades, mangroves have migrated 1.5 km landward over the past five decades (Ross et al., 2000). The landward transgression of mangroves has been attributed to reduced freshwater flow caused by the compartmentalization of the surface water upstream that is used to support the urban growth and development of South Florida. These anthropogenic modifications to the hydrology, compounded with climatic factors (e.g., sea-level rise, storm events) may ultimately alter the ecohydrology and water cycle dynamics of the mangrove ecotone (Rivera-Monroy et al., 2011).

Two main conduits deliver water from the Everglades into Florida Bay and the Gulf of Mexico, Taylor River and Shark River (Fig. 1). Taylor River, the smaller of the two rivers (247 km²), is located on the southeastern boundary of ENP and transports freshwater through a series of small, interconnected creek channels, and discharges into the northeastern parts of Florida Bay (Olmsted et al., 1980; Sutula et al., 2001) (Fig. 1). Tidal fluctuations in Taylor River are primarily controlled by wind, as the eastern portion of Florida Bay is restricted from tidal exchange with the Gulf of Mexico and the Atlantic Ocean (Wang et al., 1994). During the dry season and the associated diminished freshwater flows, salinities in Taylor River can increase to 50 psu (Brinceno et al., 2013). Shark River is the largest river (991 km²) and delivers water from the northern ENP boundary to the Gulf of Mexico after moving through relatively large and wide tidal channels along the southwestern Florida coast. Shark River experiences diurnal tidal fluctuations (~1 m) with progressively less tidal influence upstream of the Gulf of Mexico (Wdowinski et al., 2013). The largest tidal fluctuations occur during the wet season when water levels are high because of increased freshwater flows (Provost, 1973; Twilley and Chen 1998; Krauss et al. 2006).

Mangrove forests line the coastal areas and tidal channels of both Taylor and Shark Rivers. Taylor River is predominately inhabited by the scrub, or stunted *Rhizophora mangle* (red mangrove) that stand 1-2 m tall and have relatively low above ground biomass accumulation rates when compared to the much taller mangroves in Shark River (Coronado-Molina et al., 2004; Ewe et al., 2006). Along Shark River, the mangroves are a mix of three separate species; *Avicennia germinans* (black mangrove), *Laguncularia racemosa* (white mangrove), and *R. mangle* (red mangrove) that also occur along many coastlines of the Caribbean and South America. Near the mouth of Shark River, all three mangrove species occur together and the forests contain some of the largest and tallest mangroves in the region (Chen and Twilley, 1999; Simard et al., 2006). Upstream along Shark River, the mangroves become progressively smaller and shorter and the community structure changes to predominately red mangroves and *Conocarpus erectus*

(buttonwood) (Lugo and Snedaker, 1974; Chen and Twilley, 1999). Red mangroves comprise 20-100% of coastal mangrove forests in the Everglades and plant biomass decreases from ~162 Mg ha⁻¹ along the coast to 100 Mg ha⁻¹ at the inland extent of the EMER (Castañeda-Moya et al., 2013).

3. Methods

Four sites that corresponded to long standing research sites in the Florida Coastal Everglades: Long-Term Ecological Research (FCE LTER) program were monitored. Three mangrove sites were selected in Shark River; SRS4 (upstream), SRS6 (downstream), and SRS-coast (coastal) (Fig. 1). The upstream site, SRS4, is located 18.2 km from the mouth of Shark River, while SRS6 is located about 4.1 km from the mouth (Fig. 1). These two sites, SRS4 and SRS6, represent the lowest and highest salinities, respectively, along the Shark River transect. The third SRS site, SRS-coast, is located 1 km inland from the coast and located within a basin mangrove community, as characterized by Lugo and Snedaker (1974). Only one site, TS6, was monitored in Taylor River which represented the “typical” scrub mangrove environment located in the Taylor River estuary (Fig. 1). Weather towers located near TS6 and SRS6 were used for calibration and verification of the modeled surface energy parameters.

3.1 Landsat 5 TM images

Landsat 5 Thematic Mapper (Landsat) data were obtained from the US Geological Survey-Earth Explorer database and from the Florida International University (FIU) Geographic Information Systems database. Landsat data consist of seven bands in the visible [Band1 (blue: 450-520nm), Band2 (green: 520-600), Band3 (red: 630-690)], near-infrared (NIR) [Band4 (760-900nm)], mid-infrared [Band5 (1550-1750nm), and Band7 (2080-2350nm)] and thermal infrared wavelengths [Band6 (10400-12500nm)]. The spatial resolution of each band is 30 x 30m, with the exception of the thermal band, Band6, which has a resolution of 60 x 60m.

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170 Sixteen satellite images (path: 15; row: 42) were used in the study and covered a 16-year period from
171 1993-2009. The primary selection criteria for the images were based on minimal cloud cover and the
172 availability from the FIU databases. Satellite images were confined to the dry season (November-May)
173 because of a lack of cloud-free images during the wet season (May-November) when convective clouds
174 begin to form. The distribution of images throughout the dry season provided a detailed inter-seasonal
175 variability and span reported minimum (November-December) and maximum (May-June) surface energy
176 balance fluxes (Barr et al., 2014). Under those circumstances, only cloud-free images from the dry
177 season were used in this study and were not necessarily from the same year or spaced at regular
178 intervals.

179
180 Each of the satellite images was corrected for atmospheric effects using the ATCOR2 model (ReSe
181 Applications Schläpfer, Wil, Switzerland) in ERDAS Imagine (Hexagon Geospatial, Madison, AL).
182 Atmospheric corrections were determined using solar geometry, a visibility of 35 km and solar and
183 thermal regional models of rural and tropical conditions, respectively. After the satellite images were
184 corrected, spectral reflectance data from each band were extracted from a 2 x 2 pixel square (3600 m²)
185 from each of the Shark River sites, SRS4, SRS6, and SRS-coast and the Taylor River site, TS6. The spectral
186 response exhibited by each of the sites was an indicator of the stability, biophysical status, and density
187 of the respective mangrove forest. The wavelength reflectance intensity from each Landsat band and
188 the combinations of ratios of NIR to visible wavelengths were used in the satellite-based surface energy
189 balance model. The extracted data from each site were averaged from each Landsat band and used to
190 estimate the vegetation indices: normalized difference vegetation index (NDVI), soil-adjusted
191 vegetation index (SAVI) and fractional vegetation cover (FVC), as well as energy balance components.
192 The standard deviation (S.D) of the 2 x 2 pixel square was less than one reflectance percentage point.

