EFFECTS OF HURRICANE WILMA ON THE SURFACE ENERGY PARTITIONING OF MANGROVES IN THE FLORIDA EVERGLADES

A Thesis in
Meteorology
by
Daniel P. Sarmiento

© 2011 Daniel P. Sarmiento

Submitted in Partial Fulfillment
of the Requirements
for the degree of

Master of Science

May 2011
The thesis of Daniel P. Sarmiento was reviewed and approved* by the following:

Jose D. Fuentes  
Professor of Meteorology  
Thesis Adviser

Kenneth J. Davis  
Professor of Meteorology

Raymond G. Najjar, Jr.  
Associate Professor of Oceanography  
Joint Appointment with the Department of Geosciences

William H. Brune  
Department Head of Meteorology

*Signatures are on file in the Graduate School.
Abstract

The surface energy partitioning of a mangrove forest in the Florida Everglades was studied. The mangroves of the Florida Everglades are affected by a yearly cycle of dry and wet seasons. The first part of this study aimed to find the effects of the dry and wet seasons on the surface energy fluxes of the mangrove forest. The transition from the wet to dry season caused changes in the partitioning of energy into turbulent fluxes. Increases in the latent heat flux over the forest were observed in the wet season due to the increased availability of water and decreased air temperatures. The decoupling coefficient for the mangroves stayed relatively constant throughout the year, with an average range of 0.80 and 0.95, similar to other mangrove and tropical ecosystems. The strong decoupling between the forest and the atmosphere conveys that the net radiation is the main driver of the latent heat fluxes in the ecosystem. This strong decoupling is common in other mangrove and tropical forests. When the net radiation dropped below 400 W m$^{-2}$ in the wet season, the latent heat flux was below 150 W m$^{-2}$, regardless of vapor pressure deficit (VPD) values. In the dry season, the net radiation threshold was 550 W m$^{-2}$, which was expected due to the overall drop in latent heat fluxes in the dry season. VPD had a higher influence on latent heating rates in the dry season but the latent heat flux (LE) controls were still dominated by the net radiation.

Hurricane Wilma (October 2005) passed over the research site which gave us the unique opportunity to calculate the surface energy and latent heat fluxes before and after a hurricane disturbance. The second part of the study focused on how the surface energy fluxes were affected by this disturbance and why these changes occurred. After the hurricane disturbance, the aerodynamic resistance was reduced from an average of 30 s
m$^{-1}$ to 15 s m$^{-1}$. Satellite data implies that the mangrove forest has recovered from the hurricane. The aerodynamic resistance, however, has remained at about half of what was calculated before the disturbance. The changes in the aerodynamic resistances after the disturbance showed that the structure of the mangrove forest canopy was altered, changing the surface energy dynamics of the ecosystem. Comparing the data from 2004 to 2007, a stronger energy closure was measured during the dry season after the disturbance. Latent heat fluxes increased after the hurricane; these increases were due to the domination of evaporation processes in this ecosystem when the LAI was low. The ecosystem became more coupled to the atmosphere after hurricane Wilma, where the decoupling coefficient dropped to a range of 0.35 to 0.65 in the years after the disturbance.
Table of Contents

List of Tables .............................................................................................................................. vii

List of figures............................................................................................................................. viii

Acknowledgements:..................................................................................................................... xi

CHAPTER 1: Introduction ............................................................................................................. 1

Introduction and Background.................................................................................................. 1

Site description......................................................................................................................... 5

Data processing....................................................................................................................... 7

CHAPTER 2: Research methodology ......................................................................................... 8

CHAPTER 3: Surface energy partitioning of mangrove forest ecosystem .............................. 12

Meteorological and background information......................................................................... 12

Overall energy balance............................................................................................................ 13

Effects of tides on surface energy partitioning...................................................................... 15

Ecological response to atmospheric conditions ..................................................................... 17

Decoupling of the forest and the atmosphere....................................................................... 18

CHAPTER 4: The effects of hurricane Wilma on surface energy dynamics ........................... 19

Mangrove recovery and canopy roughness........................................................................... 19

Physical changes to the mangrove forest............................................................................... 21

Overall energy balance............................................................................................................ 22

Ecological response to atmospheric conditions .................................................................. 24
Decoupling of the forest and the atmosphere ................................................. 24

CHAPTER 5: Conclusions .................................................................................. 25

APPENDIX A: Tables ....................................................................................... 27

APPENDIX B: Figures ....................................................................................... 28

Literature Cited ................................................................................................. 48
List of Tables

Table 1 ........................................................................................................... 27
Fetch data for the flux tower at the site. Information based on Barr et al. 2010.

Table 2 ........................................................................................................... 27
Contains the slope and y-intercept of the best fit lines for the energy closure of the ecosystem (Figure 16)

Table 3 ........................................................................................................... 27
Contains the slope and y-intercept of the best fit lines for the turbulent energy partitioning of the ecosystem (Figure 20)
List of figures

Figure 1 .............................................................................................................. 28
Flux tower at field site before (left) and after (right) hurricane Wilma.

Figure 2 .............................................................................................................. 29
Monthly rainfall totals for the year of 2004. Data were taken from USGS
stations located along Shark River, which borders our field site.

Figure 3 .............................................................................................................. 30
Average daytime values for incoming solar radiation, air temperature,
VPD and water salinity. Incoming solar radiation is a sum for the day
spanning from sunrise to sunset. Air temperature, salinity, and VPD are
an average for values taken from 0900h to 1500h local time.

Figure 4 .............................................................................................................. 31
The hourly averages for Rnet, LE, H and G for the driest months in 2004
(December and March) and the wettest months in 2004 (July and August).

Figure 5 .............................................................................................................. 32
Partitioning of the turbulent fluxes (H and LE) and its relationship to the
available energy in the ecosystem (Rnet). Each data point represents a
half-hourly average for the dry month or wet month samples.

Figure 6 .............................................................................................................. 32
The hourly averages for water stage for the driest months in 2004
(December and March) and the wettest months in 2004 (July and August).
The splits represent data used in tidal analyses conducted.

Figure 7 .............................................................................................................. 33
The overall balance of energy for the two months separated by the tidal
samples. Each data point represents a half hourly average that occurred
between the hours of 0900 and 1500.

Figure 8 .............................................................................................................. 34
2004 dry season plot of latent heat flux (W m\(^{-2}\)) as a function of net
radiation and VPD. Values in legend represent latent heat flux values.

Figure 9 .............................................................................................................. 35
2004 wet season plot of latent heat flux (W m\(^{-2}\)) as a function of net
radiation and VPD. Values in legend represent latent heat flux values.
Figure 10 ………………………………………………………………………………………........ 36

2004 dry season plot of latent heat flux (W m$^{-2}$) as a function of salinity and net radiation. Values in legend represent latent heat flux values.

Figure 11 …………………………………………………………………………………………… 37

2004 wet season plot of latent heat flux (W m$^{-2}$) as a function of salinity and net radiation. Values in legend represent latent heat flux values.

