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Variation and uncertainty in evaporation from a subtropical estuary: Florida Bay

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ABSTRACT

Variation and uncertainty in estimated evaporation was determined over time and between two locations in Florida Bay, a subtropical estuary. Meteorological data was collected from September 2001 to August 2002 at Rabbit Key and Butternut Key within the bay. Evaporation was estimated using both vapor-flux and energy-budget based methods. The results were then placed into a long-term temporal context using 33 years of temperature and rainfall data collected in south Florida. Evaporation also was estimated from this long-term data using an empirical formula relating evaporation to clear sky solar radiation and air temperature.

Evaporation estimates for the 12 month period ranged from 144 to 175 cm yr^{-1}, depending on location and method, with an average of 163 cm yr^{-1} (±9%). Monthly values ranged from 9.2 cm to 18.5 cm, with the highest value observed in May, corresponding with the maximum in measured net radiation. Uncertainty estimates derived from measurement errors in the data were as much as 10%, and were large enough to obscure differences in evaporation between the two sites. Differences among all estimates for any month indicate the overall uncertainty in monthly evaporation, and ranged from 9% to 26%. Over a 33-year period (1970 – 2002), estimated annual evaporation from Florida Bay ranged from 148 to 181 cm yr^{-1}, with an average of 166 cm yr^{-1}. Rainfall was consistently lower in Florida Bay than evaporation, with a long-term average of 106 cm yr^{-1} Rainfall considered alone was uncorrelated with evaporation at both monthly and annual time scales; however, when the seasonal variation in clear sky radiation also was taken into account both net radiation and evaporation were significantly suppressed in months with high rainfall.

INTRODUCTION

Evaporation drives the development of estuarine hypersalinity. Hypersalinity (>35 psu) is distinctive of the estuaries where it occurs - for example in Australia (Corlis et al. 2003), Texas (Solis and Powell 1999), Brazil (Kjerfve et al. 1996), Baja, Mexico (Lavin et al. 1998) and Florida Bay (Fourqurean and Robblee 1999). Despite its importance in these and similar estuaries, evaporation in such settings has not been studied in detail, and frequently it is simply extrapolated from nearby land-based measurements. This introduces uncertainty into predictions of estuarine conditions that is difficult to quantify but may be critical in developing models to govern the supply of freshwater to such estuaries. By contrast, two recent studies of Indian River Lagoon (Sumner and Belaineh 2005) and Florida Bay (Smith 2000) estimate evaporation from meteorological data collected within these estuaries. However, these studies do not address uncertainty in the resulting evaporation estimates due to natural variability and to errors inherent in the methods used.

Questions about the variability of evaporation have particular importance for Florida Bay. Florida Bay belongs to the class of seasonally hypersaline estuaries described by Largier et al. (1997). Hypersalinity develops when water loss by evaporation exceeds the total supply of fresh water from rainfall and the inflow of surface and groundwater from the estuary's watershed. Restricted tidal exchange and consequent long residence times increase the sensitivity of some estuaries to hypersalinity caused by the imbalance between evaporation and the total supply of fresh water. In Florida Bay this imbalance arises from the strong seasonal variation in the fresh water fluxes of rainfall and runoff (Nuttle et al. 2000). Salinity values decrease during the rainy season, May to October, and increase during the dry season, November to April. Following periods of drought, salinity values of over 50 psu often occur in the north central region of the bay (Fourqurean and Robblee 1999) where circulation is limited due to the presence of mud banks (Fig. 1). A water residence time of 6 to 12 months has been estimated for one central basin of the Florida Bay (Lee et al., 2006). A regional drought between 1987 and 1990 resulted in some of the highest salinity values, near 70 psu, ever recorded in Florida Bay. During the same time period, Florida Bay was experiencing massive seagrass die-off and declines in pink shrimp harvest (Robblee et al. 1991). This was followed by increases in water turbidity (Boyer et al. 1999), cyanobacteria blooms, and mass mortality of the sponge population (Butler et al. 1995). The extreme ecological changes raised questions about the causes of the hypersalinity conditions and about the water budget of Florida Bay. Spatial variation in evaporation, if it occurs, may be an important factor contributing to the spatial distribution of hypersalinity in Florida Bay.