3.2 Satellite-based Energy budget and ET model

Several energy balance parameters and ET rates were determined using Landsat images. Instantaneous fluxes were modeled for midday (10:00-16:00) values. Latent heat of vaporization (λE) estimates were calculated as the residual in the surface energy balance equation (Soegaard, 1989; Kustas et al., 1994; Boegh et al., 2002):

$$\lambda E = R_n - H - G \quad (\text{Eq. 1})$$

where R_n is net radiation, H is sensible heat flux, and G is soil heat flux. The R_n component was estimated from the equation:

$$R_n = R_s (1-\alpha) + R_L (1-\epsilon_s) - \epsilon_s \sigma T_b^4 \quad (\text{Eq. 2})$$

where R_s is the incoming shortwave radiation, R_L is the incoming long wave radiation, α is the surface albedo, ϵ_s is surface emissivity (constant at $\epsilon_s = 0.98$), σ is the Stefan Boltzman's constant ($\sigma = 5.6703 \times 10^{-8} \text{ J m}^{-2} \text{ s}^{-1} \text{ K}^{-4}$) and T_b is surface temperature. Both R_s and R_L were measured directly from the eddy-covariance tower located at SRS6. Surface albedo, α , was estimated using a combination of Landsat bands, TM4 and TM7 as outlined in Brest (1987) and T_b was determined from the thermal band, TM6, of Landsat via the ATCOR2 model (Richter and Schlapfer, 2011).

The soil heat flux, G , was estimated by remote sensing techniques described by Clothier et al, (1986) and Kustas and Daughtry (1990). A soil-adjusted vegetation index (SAVI) was calculated using the following equation (Huete, 1988):

$$SAVI = (TM4 - TM3) / (TM4 + TM3 + 0.5) \quad (\text{Eq. 3})$$

The SAVI value was then used to determine the fractional vegetation cover, FVC (Ormsby et al., 1987; Purevdorj et al., 1998) using the linear equation:

$$FVC = 1.62 \times SAVI - 0.37 \quad (\text{Eq. 4})$$

A linear relationship between G and R_n has been noted for bare soils, but the (G/R_n) for vegetation can be different because of interactions with the canopy (Choudhury et al., 1987). Therefore, the FVC was used as a scaling factor in the equation

$$G/R_n = FVC (G/R_n)_{veg} + (1-FVC)(G/R_n)_{soil} \quad (\text{Eq. 5})$$

where $(G/R_n)_{veg}$ and $(G/R_n)_{soil}$ represent vegetation and soil end-member values and equal 0.1 and 0.5, respectively (Boegh et al., 2002). Daily ET rates (mm day^{-1}) were calculated using the equation:

$$ET = \lambda E / \lambda \quad (\text{Eq. 6})$$

where λ equals the latent heat of vaporization of water (2404 kJ kg^{-1} for water with salinity of 20 at 20°C ; Sharqawy et al., 2010). Sensible heat flux (H) was determined from the satellite-modeled R_n values using the equation:

$$H = R_n - G / (1 + 1/\beta) \quad (\text{Eq. 7})$$

where β is the ratio between H and λE , known as Bowen's ratio. A static value of $\beta = 0.603$ was used to calculate H at each site. The value of 0.603 was the 5-year average β (2006-2011) that was calculated from midday values of H and λE measured directly at SRS6. The numerator of Equation 7 was also treated as a constant where $R_n - G = R_n * 0.9$, with the assumption that G is approximately 10% of R_n .

The satellite energy balance model was designed using the model maker tool in ERDAS IMAGINE. Non-mangrove areas (e.g., sawgrass, hardwoods, and water) were masked from each of the satellite images using the 1999 Vegetation Map of the Everglades generated by the University of Georgia (Welch et al, 1999) and available at the FCE LTER website (<http://fcelter.fiu.edu>). Once the mask was overlaid on each image, Equations 1-7 were applied to each atmospherically-corrected mangrove pixel which generated model estimates of FVC , and instantaneous R_n , H , G and λE across Shark and Taylor Rivers.

3.3 Meteorological Data

A suite of atmospheric and meteorological measurements was collected continuously from 2006-2011 from an eddy-covariance tower installed within the tall mangroves at SRS6 from which all data was made available from the FCE LTER website (<http://fcelter.fiu.edu>). Explicit details of the instrument and tower deployment, specifications and corrections are outlined in Barr et al (2010) and Barr et al (2012). Incoming and outgoing radiation were measured above the canopy at half hour intervals using a Kipp and Zonen CNR1 net radiometer (Bohemia, NY) at both the Shark River (height of 27 m) and Taylor River (height of 4 meters) sites every half hour. Measurements of incoming solar radiation (i.e., R_s and R_l) at the SRS6 tower were used in Equation 2 to calculate R_n at each of the Shark River study sites, SRS4, SRS6 and SRS-coast, and at the Taylor River site, TS6. Air temperature, G , H , and λE measured at the eddy-covariance tower at SRS6 were used to test and compare the results from the satellite-derived energy balance parameters. Latent heat (λE) and H were calculated using high-frequency measurements from a three-dimensional sonic anemometer (RS-50, Gill Co., Lymington, England) and an open path infrared water vapor gas analyzer (LI-7500, LI-COR, Inc., Lincoln, Nebraska). Soil heat flux (G) was determined using heat flux plates (model HFT 31.1 Heat Flux Plates, Campbell Scientific Inc. Logan, Utah) at a depth of 0.1 m below the soil surface.

Meteorological data, such as R_n and air temperature, were also collected at a weather tower south of TS6 (Fig. 1). Environmental data, tower and instrument specifications, and deployment methods for the Taylor River weather tower are described in (Zapata-Rios and Price, 2012). When plotted together, corresponding daily and midday (10:00-16:00) daily average R_n , and 3-year midday averages (2008-2010) R_n on the DOY of each Landsat image depict slightly higher R_n at Shark River relative to Taylor River (Fig. 2). Given these similar R_n conditions between sites, and the limited ground-truthing available in the Everglades, data measured at the Taylor River tower were used to validate the satellite-modeled results of R_n from Equation 2 at TS6. Average daily values for each year were derived by averaging midday

(10:00-15:00h) measurements of each parameter for each day available of the 2006-2011 record. The daily data were then converted to a day-of-year (DOY) value to generate a 5-year daily average record. The latter dataset was then filtered through a 13-point moving average.