Figure 12 …………………………………………………………………………………………… 38

Decoupling coefficient for the ecosystem.

Figure 13 …………………………………………………………………………………………… 39

NDVI and EVI values for the mangrove forest (Barr, unpublished). Gray range corresponds to the 25% and 75% spread in the data across the 11 by 11 grid. The blue and green lines correspond to the NDVI and EVI values of the single grid cell that encompasses the flux tower.

Figure 14 …………………………………………………………………………………………… 40

Aerodynamic resistance for 2004 and 2009. Values represent daily average values for data taken from 0900 hours to 1500 hours.

Figure 15 …………………………………………………………………………………………… 41

Illustration that portrays the expected effects of the hurricane on the ecosystem and the subsequent changes to the water vapor transport processes.

Figure 16 …………………………………………………………………………………………… 42

Closure of the energy being partitioned in the ecosystem. Each data point represents a half-hourly average for the dry month or wet month samples for 2004 and 2007.

Figure 17 …………………………………………………………………………………………… 42

Average values of sensible heat flux for March (dry season sample) and August (dry season sample).

Figure 18 …………………………………………………………………………………………… 43

Average values of soil heat flux for March (dry season sample) and August (dry season sample).

Figure 19 …………………………………………………………………………………………… 43

Normalized values of the air temperature profile at the site. NOTE: The x-axis scales on the figures do not match up. This was changed in order to
better show the shape of the temperature profile in March (dry season sample).

Figure 20 ............................................................................................................. 44
Partitioning of the turbulent fluxes (H and LE) and its relationship to the available energy in the ecosystem (Rnet). Each data point represents a half-hourly average for the dry month or wet month samples for 2004 and 2007.

Figure 21 ............................................................................................................. 44
Average values of latent heat flux for March (dry season sample) and August (dry season sample).

Figure 22 ............................................................................................................. 45
2007 dry season plot of latent heat flux (W m⁻²) as a function of net radiation and VPD. Values in legend represent latent heat flux values.

Figure 23 ............................................................................................................. 46
2007 dry season plot of latent heat flux (W m⁻²) as a function of net radiation and VPD. Values in legend represent latent heat flux values.

Figure 24 ............................................................................................................. 47
Average decoupling coefficient for 2004, 2005, and 2007 - 2010. Averages were computed from data that spanned from 1000 hours to 1500 hours local time. Error bars represent the standard deviation in these averages.
Acknowledgements:

The National Park Service provided support for this research. The National Science Foundation provided support for this research through the Florida Coast Everglades Long-Term Ecological Research program under grants DBI-0620409 and DEB-9910514. The National Institute for Climate Change Research (DE-FC02-06ER64298) also provided support for this research.
CHAPTER 1: Introduction

Introduction and Background

Mangrove trees are native to salt water estuaries and are prevalent in the tropics (Twilley, 1992). Given this habitat, mangroves have adapted to survive the harsh conditions characteristic of these environments. Mangrove ecosystems can minimize soil erosion associated with the advent of sea level rise and provide a habitat for many species of fish and other animals (Hoguane et al., 1999). The combined deleterious effects of urbanization, sea level rise, and declining water quality have caused significant stress to mangrove ecosystems and have reduced mangrove forest coverage area globally (Hoguane et al., 1999).

As most of the world’s mangrove forests are being destroyed by logging, charcoal production and shrimp farming, the mangrove forests of the Everglades National Park in southern Florida are thriving. The mangrove forests in the Everglades have benefited from an overwhelming conservation effort as well as an unexpected impact due to the growing human population in south Florida, which would be detrimental to mangrove forests under most circumstances. As the human population of south Florida grows, the demand for water also grows. Fresh water is pumped from local aquifers to supply the population with fresh water, and measures had to be taken to prevent salt water intrusion. In order to prevent tainting the aquifers with salt water, they are filled with the fresh water that would otherwise flow into the Everglades. Since the flow of fresh water into the Everglades is being diverted, more saline water from the Gulf of Mexico and Florida Bay flows into the western and southern edges of the Everglades. The expanding area of saline water in the Everglades allows mangroves to compete against other local plants. If
this trend continues and the mangrove forest area continues to expand, then the mangrove forest–atmosphere interactions will become more influential to the local microclimate of southern Florida.

Though located in tropical and coastal areas, mangrove forests are confronted with limited water availability. Due to their proximity to the ocean, they are regularly inundated with salt water. The mangroves’ unique root system processes salt water via pores that filter salt ions from the water against the osmotic potential. During low tide, these same pores aid in root respiration, which would otherwise be near impossible due to the saturated soils found in mangrove ecosystems (Purnobasuki, 2004).

The function and health of a mangrove ecosystem depends on its ability to efficiently utilize water in low-lying regions inundated with salt or brackish waters. This ability is evident in the partitioning of available energy into sensible and latent heating. The amount of water available to be transpired in mangroves is controlled by changes in the tides (Hoguane et al., 1999) and yearly floods (Herrera et al. 2008). Rainfall patterns resulting from distinct wet and dry seasons are important drivers of evapotranspiration and surface energy dynamics in other tropical forests (Giambelluca et al., 2008; Loescher et al., 2005; Malhi et al., 2002).

One of the major phenomena seen in many mangroves is the occurrence of a well defined rainy and dry season; the shift into and out of wet and dry seasons impacts the local ecology as well as the energy dynamics within the ecosystem. It is important to quantify the effects that these shifts have on the energy dynamics of the mangrove ecosystem. By quantifying these effects, the mechanics that govern the transpiration in
mangroves can be better understood. Models that utilize estimations of water vapor fluxes introduced into the atmosphere may not accurately account for variability in transpiration caused by environmental changes. If the effects of the dry and wet season on the transpiration of the mangrove forest are well known, then local climate models can be adapted to account for the changes in the amount of water vapor being introduced into the atmosphere.

Energy is expended through exclusion and membrane filtration (Medina, 1999) of salt when moving water into roots, through the xylem, and finally leaf stomata where the water is transpired. This energy expenditure limits the rate and integrated amount of water that mangroves can transpire. As a result, mangrove trees have adapted stomatal control strategies in their harsh environments to sequester CO₂ from the atmosphere while minimizing water vapor loss. These strategies are evident in the ratio of water use efficiency (WUE), defined as the ratio of leaf net photosynthesis to transpiration (Barr et al., 2009). Consistently high (35 to 130 μmol CO₂ per mmol H₂O) WUE values were indentified in mangroves. WUE values are generally lower in broadleaf terrestrial tree species with values ranging from 5.10 to 6.00 μmol CO₂ per mmol H₂O (Krishnan, 2006). If the atmospheric conditions cause the mangroves to lose too much water, then mangroves will close their stomas for the sake of water conservation. Once the atmospheric conditions are favorable, the stomas reopen to allow for the uptake of CO₂.