This study examined the variation in evaporation in Florida Bay on monthly and annual time scales and compared estimates from two widely-spaced locations within the bay. It builds on and extends the work by Smith (2000) that offers evidence that evaporation varies spatially. Seasonal variation in evaporation was also examined. For instance, did estuarine evaporation follow the seasonal pattern of land-based pan evaporation data or did it follow a pattern similar to regional temperatures? The magnitude of variation in annual evaporation was examined by using patterns in temperature data (Abtew 1996) to extrapolate evaporation estimates back over a 33-year period. Finally, the sources and magnitude of uncertainty in evaporation estimates were documented as these affected the ability to discern variation in the underlying processes.

BACKGROUND

Florida Bay is a broad (>2000 km^2), shallow (~1 to 2m deep) embayment between the Florida mainland and the Florida Keys (Fig. 1). Variations in salinity shape the distribution and composition of seagrass communities that anchor the base of the food chain in the bay (Fourqurean et al. 2003). Hypersalinity affects the diversity of animal species (Sogard et al. 1989) and the net productivity of the ecosystem, as reflected in recruitment of juveniles to the Dry Tortugas shrimp fishery (Browder et al. 2002).

Evaporation represents the largest loss of freshwater from Florida Bay and is largely balanced by rainfall (Nuttle et al 2000). Direct runoff accounts for only 10% to 20% of the freshwater supply (Kelble et al. 2007) and is localized to the northeastern portion of the Bay (Hittle et al. 2001). On average, the net supply of fresh water to Florida Bay is close to zero (Nuttle et al. 2000). The long-term average salinity approaches that of seawater (~35 psu). Despite inflows of fresh water causing no net dilution or concentration of salinity on average, salinity does vary over a wide range both spatially and over time.

Salinity in Florida Bay is perhaps uniquely sensitive to variation in evaporation and rainfall. An index of the relative influence of evaporation and rainfall in an estuary is the ratio of the difference in the annual volume of rainfall minus evaporation divided by the annual volume of river inflow (Solis and Powell 1999). For most estuaries, the magnitude of this index is much less than one; i.e. evaporation and rainfall are small relative to river inflow. However, Florida Bay receives little inflow from the south Florida mainland, and this ratio varies from one year to the next over a range from -10 to 0. Spatial and temporal patterns of evaporation may be an important influence on salinity variation in Florida Bay, especially during years with little rainfall, when the ratio is near -10.

Several unresolved issues bear on the understanding of evaporation and its influence on spatial and temporal variation in salinity in Florida Bay. An estimate of 110 cm yr^{-1} for evaporation by Nuttle et al. (2000) is based on fitting a steady state model to long-term data (31 years) on the bay's hydrology and salinity. Contemporaneous with that study, Smith (2000) estimated annual evaporation might exceed 163 cm yr^{-1}, based on less than one year's data but employing a more direct approach to estimating evaporation. Smith's results are in line with Morton's estimate of 162 cm yr^{-1} for evaporation from Lake Okeechobee (Morton 1986). Lake Okeechobee is a shallow fresh water lake comparable in size to Florida Bay and about 170 km to the north. Subsequently, Abtew (2001) estimated a lower value, 135 cm yr^{-1}, for Lake Okeechobee evaporation based on a number of approaches. German (2000) measured evaporation of 160 cm yr^{-1}at sites with standing water in the Everglades wetlands. Raw pan evaporation data from Flamingo (Fig. 1) provide the highest estimate of annual evaporation, 210 cm yr^{-1} (Nuttle et al. 2000).

Differences amongst these estimates reflect both the temporal and spatial variation in evaporation and uncertainties arising from the methods used to compute the estimates. The combined magnitude of these uncertainties is of interest because uncertainty, i.e. the combination of error and unexplained variation, confounds attempts to discern differences in evaporation between different locations in the bay and from one time to another. Three sources of uncertainty are important: 1) limits on the accuracy of the sensors used, 2) the inevitable problems that arise in monitoring conditions at remote locations under harsh environmental conditions; and 3) error in the semi-empirical models used to calculate evaporation from the data. Sensor accuracy can be determined from calibration but, the difficulty in directly measuring evaporation under field conditions stands as a barrier to evaluating the overall level of uncertainty.