3.4 Data Analysis

An analysis of variance (ANOVA) was conducted to identify the spatial variability of the mangrove spectral response between each of the mangrove sites. Landsat reflectance values were organized according to site to identify relationships and differences between the various mangrove environments (i.e., fringe and basin) and mangrove types (i.e., tall and scrub). In order to test for any significant changes over time, several t-tests were employed for each individual site comparing the means between the 1990s (n=8) and 2000s (n=8).

The accuracy of the energy balance models was determined by a number of error statistics; root-mean-square-error (RMSE), normalized-root-mean-square (NRMSE), Nash-Sutcliffe, mean-absolute-percent error (MAPE), percent forecast error (PFE) and bias analyses. The RMSE was used to determine the deviation between the measured and model results, but the NRMSE was used to normalize the RMSE to the range of energy balance parameters. The Nash-Sutcliffe index is widely used in hydrologic studies to calculate model efficiency but can be sensitive to sample size, outliers, and bias (McCuen et al., 2006). Therefore a bias analysis was also recorded with the Nash-Sutcliffe index. Lastly, MAPE and PFE analyses were also conducted. The MAPE provided a percent model error but could be skewed by higher percent errors when modeled values were larger than the actual values (Makridakis and Hibon, 1995). The PFE has been shown to be a good model for accuracy which can estimate the next time period with a 95% confidence level (Klimberg et al., 2010). Highly accurate models tend to have PFE values less than 20 (Lawrence et al., 2008).

4. Results

4.1 Spectral response

Wavelengths in the near and mid infrared measured by Landsat (Band4 and Band 5) exhibited the greatest variability when compared to bands in the visual spectrum (Band1, Band2, and Band3). At the Shark River sites, reflectance values in Band4 ranged from a low of 17% at SRS-coast to a high of 44% at SRS4 (Fig. 3). The TS6 site had less variability and magnitude in Band4 and only ranged between 9% and 20% (Fig. 3). Reflectance data from the visible bands (Band1, Band2, and Band3) exhibited much less variability over the 16-year period of the Landsat acquisitions with the most variable visible reflectance at TS6 and SRS-coast. The reflectance in Band7 reached a maximum of 24-25% in May 1993 and May 2006 satellite acquisitions at SRS-coast; however, similar but smaller maxima occurred during the same periods at the other sites (Fig. 3). The thermal band, Band6, generally ranged between 10 and 33°C for each of the sites. Additionally, the highest temperature readings from Band 6 tended to occur during acquisitions that had the lowest Band4 reflectance (Fig. 3).

At the riverine mangrove sites in Shark River, SRS4 and SRS6, the overall average (n=16) spectral index values (i.e., *FVC*, *NDVI*, and *SAVI*) were nearly the same, with averages ranging between 0.81 to 0.91 for all indices (Table 1; Fig. 4). The indices remained fairly consistent over the course of the 16-year Landsat dataset when compared to values at SRS-coast and TS6 (Fig. 4). There were sharp decreases in *FVC*, *NDVI* and *SAVI* (over one S.D) in March 1993 and May 2006 for all three Shark River sites and in particular, at the SRS-coast site (Fig. 4). The spectral ratios at the SRS-coast site were about one-fifth of those from SRS4 and SRS6 in March 1993 and slowly increased back to average values after 1996. In the May 2006 Landsat image, there was a relatively uniform drop in spectral index values across all three SRS sites (Fig. 4). The scrub mangrove site at TS6 exhibited a different pattern from the mangroves in

Shark River. Values across each of the spectral indices (e.g., NDVI, SAVI, and FVC) steadily increased over time from 1993 to 2009 (Fig. 4A).

4.2 Energy Balance

The satellite-modeled R_n values were similar (within one S.D.) across most sites, except SRS4, with decadal averages ranging between 487-524 W m⁻². The northern most site, SRS4, tended to have relatively lower R_n values (425 W m²) and greater than one S.D. away from the other sites (Table 1). Sensible heat flux, H , measurements were within one S.D. of λE fluxes at SRS4 and SRS6. In contrast, λE was significantly larger than H at SRS6 and significantly lower than H at TS6 (Table 1). The Taylor River site, TS6 experienced the highest average G values (227 W m²) throughout the 16-year time period and the lowest average G was measured at SRS4 and SRS6 (129-140 W m², respectively) (Table 1). Sensible heat fluxes (H) closely mirrored R_n , accounting for slightly over 30% of the total R_n at each site. The FVC values that were used to calculate G were significantly lower ($p<0.05$) at the TS6 site when compared to the tall, Shark River mangrove sites (Table 1). Moreover, the two riverine sites, SRS4 and SRS6, exhibited significantly higher FVC values than the basin mangroves, SRS-coast and TS6.

During the 2000s, average G values were one S.D. lower than those from the 1990s at all mangrove sites, with the exception at SRS6 where the values remained constant (Fig. 5). The two largest drops in G were found at TS6 and SRS-coast. The scrub mangrove site, TS6, decreased from an average of 256 W m⁻² in the 1990s to 199 W m⁻² in the 2000s. The Shark River site, SRS-coast, also experienced a similar drop in G starting at 191 W m⁻² in the 1990s and decreasing to 151 W m⁻² and SRS4 dropped from 147 W m⁻² to 111 W m⁻² (Fig. 5). There was a decrease in average G values observed across three of the four mangrove sites from the 1990s to the 2000s, but only the reduction in G at SRS4 was significant at the

5% level ($p=0.05$) according to t-tests (Fig. 5). The other two sites, TS6 and SRS-coast, had p-values (t-tests) of 0.08 and 0.10, respectively. Sensible heat fluxes (H) remained relatively consistent over time with modeled averages ranging between 173 and 177 W m⁻² (Table 1).