In the Florida Everglades, mangroves are also adapted to the occurrence of periodic hurricane disturbances. Studies show (Roth 1992; Wadsworth 1959; Wadsworth 1964) that mangroves have characteristics of plants that are classified as “early succession” in a competitive ecosystem (Roth 1992). After hurricane Andrew in August
1992, a surge of saplings started to grow due to the abundance of matures seeds released, mainly from the red mangroves (*Rhizophora mangle*), as the hurricane passed over the forest (Baldwin et al., 2000). This study also found that other factors such as storm surge height, in addition to seed dispersal, would determine the density and the distribution of the mangrove population within the forest after a disturbance. The effects of these major disturbances on the surface energy balance and forest-atmosphere interactions are not well documented. If there are alterations in the surface energy and water vapor fluxes introduced into the atmosphere after these disturbances, then these changes must be documented and integrated into models. If the amount of water vapor being introduced into the atmosphere changes after a disturbance, then it should be possible to improve local weather models by accounting for this change in evapotranspiration.

The eddy covariance method can be used to calculate the energy fluxes in and above plant canopies. Data gathered using the eddy covariance method is usually compared to older theoretical models, such as the Granger and Gray method, the Dalton-type bulk transfer model, Bowen ratios, and the more commonly known Penman-Montheith model (Armstrong et al., 2008; Loescher et al., 2005). Additional studies have also used the decoupling coefficient to measure the amount of biological control within an ecosystem (Loescher et al., 2005). A study conducted in the Nicaraguan tropical forests used the decoupling coefficient to conclude that the latent heat flux was governed by the biological controls in the early morning hours until noon (Loescher et al., 2005). Preliminary studies done at our site concluded that during times of low air temperatures, the latent heat fluxes are suppressed and more of the overall energy is partitioned into sensible heating (Barr et al., 2009). Elevated air temperatures, high VPD values and high
salinity were all factors that lowered the net ecosystem exchange of the mangrove forest (Barr et al., 2009a; Barr et al., 2009b). Lower CO$_2$ assimilation rates in the mangrove trees would imply that the transpiration rates were also suppressed.

The objective of this paper is to investigate the physical controls on forest-atmosphere exchanges of water vapor and energy partitioning in a western Florida Everglades mangrove forest. Specifically, the effects of tidal cycles, solar radiation, and water salinity on energy flows and forest-atmosphere coupling will be quantified. To date, little is known regarding the functional controls of latent heat exchange and energy partitioning in mangroves compared to the understanding of energy exchange processes in terrestrial forests. Data analyses and use of latent heat exchange models, such as the Penman-Monteith model (Monteith, 1965), are employed to quantify the influence of biological and atmospheric controls on the ecosystem evapotranspiration. In addition, seasonally variant forcing observed during distinct dry and wet seasons are investigated as this forcing contributes to energy partitioning patterns. After the surface energy dynamics and environmental forcings on evapotranspiration of the forest were defined, the effects of a disturbance was investigated. Hurricane Wilma (October 2005) will be used as a case study to investigate the changes in the surface energy dynamics of the mangrove forest.

**Site description**

The Shark River AmeriFlux flux tower site (25.3646°N, 81.0779°W) is located in Florida Everglades National Park. Established in June 2003, the tower is 30 m tall and in the middle of a mangrove canopy (Figure 1). The dominant tree species at the site are red (R. mangle), black (A. germinans), and white (L. racemosa) mangroves reaching heights
of 15-20 m (Ewe et al., 2006). The tower was rebuilt after it was destroyed by Hurricane Wilma, which made landfall on the south western coast of Florida as a category 3 hurricane in October 2005 destroying about 30% of the trees near the flux tower. The eddy covariance (EC) system consists of a 3-D sonic anemometer (model RS-50, Gill Co., Lymington, England) and an open path infrared CO$_2$ and water vapor (H$_2$O) gas analyzer (model LI-7500, LICOR Inc., Lincoln, NB) placed 26 m above the ground. High frequency (10 Hz) measurements are stored and processed with custom software to derive half-hourly CO$_2$ concentrations, latent and sensible heat fluxes, and momentum exchanges between the forest and the overlying atmosphere. A more detailed description of flux processing software and a complete description of instrumentation are described in Barr et al. (2010). Soil heat fluxes were measured through the use of soil heat flux plates (model HFT 3.1, Campbell Scientific, Inc) and soil temperatures through the use of soil temperature probes (model 105T, Campbell Scientific, Inc.). Radiometric data for the site were collected at 27 m and included a net radiometer (model CNR 1, Kipp and Zonen, Bohemia, NY) and a pair of PAR (photosynthetically active radiation) sensors (model LI-190SB, LI-COR, Inc., Lincoln, NE) to measure incoming and reflected PAR.

Hydrologic data were continuously monitored and recorded every 15 minutes at a United States Geological Survey (USGS) station 30 m south of Shark River and 150 m west of the flux tower. Measurements included specific conductivity and temperature (model 600R water quality sampling sonde, YSI Inc., Yellow Springs, OH) of surface well water and water level (model Waterlog H-333 shaft encoder, Design Analysis Associates, Logan, UT). Previous studies (Barr et al., 2009; 2010) at the site have focused on the magnitude and controls of vertical CO$_2$ exchange across the forest-
atmosphere interface as well as some preliminary studies on the surface energy dynamics of the ecosystem, which will be expanded upon in this paper.

**Data processing**

Numerical algorithms to remove spurious spikes on the raw data (Vickers and Mahrt, 1997) were applied to the eddy covariance information. Coordinate rotation and time lag correlations were also applied to the high frequency data (Schotanus et al., 1983). Corrections for any buoyancy effects on the latent heat fluxes were also applied to the data set as outlined in Webb et al., (1980).

The tower fetch (Table 1) was thoroughly detailed and enabled us to exclude invalid data when the flux tower footprint exceeded the forest fetch (Barr et al., 2010). Probabilistic methods outlined in Schuepp et al. (1990) were used to calculate the expected footprint of fluxes. If 50% or greater of the flux being measured was within the flux tower footprint, then the data was kept. If less than 50% of the flux was within the tower fetch, then the data were deemed invalid. This allowed us to eliminate the effects from adjacent areas. Since the field site is located near the Gulf of Mexico and surrounded by rivers, it was critical to filter the data to measure only those fluxes emitted from the mangrove forests. A previous study at our site has determined when friction velocities (u*) drop below 0.21 m s\(^{-1}\) and 0.13 m s\(^{-1}\) for pre- (Barr et al., 2010) and post-Wilma data (Jordan Barr, Everglades National Park, personal communication), the turbulence in the atmosphere is too low to calculate energy fluxes through the use of the eddy covariance with our sonic anemometer. Rainy days also affected the measurement of the infrared gas analyzer. Data which were deemed invalid, by using the above standards, were excluded and these invalid data mainly occurred at night (Barr et al.,
Gaps in the data also included periods of instrument malfunction and loss of power due to extended periods of cloudy conditions and thunderstorms. Frequent trips to the field site for maintenance helped keep the gaps caused by equipment malfunctions at a minimum.