This study makes the first systematic attempt to evaluate the uncertainty in estimated evaporation from Florida Bay, and places these estimates in the context of longer term monitoring and modeling efforts. Results are compared, including error estimates, from two different methods of evaporation calculated from two widely-spaced locations in Florida Bay The results of this study have direct bearing on understanding past changes in the Florida Bay ecosystem and on attempts to forecast the effects that hydrologic restoration in the Everglades wetlands might have in the bay.

METHODS

No device exists that is able to measure evaporation directly in an estuary, as one might use a rain gage to measure rainfall amount or an anemometer to measure the speed of the wind. Instead, evaporation is calculated from measurements of related fluxes, i.e. wind and thermal energy, and physical characteristics of the water column and the overlying atmosphere (Table 1). In this study, evaporation is estimated based 1) on its physical manifestation as a diffusive flux of water vapor driven by wind-generated turbulence (Smith 2000), and 2) on its role in the thermal energy budget at the Earth's surface (Sacks et al. 1994, Sumner and Belaineh 2005). Based on its nature as a turbulent vapor flux, evaporation was estimated using (i) 30 minute average measurements of wind speed, water temperature, air temperature, and relative humidity and (ii) 30 minute average measurements of net radiation, water temperature, and air temperature. Finally, a 33-year record of evaporation was calculated based on the variable attenuation of solar radiation by water vapor in the atmosphere as indicated by regional climatic data of daily high and low air temperatures.

Data Collection

Two weather stations were constructed in Florida Bay, one near Rabbit Key and the other near Butternut Key (Fig. 1). Everglades National Park has been monitoring salinity from these platforms for over a decade. The weather stations were equipped with the instruments listed in Table 1. The wind monitor was placed on a tower at distances of 5 m and 4 m above the surface of the water at Rabbit Key and Butternut Keys, respectively. The net radiometer was placed at a distance between 2 and 3 meters above the water surface and extended from the south side of the station to prevent shading by other instruments. The temperature sensor was placed just beneath the water surface at the Rabbit Key station, but was housed in a PVC pipe near the bottom of the water column at the Butternut Key station. In the very shallow water surrounding the Butternut Key station ($\leq$1 m), vertical temperature stratification was not generally observed. Each instrument was monitored every minute with a Campbell Scientific CR10X data logger with average readings recorded every 30 minutes. Each station was powered by a battery recharged with a solar panel. Both weather stations were established in April 2001 and were fully operational by September 2001. The Rabbit Key weather station was disassembled in December 2002, while the Butternut Key weather station continues to operate. The results presented in this paper include an almost continuous record of data that covers the 12 month period from September 2001 through August 2002.

Vapor Flux Method

The vapor flux method used a mass-transfer approach to estimate evaporation as a function of turbulence (wind speed) and a vapor pressure gradient, which was dependent upon air temperature and relative humidity. Many variations of this method have been published (Penman 1948) using some version of Dalton's Law (Dalton 1802). Most of the vapor flux equations include empirical constants based upon the height of the wind speed, temperature, and humidity instruments above the water surface. Differences in data collection procedures by different research groups have led to the formulation of over 100 equations (Panu and Nguyen 1994, Singh and Xu 1997). Furthermore, many of the empirical constants were developed for evaporation over small water bodies such as swimming pools, lakes, or ponds (Singh and Xu 1997, Sartori 2000). Smaller water bodies surrounded by land experience different wind and wave conditions than the open waters of Florida Bay. To more accurately estimate evaporation over Florida Bay, the following equation developed by Sartori (2000) was used:

$$E = (0.00407V^{0.8}L^{-0.2} - 0.01107L^{-1})(P_w-P_d)/P, \quad (1)$$

where E was evaporation rate in (kg m^{-2} s^{-1}), V was the wind speed (m s^{-1}), P was the atmospheric pressure (Pa), P_w and P_d were the water vapor partial pressures at the water and dew point temperatures, respectively, and L was a characteristic length (m). The characteristic length (L) does not correspond with a fetch length, but instead corresponds to an attenuation of the mass transfer coefficient in the wind direction that generates an average evaporation rate for a surface length of unit width (Satori 2000). The Satori (2000) equation recognizes a decay in mass transfer along the distance of main wind direction, thereby producing a decrease in the evaporation rate with an increase in L. The decay is proportional to $L^{-0.2}$ in turbulent flow conditions, and $L^{-0.5}$ in laminar flow. In this exercise, turbulent flow conditions were assumed to prevail in Florida Bay.