Net radiation (R_n) modeled for Shark River and Taylor River sites using Equation 2 and R_s and R_L data from the SRS6 tower provided R_n values that compared well with the actual field-measured R_n recorded at weather towers at SRS6 and TS6 (Fig. 6). Sensible heat flux (H) was calculated as a function of R_n (Eq. 7) and therefore, H values are correlated with modeled R_n . There was also a greater deviation between measured and modeled H values when compared to R_n and λE (Fig. 6). Satellite-derived G measurements were overestimated and were nearly an order of magnitude higher for every Landsat acquisition date than the average, field-measured values at SRS6 (Fig. 6).

The modeled average values for R_n , H and λE were in agreement with the field averages despite the variability between particular dates (Fig. 6). The accuracy of the satellite-derived energy balance model was tested using the measured parameters at the eddy-covariance tower at SRS6. The modeled data had a RMSE of ranging between 11.8 W m⁻² for G and 53.0 W m⁻² for R_n at SRS6 (Table 2). The Nash-Sutcliffe index was highest (0.71-0.88) for modeled R_n and λE values and lowest for G (-12.6), while the MAPE was lowest for R_n and λE and highest for G but occurred with an overestimate bias of -113 (Table 2). The PFE indicated that most of the models were highly accurate with PFE values below 20% for all the models except for G .

4.3 Latent heating variability

Latent heat flux (λE) modeled from Landsat images ranged between 120 and 350 W m⁻² at the Shark River sites and between 50 and 160 W m⁻² at the Taylor River site (Fig. 7). The averaged λE were highest

at SRS6 (218 W m^{-2}) and lowest at TS6 (104 W m^{-2}) (Table 1). Over the 16-year period of satellite acquisitions, λE remained relatively consistent through the 1990s and became more variable in the 2000s (Fig. 6). In contrast, λE at SRS6 exhibited a different decadal variability with the highest flux occurring from 1992-1995 and the again in 2006 and 2008 (Fig. 7). Modeled λE at the Taylor River site was always lower than λE at any of the Shark River sites (e.g., SRS4, SRS6, and SRS-coast). When the Landsat data were separated into decades (i.e., 1990s and 2000s) there was little change in the averaged model λE between SRS4 and SRS6 over time. In contrast, there was an increase in average λE at SRS-coast and TS6; increasing from 110 to 160 W m^{-2} at SRS-coast and from 65 to 150 W m^{-2} at TS6.

5. Discussion

5.1 Surface energy balance variability: tall versus scrub mangroves

Net radiation (R_n), G , H and λE varied between each of the mangrove sites. Particular patterns were evident when comparing the tall and scrub mangroves. Net radiation (R_n) was strongly correlated with λE at the Shark River sites SRS4 and SRS6 ($R^2 > 0.76$), but had a lesser effect on λE at the Taylor River and SRS-coast sites ($R^2 < 0.37$) (Fig. 8A). The strong relationship between R_n and λE at the Shark River sites was most likely related to the spatial vegetation patterning between the Shark and Taylor River mangrove environments. The Shark River sites, SRS4 and SRS6, were predominately and homogenously covered by mangroves at the Landsat pixel scale (30 x 30 m grid), which was suggested by the high (> 0.8) spectral index values and the small range (0.75-1.1) of FVC values (Fig. 8B). At the Taylor River site, FVC values were much lower (< 0.6) and much more variable exhibiting a wider range (-0.3-0.6) of FVC values suggesting that each Landsat pixel was a combination of both vegetation and open water because of the smaller mangrove basal area ($2.3\text{-}6.3 \text{ m}^2 \text{ ha}^{-1}$; Coronado-Molina et al., 2004) relative to the larger basal area at SRS4 and SRS6 ($\sim 10 \text{ m}^2 \text{ ha}^{-1}$ and $40 \text{ m}^2 \text{ ha}^{-1}$ respectively; Chen and Twilley, 1999). The poor relationships between R_n and λE at SRS-coast and TS6 may be caused by the prolonged inundation that

could facilitate energy removal from the system via water flow. Mixed pixels may also occur at SRS-coast directly after strong storm events, which were suggested by the lower *FVC* as a result of the mixing of background reflectance from soils or reflectance from damaged, defoliated mangroves (Fig. 8B). Anthony et al (2000) reported similar findings and indicated that upwelling longwave radiation is higher within sparse canopies than closed canopies and therefore, R_n , and the subsequent available energy tends to be lower in sparse canopy cover.

The satellite-derived energy balance model estimates were in agreement with the measured values in Taylor and Shark River, except for *G* values (Table 2). Net radiation (R_n), *H*, and λE estimates each had MAPE of 10 or lower, and PFE values all under 20 suggesting the satellite model was a good predictor of the average observed conditions. Soil heat fluxes (*G*) were always overestimated by an order of magnitude, which was one of the major limitations of the satellite-derived model. Nonetheless, despite the errors in *G* values the estimations of λE were still highly accurate. The over estimation of *G* in combination with accurate residual λE calculations suggests that energy was also dissipated by other factors, most likely from water and tidal actions, as well as changes in water vapor pressure deficits (Barr et al., 2014).

The Bowen's ratio value of 0.603 used in the satellite-based surface energy balance equations implies that sensible heat should always be below the fluxes from λE . However, this was not the case at all the sites. Meanwhile, average λE was always greater than *H* at the two riverine mangrove sites, SRS4 and SRS6. Sensible heat flux (*H*) values were lower (>1 S.D) in the 2000s when compared to the 1990s at SRS-coast and TS6. The lower *H* values at SRS-coast and TS6 coincided with a similar decrease in *G* over the same time period (Fig. 5). The different relationships between *H* and λE at the riverine-type and basin-type mangroves suggest that there is less energy available for λE in the basin-type mangroves because

more energy may be transferred to soil and water. Yet λE modeled at SRS-coast resembles λE rates at SRS4 and SRS6. Bowen's ratio values around SRS6 can range between ~ 0.3 in the wet season and ~ 1.0 in the dry season (Barr et al., 2012). The eddy-covariance tower measures surface energy balance parameters without energy balance closure, whereas, the satellite-based models assumes an energy closure to estimate λE .