For the 2004 data, 10% of the daytime data was deemed invalid by using the metrics previously described. For 2007, this value was 40% and for 2009 the invalid data percentage dropped to 34%. The vast majority of invalid data were found through the flux tower fetch and flux footprint analysis. Changes in the canopy after the hurricane changed the aerodynamic properties of the air above the canopy (Figure 15), which will be discussed in further detail in a subsequent section; however, this change in the aerodynamic properties above the canopy would lead to a change in the fetch, which explains the sharp increase in invalid data after the hurricane. No gap filling methods for the sensible or latent heats were applied to fill in invalid data. The contour plots (Figure 8 – 11, 21, 22) in this paper do use a gap filling algorithm to fill in any gaps in the data to produce the figure. This gap filling algorithm is similar to the algorithm used in Barr et al. (2010). The data were binned as follows: 5 bins for net radiation, 4 bins for VPD, and 4 bins for salinity. These data used included only daytime data. If a specific grid space on the contour had less than 15 data points, then the data were not included as a point and was interpolated from other points on the contour grid-space.

CHAPTER 2: Research methodology

The partitioning of available energy within an ecosystem is governed by the physical characteristics and biological features of the forest as well as by properties of the atmosphere. The available energy (Rnet) in an ecosystem can be measured by taking an
energy balance of the shortwave (K) and longwave radiation (L) within the ecosystem (1).

\[ R_{net} = K \downarrow - K \uparrow + L \downarrow - L \uparrow \]  
\hspace{1cm} \text{(Eq.1)}

Energy budgets for the partitioning of available energy for terrestrial ecosystems are expressed as follows (2):

\[ R_{net} = H + LE + G + \Delta S + \Psi \]  
\hspace{1cm} \text{(Eq.2)}

Where \( R_{net} \) is available energy, and H and LE are sensible and latent heat fluxes. G is the heat flux into the soil, and \( \Delta S \) is the heat storage within the ecosystem. While these storage terms are not negligible, they change in different ecosystems and are difficult to quantify with any degree of certainty. The \( \Psi \) term is an error term to address inherent errors in estimating the various components of the energy budget (Foken, 2008).

The latent heat flux is the water vapor flux exchanged from the forest to the atmosphere. The flow of water vapor between the forest and the atmosphere is controlled by multiple factors. Resistances to water vapor transfer from the forest to the atmosphere are often modeled using an analogy to Ohm’s law. Ecological resistances include the atmospheric and canopy resistances, which in turn depends on leaf physiology. Aerodynamic resistances can be affected by the structure of the forest canopy. The roughness of the canopy and the sizes of the leaves in the canopy all contribute to the amount of turbulence that is created in the layer of air above the forest canopy. The aerodynamic resistance can be calculated by summing the momentum transfer resistance \( (R_{mom}) \) in (3) with the boundary layer resistance \( (R_B) \) of the plant canopy in (4).
In equation 4 above, B represents the Stanton number. For uniform canopies, the Stanton number can be assumed to be 0.205 (Garratt et al., 1992). U is the resultant wind velocity (m s\(^{-1}\)) and \(u^*\) is the calculated friction velocity (m s\(^{-1}\)). The friction velocity is calculated using the sonic anemometer data. The deviations from the mean (\(u', v',\) and \(w'\)) were calculated from the raw data (5a-c). The covariance in u and v directions with the vertical wind was calculated (6a, 6b). The friction velocity was calculated from these covariance calculations (7).

\[
u' = u_{AVG} - u \quad v' = v_{AVG} - v \quad w' = w_{AVG} - w \quad \text{(Eq. 5a-c)}
\]

\[
u_{COV} = u'w' \quad v_{COV} = v'w' \quad \text{(Eq. 6a-b)}
\]

\[
u^* = \sqrt{4(u'w')^2 + (v'w')^2} \quad \text{(Eq. 7)}
\]

The second major contributor to the resistance of latent heat transfer to the atmosphere is the bulk canopy resistance. Through the manipulation of the Penman-Monteith equation, the bulk canopy conductance to water vapor transfer can be expressed as the following (Vourlitis et al., 2008):

\[
G_c = G a \left( \frac{S \times \text{R}_{\text{net}} - G}{\text{LE} \times \nu} + \rho_{\text{air}} \times C_p_{\text{air}} \times D \times G a \right) \left( \frac{S}{\nu} - 1 \right)^{-1} \quad \text{(Eq. 8)}
\]

In the above equation, LE is the latent heat flux (W m\(^{-2}\)), S is the rate of change of saturated water vapor pressure with temperature (kPa K\(^{-1}\)), R\(_{\text{net}}\) is net radiation (W m\(^{-2}\)), \(\rho_{\text{air}}\) is the density of dry air at a given temperature, \(C_p_{\text{air}}\) is the heat capacity of air, D is
the water vapor pressure deficit (kPa), \( G_a \) is the aerodynamic conductance \((\text{m} \, \text{s}^{-1})\), \( \gamma \) is the psychrometric constant \((\text{kPa} \, \text{K}^{-1})\), and \( G_c \) is bulk canopy conductance \((\text{m} \, \text{s}^{-1})\). A conversion can be implemented to convert the bulk canopy resistance to a bulk canopy conductance \( (G_S) \) in \( \text{mol} \, \text{m}^{-2} \, \text{s}^{-1} \) \((9)\). \( P \) is the atmospheric pressure in kPa, \( R \) is the universal gas constant \((\text{kJ} \, \text{mol}^{-1} \, \text{K}^{-1})\), and \( T \) is the air temperature in K.

\[
G_S = \frac{P}{R_s \times R \times T}
\]  
(Eq.9)

The Priestley-Taylor equation (Priestley et al. 1972) for water vapor transport models the equilibrium transpiration of a forest when the atmospheric resistance is large. When this condition (large atmospheric resistance) is applied to the Penman-Monteith equation, the result is the Priestley-Taylor model for the equilibrium latent heat flux of water vapor for a given forest canopy \((10)\):

\[
LE_{PT} = \frac{s}{s+\gamma} (R_{net} - G)
\]  
(Eq.10)

A common assumption is that most forests will have a Priestley-Taylor coefficient of 1.26 (Monteith, 1981). After this publication, however, subsequent studies have shown that the Priestly-Taylor coefficient varies from forest to forest. The Priestley-Taylor coefficient also varies based on changing conductance, which is influenced by changing meteorological variables.