The Satori (2000) equation using an L=100 m was applied to weather data obtained at the Long Key C-MAN station, LONF1 (located in Florida Bay), from February to July 1999 (Ned

Smith, Harbor Branch Oceanographic Institution, unpublished data), and then compared to evaporation estimates using a bulk aerodynamic formula as suggested by Pond et al. (1974) and used by Smith (2000). The result was a close agreement between the two methods. The estimate obtained using the Satori (2000) approach was consistently lower than the estimate using the Smith (2000) method, yet agreed with Smith (2002) results within 5%. Based upon these results, evaporation rates of Florida Bay were estimated using an L=100 m assuming an error of ±5%. Uncertainty related to the instruments used for this method was summed to obtain a total error of 10.5% (Table 1).

Energy Budget Method

The energy budget method was based on the principal that the latent heat flux associated with evaporation was a major component in the thermal energy budget of the bay (Sacks et al. 1994; Sumner and Belaineh 2005). The Priestly-Taylor formula (Priestly and Taylor 1972) was used:

$$E = \alpha \frac{\Delta}{\Delta + \gamma}\left(R_{NET} - Q_{STORE}\right) \qquad (2)$$

in which E was the evaporative energy in W m^{-2}, R_{net} was the net radiation flux at the surface and Q_{STORE} was the change in heat stored in the water column (both in W m^{-2}), Δ was the slope of the saturation water vapor pressure curve at the temperature of the air (Dingman 2002) and γ was the psychrometric constant (both in kPa K^{-1}). A value of 1.26 for the empirical coefficient α in the Priestly-Taylor formula was used.

Q_{STORE} $(W\,m^{-2})$ was estimated as

$$Q_{STORE} = 0.2778 \frac{T_{w2} - T_{w1}}{\Delta t} \rho_w C_w D \quad (3)$$

where, T_{w1}-T_{w2} is the difference in water temperature between consecutive measurements, Δt is the measurement interval (0.5 hr), ρ_w density of water (1023 Kg m^{-3} for seawater at 25 ^oC), C_w is the heat capacity of water (4.186 J g^{-1} $^oC^{-1}$), and D is the water depth. Nominal values of 1 m for water depth and 1000 Kg m^{-3} for the density of water were used, uncorrected for variations in temperature and salinity, at both locations. The value 0.2778 is a conversion factor with units W hr g J^{-1} Kg^{-1}.

The psychrometric constant is not strictly a constant, but varies with atmospheric pressure (P) and the latent heat of vaporization (λ_v) according to the equation:

$$\gamma = \frac{C_a \cdot P}{0.622 \cdot \lambda_v} \quad (4)$$

where, C_a is the heat capacity of air at 1.00 x 10^{-3} MJ kg^{-1} K^{-1} (Dingman 2002). The latent heat of vaporization varies with the temperature of the air (T_a) in degrees Celcius according to:

$$\lambda_v = 2.50 - 2.36x10^{-3} T_a. \quad (5)$$

In equations 1 and 4 a constant atmospheric pressure of 101.3 kPa was assumed.

Some of the error in evaporation estimated by Equation 2 derives from errors in measurements of air and water temperature and net radiation (Table 1). The net radiometer used had an uncorrected error of 1% to 6%, with the highest error for positive fluxes at wind speeds of 7 m s^{-1}. This is consistent with results reported by Halldin and Lindroth (1992), who found that the Fritschen type net radiometers used here have errors of 9 W m^{-2} to 30 W m^{-2}, with the larger error observed in night time measurements due to condensation on the dome. The air temperature probe has an accuracy of ±0.3°C. For an average air temperature of 24.6°C, this equates to an error of less than 1%. The total expected error in the energy-budget estimate of evaporation was dominated by the contribution from net radiation, from 1 to 7%.