Modeled H values were greater than one S.D higher than λE values at TS6 and greater than one S.D. lower than λE at SRS6 (Table 1). The magnitude of H values ($100\text{--}250\text{ W m}^{-2}$; Fig 6) across all the study sites tend to be higher than typical H values found in subtropical and tropical forests ($10\text{--}30\text{ W m}^{-2}$; da Rocha et al., 2004) and subtropical wetlands ($20\text{--}70\text{ W m}^{-2}$; Schedlbauer et al., 2011). The higher H values reported in the current study are an average of midday values, while the other studies reported daily values (da Rocha et al., 2004; Schedlbauer et al., 2011). The discrepancy between the modeled H fluxes in the present study could arise from the calculation used to determine H at each site. Bowen's ratio and the numerator in Equation 7 were kept constant throughout each of the Landsat images and could cause over or underestimates of H , depending on the time of year. Despite the static values used in the calculations, there was still relatively good agreement between measured and modeled H values (Table 2; Fig. 6).

The spatial differences between the Shark and Taylor River study areas were manifested in the FVC , EVI , and $NDVI$ spectral indices calculated from Landsat images (Fig. 4). Satyanarayana et al (2011) measured similar responses in $NDVI$, using multispectral data from the Quickbird satellite, from varying mangrove communities; larger, healthier sites generally had higher $NDVI$ values and environmentally stressed sites typically had lower $NDVI$ values. The highest variability in FVC was exhibited at SRS-coast and could be a function of storm related damage and the location of the mangroves in a basin-type environment (Table

1). In combination with the lower *FVC* values, TS6 also exhibited higher *G* values than the Shark River mangrove sites (Fig. 5). Soil heat flux (*G*) has been shown to be sensitive to changes in vegetation cover because as vegetation covers and shades more ground, it dampens the incoming solar energy, and effectively attenuates the temperature transfer to the soil and, thereby, reduces *G* (Yang et al., 1999). Therefore, the higher *G* estimated at the Taylor River site during the entire 16-year study period suggest that there was more energy transferred to the soils and most likely, the water than at the taller and heavily vegetated sites of Shark River. The limited tidal flushing, continual inundation, and the low *FVC* in the Taylor River scrub mangrove forests play a major role in surface energy processes, and perhaps, in conjunction with the higher water use efficiency, limit ET.

Latent heat (λE) calculated for the current study derived from spectral data collected from Landsat with minimal inputs from field data (i.e., R_s and R_L) measured at SRS6 agreed well with the field measured R_n values at SRS6. In addition, R_n values calculated at TS6 (using R_s and R_L inputs from the weather tower near TS6) also coincided with field-measured R_n (Fig. 6A). Modeled λE values generally exhibited more spatial variability on the southwestern coast near Shark River than on the southern coast near Taylor River (Fig. 9 & 10). The southwest coast is primarily composed of homogenous stands of mangroves over 8 m tall with large basal areas, whereas the mangroves in around Taylor River are predominantly less than 4 meters and spatially discontinuous (Simard et al., 2006). The relatively homogenous modeled λE in the scrub mangroves around Taylor River was most likely related to the structure and low stature of the mangroves and the relatively stable shallow groundwater geochemical conditions as compared to the more variable conditions along Shark River (Zapata-Rios, 2009; Lagomasino 2014) (Fig. 10). In addition, Lagomasino (2014)) reported that the spectral signature of the scrub mangrove leaves remain consistent throughout the year, and suggested that the stable, shallow groundwater chemistry may lead to persistent biophysical stress. Similarly, Hao et al, (2009) suggested the lowered photosynthetic

activity in mangroves was caused by higher interstitial soil salinity and lack of tidal flushing while higher carbon-13 isotope values (Lin and Sternberg, 1992) and the increase in water use efficiency (Lovelock and Feller, 2003) in scrub mangroves also support the notion that scrub mangroves are almost continuously under stressed conditions.

5.2 Forest latent heat comparisons

The present study has provided some of the first satellite-based surface energy balance models for mangrove forests. As the results indicate, λE values can vary significantly (104-218 W m⁻²; Table 1) in mangrove forests based upon canopy cover and mangrove height. Complications in estimating λE in mangrove forests arise from added physical forcings such as inundation, tidal flushing and storm activity. Nevertheless, the results from the present study provide λE estimates that are comparable among other forested ecosystems (Table 3). The λE estimated in the present study were made as instantaneous calculations with respect to midday values (10:00-16:00), and therefore, reflect near-maximum rates. In addition, the satellite images were acquired on cloud free days, which in turn, represented ideal energy conditions. Estimated λE were within the range of instantaneous midday λE measured from eddy-covariance data (Barr et al., 2014) and satellite data (Zahira et al., 2009) in mangrove forests in the Everglades and India, respectively (Table 3). Field measurements from mangrove forests in Thailand were slightly higher (200-425 W m⁻²; Monji et al., 2002). When compared to other forest types, mangroves are on par with satellite-based λE estimates from coniferous forests (100-180 W m⁻²; Venalainen et al., 1999) and within the wide range of temperature deciduous forests (40-400 W m⁻²; Baldocchi and Wilson, 2001) (Table 3). Lastly, mangrove forests in Florida fall just short of Mediterranean evergreens (223-393 W m⁻²; Zahira et al., 2009) and tropical rain forests (260-310 W m⁻²; Malhi et al., 2002).

5.3 Change over time

Hydrogeomorphic and biophysical features along with restoration efforts between Shark River and Taylor River area may provide insight into the long-term changes to the energy balance parameters and ET in the Everglades mangrove region. The scrub mangrove site, TS6, had an increase in averaged, satellite-based λE from the 1990s to the 2000s. The increase in λE at TS6 was in conjunction with an increase in FVC and a decrease in G (Fig. 4A & 7A). The cause of these trends over the recent decades may be linked to the growth and expansion of the scrub mangrove patches in the Taylor River area, as previously reported in the mid-1990s by Ross et al (2000) and more recently, Rivera-Monroy (personal communication 2013).

The increase in FVC observed at TS6 between the 1990s and the 2000s suggests more vegetation shading of the water and soil, and more homogenization of the Landsat pixels, and in turn less energy was transferred to water and soils in the recent decade. Variability in λE over time is closely associated with sharp decreases to FVC and G in satellite images collected after strong tropical storm events (Fig. 7). Increased λE after tropical storms were above 250 W m^{-2} at SRS6 and above 150 W m^{-2} at SRS5. The storms, however, did not play a clear role at the SRS-coast and TS6 sites. This observation was most likely a result of different environmental impacts to these specific regions. At SRS-coast there was more tree mortality/defoliation relative to SRS4 and SRS6 as suggested by low FVC values (<0.5) and documented by surveys (Smith et al., 1994). Meanwhile, the change in λE at TS6 was incremental and increased with increasing FVC (Fig. 7).