The surface decoupling coefficient (Jarvis et al., 1986) in \((11)\) expresses the relative decoupling of a vegetation surface from the atmosphere based on the difference in observed latent heating from either boundary condition. By calculating the decoupling
coefficient, we are able to determine what drives the latent heat fluxes in the atmosphere. As \( \Omega \) approaches 0, the latent heat fluxes in the forest are driven by the water vapor pressure deficit in the atmosphere. This represents a perfectly coupled forest-atmosphere system. As \( \Omega \) approaches 1 then the water vapor pressure deficit becomes less influential and the net radiation is the main driver of the latent heat flux. This is a decoupled system and biological controls have a greater influence on the latent heat flux.

\[
\Omega = \frac{(\varepsilon+1)}{(\varepsilon+1 + \frac{\delta_{aero}}{\delta_S})} \quad \text{(Eq. 11)}
\]

CHAPTER 3: Surface energy partitioning of mangrove forest ecosystem

The next part of this paper will focus on the surface energy dynamics of the mangroves based on data that were gathered in 2004.

Meteorological and background information

The rainfall data for 2004 (Figure 2) shows the dry season ending in mid to late May for this particular year. The solar radiation during the summer months was lower than values seen in the spring (Figure 3). The decrease in total solar radiation in the summer time was due to the increase in cloudy and overcast conditions that are associated with the wet season. Peak salinity in 2004 was reached in June with an average salinity of 34.2 parts per thousand (Figure 3). The onset of the wet season dilutes the sea water and is responsible for the decrease in salinity seen in the latter half of the calendar year. There was a lag associated with the change in salinity and the monthly rainfall totals. The salinity peaks as the dry season ends and the lowest salinities are seen in the weeks before the dry season begins. The water vapor pressure deficit was high
during the wet season, peaking at an average of 2.2 kPa, and the low for the year occurred during the dry season with an average vapor pressure deficit (VPD) of 1.05 kPa. VPDs were calculated using relative humidity and temperature data at 27 m. When temperature data from the thermistor at 27 m were unreliable, temperature data from other thermistors above the plant canopy were used.

**Overall energy balance**

Half-hourly averages were taken for the net radiation (Rnet), soil heat flux (G), latent heat flux (LE) and sensible heat flux (H). The previous figures (Figure 4) show the diurnal patterns for the months of December, March, July and August in 2004.

One of the main components of the energy storage is the storage of energy in the biomass. Biomass in the ecosystem will absorb energy as the day progresses. In order to quantify this biomass storage, accurate measurements of the biomass (mass, heat capacity, rate of temperature change) must all be known (McCaughty, 1984; Meyers et al., 2004). Another common energy storage component is storage of energy in air below the canopy. For forests with high canopies (8+ meters), this component is important in calculating the ecosystem energy storage (McCaughty, 1984; Moore et al., 1986). While shorter canopies will also have canopy storage, the amount of energy stored is small compared to the overall energy storage term (Wilson et al., 2002). Photosynthesis in the ecosystem can also account for energy storage in an ecosystem (Meyers et al., 2004) and can be as large as 1% to 2% of the available energy (Wilson et al., 2002). There are other instrumental biases that introduce errors into energy measurements. Soil heat flux plates have been shown to introduce slight biases into soil heat flux measurements (Mayocchi et al., 1995; VanLoon et al., 1998). An extensive field campaign can be performed to
investigate these components of the surface energy ecosystem storage for the mangrove forest; however, at the current time, none of these facets have been investigated.

In other ecosystems, the dry months signal a decrease in transpiration and an increase in the overall radiation load, which causes a decrease in the latent heat flux and an increase in the sensible heat flux (Malhi et al., 2002). The rainfall amount changed from 6.6 mm and 5.8 mm in the months of December and March to a rainfall amount above 150 mm in the months of July and August, however the latent heat fluxes varied from 160 W m\(^{-2}\) to 250 W m\(^{-2}\) during this same time period. Without taking December into account, this change became smaller with the latent heat fluxes varying by 95 W m\(^{-2}\) during the highest point in the diurnal pattern. Increases in the latent heat during the wet season were attributed to both an increase in the radiation load and a higher availability of water in the ecosystem. It will be shown later in this paper that latent heating of the mangrove forest is closely tied to the overall radiation load of the forest. A suppression of the sensible heat flux was also observed in the wet season. While individual energy fluxes responded to changes in the radiation load, the partitioning of energy between latent and sensible heat change according to biological and environmental factors, such as LAI (leaf area index), VPD and water availability (Giambelluca et al., 2009).

The partitioning of the turbulent energy fluxes (LE and H) and its relationship to the available energy in the ecosystem (Figure 5) allowed us to view a distinct separation in the partitioning between the wet and dry seasons. The time of year has a minimal effect on the slope of the partitioning of the latent and sensible heat fluxes. The slope showed that a higher proportion of energy in the ecosystem was in the latent heat flux. The seasonality did change the overall energy partitioning: the wet season increased the
overall latent heat flux percentage by thirteen percent, which was attributed to the increase in the available water.

**Effects of tides on surface energy partitioning**

Tidal influences on energy partitioning in the mangrove forest were also analyzed. The influences of tides would be difficult to quantify on a yearly or monthly scale due to the cyclical nature of the high and low tide points that occur every lunar month. At the daily scale, there was a high and low tide cycle present. All the days of the chosen month were sorted by the stage level at noon, the time was chosen in order to isolate the late morning and early afternoon hours that were affected by the high and low tides. The sorted data were then used to create low and high tide groups of data for each month. By taking the days that had the 30% lowest and the 30% highest stage levels at noon, two subsets of data were created: the “high tide” set where the high tide peaked at noon and the “low tide” set where there was a water stage minimum at noon. Figure 6 shows the daily stage pattern for the months of March and December (dry season sample) for the days extracted for the tidal analysis. Figure 5 also shows the water stage averages for the wet season sample (July and August).

There were differences in the daily tidal cycles shown between the two seasons. Note that the water stage range used in the dry season differs from the range used in the wet season sample. Cycles for low and high tide samples in March, July and December did not overlap. This differs from what was illustrated in the tidal samples for August. Similarities in the tidal signal for the hours outside of 10:00 am to 3:00 pm (evening and early morning hours) for the low and high tide August samples limited this initial analysis to the late morning and early afternoon hours.
Taking the separated high and low tide subsets of data and analyzing the overall energy balance allowed us to investigate the effects of the tides on the surface energy balance. By looking at the overall energy balance ($R_{net} - G$ VS $H + LE$) (Figure 7), any shifts in the energy balance between the high and low tide samples can be isolated. If there is a significant change in the energy closure between the high and low tide samples, then that would imply changes in the energy partitioning under different tidal conditions. This is also under the assumptions that the storage term changes are negligible on a short time scale and the errors associated with the instrumentation do not change over the month. This is made under the assumption that storage energy terms are negligible and constant on small time scales and instrumentation errors do not change on a monthly time scale.