Long-term estimate - Radiation Method

In order to investigate the possible range of variation in annual evaporation over a 33-year period a method described by Abtew (1996) was used. Evaporation was calculated as a fraction of the estimated total solar radiation for south Florida according to the following equation:

$$E=K_1R_s/\lambda \tag{6}$$

where E was evaporation rate (cm d^{-1}), R_s was total solar radiation (MJ m^{-2} d^{-1}), λ was the latent heat of vaporization of water (MJ kg^{-1}), and K_1 was a dimensionless coefficient. A value of 0.53 for K_1 was used in this investigation as it was determined appropriate for open water areas according to Abtew (1996). Since total solar radiation is often not provided from many meteorological stations, Allen (1997) developed a method to estimate R_s as a function of the daily temperature range (T_{max}-T_{min}) according to the following equation:

$$R_s = K_2(T_{max}-T_{min})^{1/2}R_a \qquad (7)$$

where R_a was the clear sky radiation for a given time of year and latitude (Fig. 2), and K_2 was an empirical constant. For this investigation, the daily temperature range was interpolated over the bay from temperature records measured at Flamingo, Royal Palm, and Tavernier (Fig. 1). Initially, equations 6 and 7 were solved by forcing the evaporation value in equation 6 equal to the average monthly evaporation estimates produced from the vapor flux and radiation based methods for the 12-month data period to result in a best fit value for K_2. This value for K_2 (0.65) was then applied to the temperature data collected from the Flamingo, Tavernier, and Royal Palm stations. The error produced in this method was related to the error in the temperature measurements of 1% as well as the error in the estimate of solar radiation based on the empirically-derived Equation 7, i.e. an addition error of about 2.4% related to the goodness of it of the value for the coefficient K_2.

RESULTS

Data Quality

A 12-month period of data, 1 September 2001 through 31 August 2002, was selected for detailed analysis. Out of nearly two years of monitoring data collected, this period encompasses the least number of recognized errors and gaps in the data. Within the selected period, 15 days of data were missing from the Rabbit Key platform during the month of March 2002, which represented approximately 4.5% of the entire year. Operational problems contributed to a relatively large number of gaps in the data early in the deployment, which started in the spring of 2001. As expected, maintaining radiation sensors at remote locations proved to be a challenge. These sensors were subject to fouling by birds, and to the normal wear and tear on everything deployed in the semi-tropical estuarine environment of Florida Bay.

Differences Between Sites

Significant differences between some of the variables monitored at the Rabbit Key and Butternut Key platforms (Table 2) were detected. Differences in the monthly averaged data were judged to be significant if the magnitude exceeded the expected measurement error (Table 1). By this criterion water temperature and wind speed were different at the two sites, but air temperature and relative humidity were essentially the same, discounting the month with partial data coverage at the Rabbit Key platform. Water temperature exhibited slightly higher amplitude of seasonal variation at the Rabbit Key platform, possibly due to sensor location at the surface versus at the bottom at Butternut Key, but there was no significant difference between the 12-month averages at the two sites. In contrast, wind speed was consistently higher at the Rabbit platform, 11 percent higher on average. Wind speed increases with height, but the difference in instrument height between the two sites (5 m at Rabbit Key vs. 4 m at Butternut Key) accounts for a difference in wind speed of only about 3 percent. This estimate is based on the usual assumption of a logarithmic distribution of wind speed and a conservative estimate of 0.001 m for the roughness height (Helfrich et al. 1982).

Differences in net radiation and rainfall between the two sites (Table 2) were detected. Net radiation exhibited higher amplitude of seasonal variation at the Butternut Key platform, but both sites recorded essentially the same amount of net radiation averaged over the 12-month period, 142 W m^{-2}. This is about 10% higher than the top of the range of annual values for net radiation that German (2000) measured in the Everglades wetlands. Rainfall was consistently higher at the Butternut Key platform, but data from both sites exhibit the same pattern of seasonal variation (Fig. 2).

Variation in Estimated Evaporation

Values of monthly evaporation estimated by applying the vapor flux and energy budget methods (Equations 1 and 2) separately to the data from the two platforms all followed the same seasonal pattern of variation (Fig. 2). The highest average evaporation rates (13-18.5 cm per month) occurred during late spring and summer, i.e. April through October. The lowest average evaporation rates (9.2-11.7 cm per month) occurred during late fall and winter, i.e. November through March. The storage and release of energy in the water column, Q_{STORE}, was a significant component of the surface energy budget computed hourly over the course of a day (Fig. 3). However net average values of Q_{STORE} computed over a month were less than 5% of the heat flux due to evaporation, as also found by Shoemaker et al. (2005); and possibly this flux could be neglected in estimating evaporation over longer time periods.