5.4 Physical forcings on energy balance

South Florida is prone to tropical cyclone activity and has had a number of tropical storms and hurricanes pass over or near the study area during the 16-year time span of the Landsat data. Three

hurricanes during that time period of are particular interest because they were significant storms and coincide closely with Landsat image acquisitions: hurricanes Andrew (1992), Katrina (2005) and Wilma (2005). Weaker tropical storms including Harvey (1999), Irene (1999), Ernesto (2006) and Fay (2008) also affected the study area.

Mangroves are well adapted and resilient against storm conditions to some degree. After strong storms, larger mangroves with a diameter-breast-height (DBH) greater than 5 cm have a significantly higher chance of mortality than smaller mangroves (Smith et al., 1994; Risi et al., 1995). Additionally, Smith et al., (1994) documented a nearly 50% increase in mangrove mortality rates months and years after the passing of Hurricane Andrew (category 4) through South Florida in August 1992. The observation of initial tree mortality directly after the storm followed by a continued increase in post-storm mangrove mortality, associated with storm surge damage and salinization, may be the cause of the higher mid-NIR response (Fig. 3) and lower vegetation index response (Fig. 4) noted in this study at SRS-coast. Fractional vegetation cover (*FVC*), *NDVI*, and *SAVI* values were at their lowest values at SRS-coast in the 3 years following Hurricane Andrew. Likewise, the spectral indices were also lowest at the TS6 directly after Hurricane Andrew. Below average *FVC*, *NDVI* and *SAVI* values also occur across all three Shark River sites in the May 2006 Landsat image, which was acquired a few months after the passage of hurricanes Katrina and Wilma in 2005.

Previous studies have indicated that the structure of mangroves stands can influence the disturbance effects caused by storms (Ward et al., 2006). Surveys conducted after hurricane Andrew and hurricane Wilma identified higher mangrove mortality rates in basin-type mangroves after Hurricane Wilma, but relatively more damage was caused to island and fringe-type mangroves after the passage of Hurricane Andrew (Smith et al., 2009). The local minimums in *FVC*, *NDVI*, and *SAVI* measured from the Landsat

images March 1993 and May 2006 suggest significant damage to the mangroves at each of the Shark River sites following hurricanes Andrew and Wilma with the greatest detriment occurring at SRS-coast, as indicated by the much lower index values (Fig. 4C). Barr et al (2012) presented a similar spectral index (i.e., EVI) response after Hurricane Wilma using MODIS. The relatively quick recovery (~1 year) suggested by the Landsat data was also mirrored in the MODIS EVI data where EVI values return to pre-Wilma conditions approximately one year after the storm (Barr et al., 2012). The drop in spectral vegetation indices, *FVC*, *NDVI* and *SAVI*, recorded in acquisitions following hurricanes Andrew (1992) and Wilma (2005) was most likely caused by a combination of defoliation and tree mortality from strong winds during the hurricane and the subsequent storm surge.

Despite the surveys conducted after Hurricane Andrew identifying most of the damage areas in fringe and island mangroves (Smith et al., 2009), there was very little change in spectral values at SRS4 and SRS6, both fringe mangrove sites, as opposed to the damage done in the basin mangroves at SRS-coast (Fig. 4). The eye wall of Hurricane Andrew passed just north of the SRS4 and SRS6. Storm surge (1-4 m) related to the southern eyewall flooded the mangrove wetlands up to 10 km inland and deposited up to 20-50 cm of carbonate-rich muds (Risi et al., 1995; Swiadek, 1997). The resulting surge and reduced tidal flushing in the basin mangroves around SRS-coast may be the cause of the increased mangrove mortality at SRS-coast relative to SRS4 and SRS6 and the reason there was a more significant drop in *FVC* and other spectral indices at SRS-coast.

In addition to the spectral response, the modeled *G* values from SRS-coast and TS6 exhibited a decrease from the 1990s to the 2000s (Fig. 5). Occurring in tandem with the lower average *G* values in the 2000s, average λE increased over the same time period. The decrease in *G* at SRS-coast and TS6 can be attributed to an increase in vegetation growth and mangrove recovery following Hurricane Andrew.

Reflectance values in TM1 and TM3 also decrease from 1993 to 2009 at the TS6 site suggesting increased absorption from photosynthetic pigments caused by new leaf growth in the scrub mangroves at Taylor River (Fig. 3A). Recently, researchers have measured an increase in above ground net primary production of mangroves from $\sim 1800 \text{ g C m}^{-2} \text{ yr}^{-1}$ in 2001 to $\sim 5800 \text{ g C m}^{-2} \text{ yr}^{-1}$ in 2004 at a site near TS6 (Ewe et al., 2006) as well as an increase in scrub red mangrove patch sizes from 2003 to recent (Rivera-Monroy, personal communication, 2013). The combination of a steady increase in *FVC* and steady decrease in *G* at TS6 can be directly linked to increased scrub mangrove production as individual mangrove patches have grown larger. River discharge has not shown any significant increase since the inception of the Taylor River Slough restoration despite recent studies indicating a strong link between water flushing times and freshwater input (e.g., local management practices) (Sandoval 2013). Therefore, the increase in λE and *FVC* at TS6 may be related to short-term changes in sea-level that have been more conducive to the growth and expansion of mangroves (e.g., nutrient inputs).