The overall energy regression lines for the dry season demonstrate that there was not a change between the daytime high tide and low tide balance of energy. This illustrated that the tidal influences on the overall energy partitioning of the ecosystem were negligible or the magnitude of the changes were insignificant in the dry season. The overall energy regressions for the wet season did not overlap as well as those for the dry season. This was likely due to the fact that there was a greater change in the sensible heat fluxes between the high and low tide samples in the wet season. The magnitude of the tides was also greater in the wet season and caused greater inundation of the site (peak water stage of ~0.3 m), which amplified the tidal effects on energy partitioning. It was suspected that there would be a change of the energy partitioning with the tides and the wet season data did succeed in proving that there could be an influence. During times of inundation, there is more water available for evaporation, which would increase the latent
heat fluxes. Inundation would also cause the dynamics of soil heat fluxes to change. During extreme high tides, the forest can sometimes be under 50 cm of water. This water layer on the soils should change the soil heating and cooling dynamics, which causing a change in the soil heat fluxes, but a more targeted investigation of the tidal influence is needed to confirm this hypothesis.

**Ecological response to atmospheric conditions**

Latent heat as a function of both net radiation and VPD (Figure 8 & 9) showed an increase in overall latent heating in the wet season (based on area of contour plot). While a slight change in latent heat flux was observed with changing VPD, the main control of LE was found to be net radiation. In the wet season, the ecosystem latent heat flux increased sharply at net radiation values that exceeded 400 W m\(^{-2}\). In the dry season, this net radiation limit was higher (~575 W m\(^{-2}\)). This phenomenon resulted from changes in water availability between the different seasons. The inference can be made that it takes more available energy to evaporate water in the dry season than it would in the wet season. The increases in latent heating occurred at all ranges of VPD. There was a connection seen between VPD and latent heat fluxes in the dry season, which suggests that the ecosystem is more coupled during the dry season.

Plotting LE as a function of VPD and salinity (Figure 10 & 11) revealed that latent heat fluxes in the ecosystem were not affected by salinity levels. While it is true that hyper-saline conditions will stress mangroves, the salinity levels recorded in 2004 seem to be within the mangrove tolerance levels. The data also suggest that the latent heat flux has a strong correlation to the amount of net radiation present in the ecosystem. A strong decoupling (net radiation controlled latent heating) was also seen in the salinity
plots. This suggests that changes in salinity do not affect the coupling of the ecosystem to the atmosphere.

**Decoupling of the forest and the atmosphere**

The $\Omega$ shows the biological controls and their contributions to the water vapor flux. The decreasing $\Omega$ trend indicated that the biological controls in the mangroves increased as the day moved from morning to early afternoon. The decreasing $\Omega$ trend is also indicative of the fact that VPD is becoming more important in determining latent heat fluxes for that period of time. By increasing biological controls during the time of day when evaporative demands are highest (Figure 12), the mangroves can conserve water. This is very important since mangroves expend energy desalinating the sea water. This mechanism allowed the mangroves to deal with the stresses caused by the lack of fresh water sources and high evaporative demands which occurred in the midday and early afternoon hours. Another study of a tropical forest exhibited the same trend where the decoupling coefficient increased from 0.6 to 0.85 in the early morning hours, but the decoupling coefficient steadily decreased as the day progressed toward afternoon and evening hours (Loescher et al., 2005). Other tropical forests have similar ranges (between 0.7 and 0.8) for the decoupling coefficient (Roberts et al., 1990; Meinzer et al., 1995; Meinzer et al., 1997). These tropical decoupling coefficients were high relative to broader leaf plants, such as red maples, whose decoupling coefficient has been calculated to be as low as 0.20 (Wullschleger et al., 2000). Factors that impacted decoupling include canopy structure, LAI, leaf surface area and water availability. These factors impacted the friction velocity, VPD and the conductance. The decoupling coefficients of mangrove forests in India have been reported to change with the monsoon season.
Before the monsoon season, the decoupling coefficient in the Indian mangroves was 0.76 but it dropped to 0.54 and rose to 0.95 afterward (Ganguly et al., 2008). This seasonally-driven change of decoupling between the forests and atmosphere were not seen at our study site because it does not receive the massive amounts of rainfall that the Indian mangroves do (175 cm and 60 cm for the SW and NE monsoon, respectively) (Ganguly et al., 2008). This indicates that only abnormally large amounts of rainfall for the Florida mangrove forest would cause a change in the average decoupling.

There was a noticeable change in the water vapor deficits for the dry and wet seasons, which was expected; however, there was no variation in the decoupling coefficient despite changes in evaporative demands, water salinity, and air temperatures (Figure 3). This suggests that the mangroves maintained a consistent control over the amount of water that they transpired regardless of variables that would normally affect the decoupling between the forest canopy and the atmosphere. This differs from the Southeast Asian mangrove forests which are under the influence of the monsoon seasons (Ganguly et al., 2008). While the rainfall in the Florida Everglades changes on a seasonal basis, the magnitude of this change is not as large as that seen in the monsoons of Southeast Asia. It is easy to see why the decoupling coefficient does not change depending on the season.

**CHAPTER 4: The effects of hurricane Wilma on surface energy dynamics**

**Mangrove recovery and canopy roughness**

After hurricane Wilma, the canopy was thinned out with the killing off and defoliation of many trees in the mangrove forest (Figure 15). The magnitude of
defoliation after the hurricane disturbance was verified through the use of satellite data (Figure 13). The data were gathered from the MODIS database in which the grid cells that are 500 square meters. A 6-day composite of data within a box of 11 by 11 grid cells was used to construct Figure 13. The center grid cell of the 11 x 11 box contains the flux tower. No on-site verification of the NDVI and EVI was done. Both the NDVI and EVI data show a drop in NDVI and EVI after hurricane Wilma. Using the satellite data, it seems that the ecosystem took over a year to recover from the disturbance (Jordan Barr, Everglades National Park, personal communication). The NVDI of the ecosystem reached pre-Wilma levels by 2007, however, the EVI is about 0.05 lower than pre-Wilma levels well into the present day (Jordan Barr, Everglades National Park, personal communication). The EVI is more dependent on the canopy structure of the forest, unlike the NDVI, which is more closely tied to the “greenness” of the forest canopy (Huete et al., 2002). The following was inferred from the satellite data: while the forest productivity has reached pre-Wilma levels, the structure of the forest canopy has not returned to the pre-Wilma state. To verify this, the aerodynamic resistances were calculated for 2004 and 2009 (Figure 14). Aerodynamic resistance is affected by the roughness characteristics of the forest canopy. If the structure of the forest canopy has changed, the roughness of the forest canopy will be altered, which will result in a change to the aerodynamic resistance. In 2009, the resistance rarely exceeded 15 s m\(^{-1}\), which is unlike 2004 where the aerodynamic resistance averaged ~30 s m\(^{-1}\) and would regularly peak over 40 s m\(^{-1}\). This verifies the inferences made from the satellite data. The canopy of the mangrove forest still does not exhibit the same structure that was present before the hurricane. Aerodynamic resistances in crop species, such as wheat and winter barley,
have been estimated to be as low as 27 and 29 s m\(^{-1}\) and as high as 105 s m\(^{-1}\) for maize (Boegh et al., 2002). Tropical forests had varying aerodynamic resistances, spanning from 20 s m\(^{-1}\) to 400 s m\(^{-1}\) (Roberts et al., 1990; Meinzer et al., 1997; Loescher et al., 2005). The variance in the aerodynamic resistance was influenced by depth of the canopy, shape and area of the leaves, LAI and prevailing winds. The aerodynamic resistance decreased after the disturbance, signifying that water vapor transport from the forest to the atmosphere will occur more readily following the disturbance; therefore, there should be a higher latent heat flux from the forest to the atmosphere if all other resistances (mainly the biological resistances) remain constant.