The peak values for estimated evaporation and measured net radiation occurred in May (Fig. 2). This was advanced relative to the expected timing based on peak clear-sky radiation, which occurred in June (Fig. 2), and the peak air temperature, which occurred in August (Table 2). In addition, there was a significant drop in evaporation in June coinciding with a period of highest rainfall (Fig. 2).

Might the variation in net radiation and rainfall be related? There was no correlation between monthly values of rainfall ($R^2<0.01$), or between rainfall and net radiation ($R^2 < 0.02$). However there was a very significant relationship between rainfall and net radiation when the seasonal variation in clear-sky solar radiation (Fig. 2) was also taken into account. Multiple linear regression was used to investigate the following model on log-transformed radiation data:

$$ln(R_{NET}) = A + B\ Q_{RAIN} + C\ ln(R_S) \tag{8}$$

with R_{NET} as monthly average net radiation (W m^{-2}); Q_{RAIN} as the monthly depth of rainfall (cm); R_S as the monthly average clear-sky radiation (W m^{-2}) from List (1984), and A, B and C as coefficients. The coefficient for rainfall was negative and significantly different than zero ($p<0.01$), and the coefficient for clear-sky radiation was equal to 1.0, within a 95% confidence interval. Transformed back into natural units, this model represented net radiation as a proportion of clear-sky radiation multiplied by a negative exponential function of rainfall. Apparently, increased cloud cover during months with higher rainfall decreased the net flux of radiant energy available to drive evaporation.

Uncertainty

The coefficient of variation (expressed as a percentage) was used in the evaporation estimates in any given month as a measure of the overall uncertainty in the estimated monthly evaporation. This value ranged from 9% to 26%, with an average monthly uncertainty of 15%. This magnitude exceeds the uncertainty that can be explained by propagating the expected measurement errors in the data (Table 1). By the same measure, the estimated 12-month evaporation was 163 cm yr^{-1} with an uncertainty of ±9%. The magnitude of these estimates suggested that factors other than the expected accuracy of the instrumentation contributed to the overall uncertainty in estimated evaporation.

Estimated long-term variation

The results of the long-term estimate of evaporation produced a 33-year annual average of 166 cm yr^{-1} with a coefficient of variation of ±5% (Fig. 4a). Between 1970 and 2002, evaporation estimates ranged from 148 cm yr^{-1} to 181 cm yr^{-1}. We compare this to ±10% in the range of variation in a 19-yr record of photosynthetically active radiation (PAR) compiled by Fisher et al. (2003). If we assume that on longer time scales, i.e. monthly or greater, wet environment evaporation varies directly with solar radiation, then the long-term radiation reported by Fisher et al. (2003) corroborates our estimate for variability of annual evaporation from Florida Bay.

Below average evaporation occurred during two 6-year cycles starting in 1970 and again in 1990. Higher than average evaporation was estimated for the 15-year period between 1976 and 1989, and then again between 1996 and 2001. The average monthly evaporation estimated from the long-term data varied from 10 cm in November and December to 17 cm in May (Fig. 5a) and was only slightly smaller in range than the 9 to 18 cm per month obtained from the weather stations. A similar seasonal pattern in evaporation was produced from the long-term data as observed from the weather station data, with the highest values in May.

Over the same 33-year time period, rainfall measured for the NOAA Division 7 summary averaged 106 cm yr^{-1}, and ranged from 62 cm yr^{-1} to 152 cm yr^{-1} (Fig. 4b). Average monthly rainfall values ranged from 4 cm per month to 16 cm per month, with lower values occurring in the dry-season from November through April, and higher values occurring in the wet-season from May through October (Fig. 5b). A bi-modal distribution of rainfall occurred in the wet season with peaks in May and September (Fig. 5b) as was observed in the weather station data from Florida Bay (Fig. 2). There was no correlation (R^2<0.02) between the Division 7 rainfall and evaporation estimated from the 33-year data set for both the monthly and annual time scales.