Sharp increases in satellite-based λE were identified after storm events (1993 & 2005) at the SRS6 site (Fig. 7). Latent heat flux (λE) estimated at SRS4, SRS-coast, and SRS6 sites were relatively equal throughout the study period, except for time periods directly after strong storm events when satellite-based λE at SRS6 were nearly double the rates at SRS4 and SRS-coast. A possible explanation for the higher λE at SRS6 directly following hurricanes, even though our results show no direct evidence of this, could be from increased nutrients that were brought onshore by the storm surge associated with the passage of hurricanes Andrew and Wilma. Phosphorus-limited mangrove environments, like in the Shark River and Taylor River portions of the Everglades, have been shown to have low leaf water potential, low stomatal conductance, photosynthetic carbon-assimilation rates, and less conductive xylem (Lovelock et al., 2006). The water stress factors noted by Lovelock et al (2006) were mitigated when more P was added to the system. The storm deposits from Hurricane Wilma showed a relative increase in Ca-bound

P (20-25% of total P pool) compared to the composition from the top soil (Castañeda-Moya et al., 2010). A similar increase in λE occurred in the April 2008 image (Fig. 7). The elevated λE estimated in the April 2008 images is associated with elevated R_n values that were ~ 1.5 times greater than the average measured values for that particular day. This misestimate may be a result of modeling parameters, as there was no significant change in the spectral reflectance nor the spectral indices for April 2008 (Fig. 3 & 4).

Moreover, λE has also been linked to changes in vapor pressure deficits (Barr et al., 2014). In that study, Barr et al (2014) measured low VPD during the dry season relative to the doubled VPD during the wet season. The opening of the mangrove forest canopy from defoliation and tree mortality after strong storms (e.g., Hurricanes Andrew, Wilma, and Katrina) can lead to reductions in H , enabling more energy to be partitioned into λE , as seen in elevated wet and dry season λE values directly after Hurricanes Katrina and Wilma in 2005 (Barr et al., 2012). Similar results were identified in the present study (Figure 7). More importantly, using remote sensing techniques, an extrapolation of λE values across the mangrove ecotone has been presented and has provided detailed information about the spatial variability in surface energy processes in mangrove ecosystem beyond the single site measurements.

The mangrove forests have been identified as having β characteristics of semi-arid regions ($\beta > 1.0$) during the dry season and broadleaf deciduous forests ($\beta < 0.5$) during the wet season (Barr et al., 2014). In lieu of this, and in addition to the VPD variability and tidal fluctuations, the results presented here are preliminary estimates of surface energy balance modeling for mangrove forests. These satellite-based surface balance components estimated by the present study provide insight to regional surface energy dynamics that can be overlooked at the field site scale.

The regional maps of λE that were generated using Landsat imagery demonstrated the variability of λE across the mangrove ecotones (e.g., tall versus scrub mangroves) and each ecotone's λE response to strong tropical storms and steady-state or typical conditions for the Shark River area (Fig. 9) and Taylor River area (Fig. 10). The southwestern mangroves in the Shark River vicinity exhibited high spatial variability in λE values images collected within 1-3 years after the storm (Fig. 10A). Latent heat values (λE) were highest in the islands around SRS6 and along Shark River, whereas to the north, λE values were lower by $\sim 58 \text{ W m}^{-2}$. Many of the mangroves north of Shark River are separated from tidal channels and were also along the trajectory of the tropical storms (Fig. 9A). Latent heat (λE) maps from the area identified two mangrove responses after storms; 1) mortality and defoliation from storm surge and high winds (Smith et al., 1994) as suggested by the low *FVC* values (<0.5), and 2) and elevated λE values in hot-spot areas. Under more meteorologically stable conditions, for instance the November 2008 map, indicates more homogeneity in λE values across the mangroves most likely related to forest regrowth and recovery (Fig. 9B).

The λE values for mangroves along the southern coast around Taylor River remained generally consistent throughout the region and for the most part were independent of the storm conditions (Fig. 10). In the March 1993 image collected after Hurricane Andrew, the modeled λE values were low ($180\text{--}260 \text{ W m}^{-2}$) across the scrub mangrove region (Fig. 10A). Fifteen years later in November 2008 the λE values in the scrub mangroves have increased, yet still have little spatial variability ($300\text{--}360 \text{ W m}^{-2}$) and most likely reflect the increase in mangrove basal area (Ross et al., 2000; Rivera-Monroy, personal communication) (Fig. 10B).

6. Conclusions

623 The Everglades have endured numerous modifications from both human engineering (e.g., canals,
624 levees) and natural events (e.g., tropical storms, sea-level rise). Long-term datasets acquired from the
625 NASA Landsat mission and the FCE LTER project have provided insight into the spatial and temporal
626 variability of λE and energy balance components in the Everglades, and more specifically, how the
627 mangrove ecotone has responded to multiple hurricane events and restoration projects during the
628 recent decades. Decreases in NDVI, SAVI, and *FVC* measured from Landsat images after hurricane events
629 identified mangrove mortality that was directly related to damage from strong winds and storm surge.
630 Modeled *G* values in the scrub mangroves decreased from the 1990s to the 2000s indicating new growth
631 and regrowth to areas around Taylor River in the coastal Everglades. Latent heat (λE) remained relatively
632 constant across all sites with the exception of SRS6 that exhibited higher ET rates following strong
633 hurricanes. Minimum λE were found in the scrub mangroves while maximum fluxes were obtained from
634 the tall mangroves. There was also a decrease in *G* and an increase in *FVC* in the scrub mangroves over
635 time that was also accompanied by a rise in λE as a result of increases in biomass and the greater
636 available energy over the same time period. Despite some limitations to the satellite surface energy
637 model related to physical forcings, the close comparisons among the site-specific energy balance
638 parameters and values from the literature suggest that there are other exports of energy from the
639 environment from water heat flux and tidal fluctuations.

640

641 Additional Everglades-related restoration projects that are expected to affect both Shark and Taylor
642 River have been completed or planned in the years since the last Landsat image (2008) used in the
643 present study. Continued monitoring through remote sensing can provide better regional understanding
644 of how the mangrove environment responds to natural and anthropogenic intervention. Moreover,
645 linking changes to the hydrogeological, meteorological and biophysical conditions in the coastal
646 mangroves in tropical and subtropical coastal wetlands are important for global water, energy and

carbon budgets. Moreover, this study highlights the variability in surface energy across various mangrove environments and biomass productivity while at the same time illustrates the accuracy, as well as the uncertainty, in estimating surface energy balance in complex, tidally influenced ecosystems. The inclusion of older images from the long-term Landsat archive (1970s-2000s) and the new acquisitions from Landsat 8 as part of the Landsat Continuity Mission (2013-present) will undoubtedly provide crucial spatial and temporal diagnostics of changes to λE , the energy balance and biophysical conditions that may not be detected at the field-scale. Energy balance modeling in the coastal Everglades, though difficult because of many physical forcings, has the potential to be used in other similar environments throughout the Caribbean where data collection is minimal and could provide for better interpretations of the region.