**Physical changes to the mangrove forest**

Figure 15 illustrates the conditions of the mangrove forest before and after the hurricane. The quasi-steady state of the forest before the disturbance has a thick forest canopy. The canopy absorbs and scatters incoming solar radiation that enters the atmosphere. Transpiration from the canopy was the main source of water vapor flux from the forest to the atmosphere. The forest soils were saturated and influenced by the tides, however, water vapor originating from the understory and the soils are not mixed into the air above the canopy. After a disturbance, the canopy thins out and many of the trees die. The incoming solar radiation now penetrates deeper into the understory and the forest soils. The transpiration of the ecosystem is cut down dramatically due to the loss of 30% of the mangroves following the hurricane (Barr et al., 2009). The moist soils and understory are exposed to more solar radiation; there will be more evaporation contribution to the water vapor flux. Water vapor present in the understory was more
easily mixed into the atmosphere due to a decrease in the aerodynamic resistance and a decrease in the stability of air within the forest canopy.

**Overall energy balance**

The energy balance of the ecosystem post-Wilma was compared to the energy balance analyzed for the pre-Wilma ecosystem (Figure 16). The overall closure of the energy balance has dramatically increased for the dry season after the disturbance (Table 2); however, the wet season closure has stayed relatively the same. After the hurricane, a decrease in biomass and more mixing of the air in the understory resulted in less ecosystem energy storage, which increased the energy closure of the forest. There was also a shift in the partitioning seen in the wet season data after Wilma. At lower Rnet – G values, the ecosystem was partitioning more of the available energy into the sensible and latent heat fluxes. The overall system exhibited a larger deviation from complete closure at higher values of available energy and turbulent fluxes. The change in the closure of energy in the ecosystem indicated that there have been changes to dynamics that control the partitioning of energy into LE, H, and G. Sensible heat fluxes have not been affected by the disturbance (Figure 17); however, the soil heat fluxes of the forest were affected (Figure 18). The sudden changes in the soil heat fluxes in 2007 are also related to large changes in the soil temperatures of the forest. With an increase of solar energy load reaching the understory, the air profile within the canopy was altered. Air profile averages (Figure 19) range from 1 m above the soil up to 26 m, about 10 meters above the mangrove forest canopy. The air temperature profile before Wilma shows a steady increase of temperature with height, implying a stratification of air throughout the forest. The temperature at 1.5 m would be about 9% cooler in the wet season and 3.5% cooler in
the dry season. This layer of stable air hindered any transport of water vapor in the vertical direction. After Wilma, the layers of air in the understory were more unstable than before the hurricane. The temperature differences between the air at 1.5 m and 25 m dropped to 3% in the wet season and about 1.5% in the dry season. There were two layers of air, one between 1.5 m and 7 m, the other between 10 m and 15 m, where the temperature decreases with height. This indicated a more efficient mixing occurring between the air in the understory of the forest and the atmosphere. While the entire layer is not unstable, the profiles indicated a weakening in the stratification of air within the forest, which allowed for water vapor transport into the atmosphere to occur more readily.

The partitioning of the turbulent fluxes was also altered by the disturbance (Figure 20). In both the wet and dry seasons, the ecosystem was partitioning more of the available energy into latent heating. Again, this was a result of the combination of all the previous effects of the disturbance on the ecosystem. This increased partitioning of net radiation into the latent heat could be explained in one of the following three ways: it could result from an increase in overall latent heating, a decrease in sensible heating, or a combination of both. It was previously shown that the sensible heating in the ecosystem did not change after the disturbance. The increase in the energy partition into the latent heat could therefore only be explained by an increase in the overall latent heat flux of the ecosystem. The increase in the amount of latent heat partitioning as net radiation changes (the slope of the line) has also changed post-Wilma (Table 3). Measurements of the latent heating for the ecosystem (Figure 21) confirmed the conclusions that were drawn
from the previous figures and analysis; the latent heat flux has increased in the ecosystem after hurricane Wilma.

**Ecological response to atmospheric conditions**

A contour plot of net radiation, VPD and latent heat flux for the dry and wet season of 2007 (Figure 22 & 23) can be compared to 2004 data (Figure 7 and 8) to determine changes of latent heat dynamics. The total area of the contour plots allowed us to confirm that there was a higher latent heat flux in the ecosystem in 2007. There were no constraints on latent heat fluxes by the net radiation seen in the data, which was seen in the 2004 data. This suggested that the latent heat fluxes were controlled by the vapor pressure deficit after the hurricane, whereas the latent heat was being regulated by the available energy before the disturbance.

**Decoupling of the forest and the atmosphere**

The decoupling coefficient in 2007 has decreased for the ecosystem (Figure 12 & 24). Figure 12 shows that the decoupling coefficient pattern over the course of a day remained the same before and after the hurricane. This suggests that the biological controls of the mangroves have not changed in any significant way, which was expected. The 2007 data also shows that the decoupling coefficient remained relatively equal in the wet and dry seasons. Since the difference in the amount of rainfall between the wet and dry seasons did not change after the disturbance, the decoupling of the ecosystem should remain somewhat constant between the seasons. Figure 24 shows the average daytime decoupling of the ecosystem for 2004, 2007 and 2009. The changes after the disturbance were clearly seen. The decreases in the decoupling coefficient conveyed that the latent heat fluxes in the ecosystem were more dependent on the vapor pressure deficit whereas
the latent heat fluxes were almost exclusively dependent on the net radiation before the disturbance.

CHAPTER 5: Conclusions

- The mangrove ecosystem in the Florida Everglades has the similar surface energy partitioning of other mangrove ecosystems in Southeast Asia. The mangrove forest closely mimics the energy dynamics seen in other tropical forests with seasonal changes in humidity and moderate rainfall (Loescher et al., 2005; Malhi et al., 2002). Latent heat fluxes of the forest were controlled by net radiation regardless of the atmospheric VPD.

- The decoupling coefficient calculated from the 2004 data suggests that mangrove biological controls regulate much of the latent heat flux in the ecosystem. There was no change in the overall decoupling coefficient between the wet and dry season, which is seen in other mangrove ecosystems (Ganguly et al., 2008). While there was a change in the rainfall amounts in the wet and dry season in the Florida Everglades, the difference and total amount of rainfall was not large enough to cause a change in the coupling of the ecosystem.

- While the forest has mostly recovered from the hurricane disturbance in 2005, the structure of the canopy has changed. The aerodynamic resistance, which is affected by canopy roughness, has been reduced after the hurricane. Changes in the canopy roughness have also changed the thresholds and limits used to filter out valid data that were gathered from our flux tower.

- The energy dynamics of the ecosystem have changed. Higher instability of the air under the canopy has allowed more water vapor from underneath the canopy to be
mixed into the atmosphere. The soil heat fluxes have increased as daily soil temperature ranges have increased. Due to the gaps in the canopy, more solar radiation was able to penetrate into the understory of the forest, which allowed the heating of the soils. This resulted in the increase of latent heat flux after the disturbance. Energy partitioning between latent and sensible heat also changed. 13% more of the available energy is being partitioned into latent heating after the hurricane.

- Post Wilma, the ecosystem was less decoupled from the atmosphere. The decoupling coefficient before the hurricane ranged from 0.7 to 0.9 and after the hurricane this range decreased to 0.4 to 0.6. After the hurricane, vapor pressure deficit was more influential on the latent heat flux of the ecosystem as evaporation became a bigger component in the evapotranspiration of the ecosystem. The coupling of the mangroves after the hurricane was more similar to salt marshes with grasses. This magnitude of coupling in the forest was not seen in any other mangrove or tropical forest.
APPENDIX A: Tables

<table>
<thead>
<tr>
<th>Flux tower fetch distances based on direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction (0° = N; advancing clockwise)</td>
</tr>
<tr>
<td>0° - 70°</td>
</tr>
<tr>
<td>70° - 120°</td>
</tr>
<tr>
<td>120° - 135°</td>
</tr>
<tr>
<td>135° - 180°</td>
</tr>
<tr>
<td>180° - 270°</td>
</tr>
<tr>
<td>270° - 360°</td>
</tr>
</tbody>
</table>

Table 1. Fetch data for the flux tower at the site. Information based on Barr et al. 2010.

\[(H+LE) = a \cdot (Rnet - G) + b\]

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 Dry Season</td>
<td>0.58</td>
<td>60.46</td>
</tr>
<tr>
<td>2004 Wet Season</td>
<td>0.56</td>
<td>63.69</td>
</tr>
<tr>
<td>2007 Dry Season</td>
<td>0.73</td>
<td>63.15</td>
</tr>
<tr>
<td>2007 Wet Season</td>
<td>0.51</td>
<td>143.37</td>
</tr>
</tbody>
</table>

Table 2. Contains the slope and y-intercept of the best-fit lines for the energy closure of the ecosystem (Figure 16).

\[\text{Ratio} = a \cdot (Rnet) + b\]

<table>
<thead>
<tr>
<th></th>
<th>a *10^4</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 Dry Season</td>
<td>-3.24</td>
<td>0.69</td>
</tr>
<tr>
<td>2004 Wet Season</td>
<td>-3.41</td>
<td>0.84</td>
</tr>
<tr>
<td>2007 Dry Season</td>
<td>-2.74</td>
<td>0.78</td>
</tr>
<tr>
<td>2007 Wet Season</td>
<td>-2.49</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Table 3. Contains the slope and y-intercept of the best fit lines for the turbulent energy partitioning of the ecosystem (Figure 20)
APPENDIX B: Figures

Figure 1. Flux tower at field site before (left) and after (right) hurricane Wilma.
Figure 2. Monthly rainfall totals for the year of 2004. Data were taken from USGS stations located along Shark River, which borders our field site.
Figure 3. Average daytime values for incoming solar radiation, air temperature, VPD and water salinity. Incoming solar radiation is a sum for the day spanning from sunrise to sunset. Air temperature, salinity, and VPD are an average for values taken from 0900h to 1500h local time.
Figure 4. The hourly averages for $R_{\text{net}}$, LE, H and G for the driest months in 2004 (December and March) and the wettest months in 2004 (July and August).
Figure 5. Partitioning of the turbulent fluxes (H and LE) and its relationship to the available energy in the ecosystem (Rnet). Each data point represents a half-hourly average for the dry month or wet month samples.

Figure 6. The hourly averages for water stage for the driest months in 2004 (December and March) and the wettest months in 2004 (July and August). The splits represent data used in tidal analyses conducted.
Figure 7. The overall balance of energy for the two months separated by the tidal samples. Each data point represents a half hourly average that occurred between the hours of 0900 and 1500.
Figure 8. 2004 dry season plot of latent heat flux (W m$^{-2}$) as a function of net radiation and VPD. Values in legend represent latent heat flux values.
Figure 9. 2004 wet season plot of latent heat flux (W m$^2$) as a function of net radiation and VPD. Values in legend represent latent heat flux values.
Figure 10. 2004 dry season plot of latent heat flux (W m\(^{-2}\)) as a function of salinity and net radiation. Values in legend represent latent heat flux values.
Figure 11. 2004 wet season plot of latent heat flux (W m$^{-2}$) as a function of salinity and net radiation. Values in legend represent latent heat flux values.
Figure 12. Decoupling coefficient for the ecosystem.
Figure 13. NDVI and EVI values for the mangrove forest (Barr, unpublished). Gray range corresponds to the 25% and 75% spread in the data across the 11 by 11 grid. The blue and green lines correspond to the NDVI and EVI values of the single grid cell that encompass the flux tower.
Figure 14. Aerodynamic resistance for 2004 and 2009. Values represent daily average values for data taken from 0900 hours to 1500 hours.
Figure 15. Illustration that portrays the expected effects of the hurricane on the ecosystem and the subsequent changes to the water vapor transport processes.
Figure 16. Closure of the energy being partitioned in the ecosystem. Each data point represents a half-hourly average for the dry month or wet month samples for 2004 and 2007.

Figure 17. Average values of sensible heat flux for March (dry season sample) and August (dry season sample).
Figure 18. Average values of soil heat flux for March (dry season sample) and August (dry season sample).

Figure 19. Normalized values of the air temperature profile at the site. NOTE: The x-axis scales on the figures do not match up. This was changed in order to better show the shape of the temperature profile in March (dry season sample).
Figure 20. Partitioning of the turbulent fluxes (H and LE) and its relationship to the available energy in the ecosystem (Rnet). Each data point represents a half-hourly average for the dry month or wet month samples for 2004 and 2007.

Figure 21. Average values of latent heat flux for March (dry season sample) and August (dry season sample).
Figure 22. 2007 dry season plot of latent heat flux (W m$^{-2}$) as a function of net radiation and VPD. Values in legend represent latent heat flux values.
Figure 23. 2007 dry season plot of latent heat flux (W m$^{-2}$) as a function of net radiation and VPD. Values in legend represent latent heat flux values.
Figure 24. Average decoupling coefficient for 2004, 2005, and 2007 - 2010. Averages were computed from data that spanned from 1000 hours to 1500 hours local time. Error bars represent the standard deviation in these averages.
Literature Cited