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927 **Table Captions**

928 Table 1. Average values and standard deviations of fractional vegetation cover (FVC), net radiation (R_n),
929 soil heat flux (G), sensible heat flux (H), and latent heat flux (λE) for each site. The units for R_n , G , H and
930 λE are in $W\ m^{-2}$.

931

932 Table 2. Error analyses table for measured versus modeled values energy balance parameters at TS6 and
933 SRS6. PFE= Percent Forecast Error; MAPE= Mean Absolute Percent Error; RMSE=Root Mean Square
934 Error; NRMSE= Normalized RMSE; CVMSE=Coefficient of Variation RMSE. Y_t are the measured values, F_t
935 are the modeled values, Y_{t+1} , is the next forecasted value, Y_{avg} is the mean of the measured values, Y_{max}
936 and Y_{min} are the maximum and minimum of the measured values, respectively, n is the number of
937 samples and s_e is the standard error of the measured values.

938

939 Table 3. Comparison of midday values of satellite-modeled and field-measured latent heat flux (λE ; $W\ m^{-2}\ day^{-1}$) for various types of forested vegetation communities.

941

Figure Captions

Figure 1. Location of Florida (A), South Florida, Lake Okeechobee and Everglades National Park (B) and mangrove study sites in Everglades National Park (C). Dashed gray boxes indicated the locations of evapotranspiration maps in Figures 9 and 10.

Figure 2. Half-hourly, daily and instantaneous (midday) net radiation (R_n) recorded at the tower at in Shark River versus R_n recorded at the tower in Taylor River. The gray dashed line represents the 1:1 line.

Figure 3. Reflectance values of all visible and infrared Landsat bands and corrected surface temperature (Landsat Band6) through time at the (A) scrub mangrove site TS6, and tall mangrove sites (B) SRSS-coast, (C) SRS4, and (D) SRS6.

Figure 4. Landsat 5TM-derived spectral indices, Normalized Difference Vegetation Index, Fractional Vegetation Cover and Soil-Adjusted Vegetation Index at (A) TS6, (B) SRS-coast, (C) SRS4, and (D) SRS6. The grey and black dashed lines indicated the arithmetic mean ($n=16$) for SAVI and FVC, respectively.

Figure 5. Multi-year average of net radiation (R_n), soil heat flux (G), sensible heat flux (H), latent heat of evaporation (λE) and $FVC*100$ for the 1990s and the 2000s for each site. Error bars denote one standard deviation ($n=8$).

Figure 6. Measured versus modeled scatter plots of (A) net radiation (R_n), (B) soil heat flux (G), (C) sensible heat flux (H) and (D) latent heat (λE). Grey dashed line represents a 1: 1 ratio.

964

965 Figure 7. Satellite-based latent heat flux (λE) in W m^{-2} for each image acquisition at (A) TS6, (B) SRS-
966 coast, (C) SRS4, and (D) SRS6.

967

968 Figure 8. (A) Net radiation (R_n) versus latent heat (λE) and (B) fractional vegetation cover (FVC) versus
969 latent heat plots for each site.

970

971 Figure 9. Modeled latent heat (λE) values in the tall mangroves in southwestern Florida near Shark River
972 in (A) post-Hurricane Andrew conditions (March 1993 acquisition) and in (B) steady-state conditions
973 (November 2008). Trajectories of tropical storms are shown in Figure 10A. Mangrove study sites are
974 marked with black diamonds. The location of the mapped area is defined in Figure 1.

975

976 Figure 10. Modeled latent heat (λE) values in the scrub mangroves in southern Florida near Taylor River
977 in (A) post-Hurricane Andrew conditions (March 1993 acquisition) and in (B) steady-state conditions
978 (November 2008). Mangrove study sites are marked with black diamonds. The location of the mapped
979 area is defined in Figure 1.

Table 1

	Site	FVC x 100	R_n	G	H	λE
Shark River	SRS4	90.4 ± 2.8	425.4 ± 27.5	129.2 ± 8.8	172.3 ± 13	160.5 ± 14.3
	SRS-coast	64.4 ± 7.7	512.8 ± 25	174.6 ± 14.8	173.5 ± 13.1	175.5 ± 14.5
	SRS6	83.9 ± 3.8	523.9 ± 26.2	139.9 ± 8	174.2 ± 13.3	218 ± 19.6
Taylor River	TS6	16.4 ± 5.5	487.3 ± 33.8	227.4 ± 17.3	177.4 ± 13.9	104.4 ± 9.9

Table 2

Error Analysis	Formula	TS_ R_n	SRS_ R_n	SRS_ G	SRS_ H	SRS_ λE	SRS6/TS6
PFE (%)	$(2 \times s_e/Y_{t+1}) \times 100$	13.0	11.6	21.6	15.6	19.5	11.6
MAPE (%)	$\Sigma(Y_t - F_t)/Y_t/n$	5.84	10.2	80.3	19.8	8.21	43.5
Nash-Sutcliffe	$\Sigma(Y_t - F_t)^2 / \Sigma(Y_t - Y_{avg})^2$	0.79	0.71	-12.6	-0.21	0.88	0.24
RMSE (W m ⁻²)	$\sqrt{\Sigma(Y_t - F_t)^2/n}$	55.0	53.0	11.8	46.4	29.4	64.1
NRMSE	RMSE/($Y_{max} - Y_{min}$)	11.5	13.8	8.55	29.6	12.2	18.5
Bias (W m ⁻²)	$\Sigma(Y_t - F_t)/n$	21.9	-26.0	113	-0.11	1.31	-155

Table 3

Biome	Location	Satellite models	Reference	Field data	Reference
Mangrove Forests	Florida	104-218	present study	115-231	Barr et al., 2014
	Thailand			200-425	Monji et al., 2002
	India	125-190	Ganguly et al., 2008		
Mediterranean Evergreen	Algeria	223-393	Zahira et al., 2009		
Tropical Rain Forest	Brazil			260-310	Malhi et al., 2002
Coniferous Forest	Sweden	100-180	Venäläinen et al., 1999		
Temperate Deciduous Forest	Tennessee			40-400	Baldocchi and Wilson, 2001

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