DISCUSSION

The results of this study point to uncertainty in estimated evaporation as a fundamental limitation on the ability to predict how salinity in Florida Bay will respond to anticipated changes in the hydrology of the Everglades. The Everglades wetlands are located immediately upstream from the bay, and water managers are committed to reverse the hydrologic effects of efforts to drain these wetlands early in the 20th Century. The uncertainty in the estimated monthly evaporation values, about ±15%, is large relative to both the net supply of fresh water to the bay and to the current contribution of inflow from the Everglades wetlands on an annual basis as estimated by Nuttle et al. (2000). Further, it appears that this uncertainty might disguise real spatial differences in evaporation from different locations within the bay. Differences between the two monitoring locations in some factors related to evaporation, e.g. water temperature, wind speed, and net radiation were detected. However, differences between these two sites in estimated evaporation were usually smaller than the differences between the estimates by different methods at either site (Fig. 2).

The uncertainty in the annual estimate of evaporation based upon the 12-month data (±9%) was lower than the monthly estimates (up to 26%), while the estimated long-term variation in annual evaporation was ±5%. In the Everglades wetlands located just north of Florida Bay, Shoemaker and Sumner (2006) report errors in estimating evapotranspiration ranging from 9 to 27% for the long-term radiation method (Equation 6) and 11 to 37% for the

Priestly-Taylor method. Those error estimates were based upon daily values for evapotranspiration. Combining those results with this study indicates a decrease in uncertainty in the estimates of evaporation with longer time scales.

The expected error in the sensors deployed to monitor conditions at the two sites accounts for about half of the total uncertainty in estimated evaporation from Florida Bay. The remainder derives from other sources that cannot be quantified directly. These include problems in collecting the data, discussed above, and errors in the methods used to estimate evaporation from the data. For example, inherent in the vapor flux calculation (Equation 1) is the assumption that wind speed governs the intensity of turbulent mixing in the atmosphere. This assumption breaks down at low wind speeds, generally less than 4 m/s (Helfrich et al. 1982), due to the additional influence on turbulence by buoyancy-driven convection. Lower wind speeds measured at Butternut Key, particularly in the later half of the 12-month period, may have contributed to an error in estimation by the vapor flux method at this location. Variable estuarine water quality also might contribute to this uncertainty. Both salinity and films of organic material at the water surface suppress evaporation by decreasing the vapor pressure in equilibrium with the liquid phase. Salinity at seawater strength will decrease evaporation by 4% relative to evaporation from fresh water (Steinhorn 1991).

From the 1950s to 1990s, hypersalinity in the central region of Florida Bay has occurred at the end of droughts (Fourqurean and Robblee, 1999). The highest salinity values of 70 measured in Florida Bay in 1989 coincided with the second to lowest recorded rainfall of 67 cm (Fig. 4b). However, 1989 also coincided with the end of a 13-year period of above average evaporation (Fig. 4a). A high salinity value of greater than 41 was measured in Florida Bay in 2001 (Kelble et al. 2007) following a 5-year interval of above average evaporation. Rainfall in

2001 was above average at 130 cm, while the previous year of 2000 was only slightly below average at 100 cm. This leads to the question of whether periods of long-term above average evaporation (5 to 15 years) are necessary to drive hypersaline conditions, as opposed to lack of rainfall. Most likely the combined effects of above average evaporation and the timing of the rainfall play a role in hypersaline conditions in Florida Bay. For instance, a lack of freshwater input combined with restricted circulation and residence times of 6 to 12 months in the central part of the bay resulted in hypersalinity conditions during the dry season (Lee et al. 2006).

Year-to-year variation in evaporation cannot be ignored. The range in annual evaporation from Florida Bay over a recent 33-year period is 33 cm or 20%. Over the same period, the range of annual rainfall has been 90 cm, almost three times larger. Sumner and Belaineh (2005) suggest that the smaller temporal variations in evaporation can be ignored in estimating the combined effect of evaporation and rainfall on estuarine salinity for an estuary in eastern Florida. Rainfall has a significant effect on the variation in net radiation aggregated by month. Apparently, the generally higher degree of cloudiness during rainy months reduces the input of solar radiation that would be available to drive evaporation. If evaporation is suppressed during months of higher rainfall, then this mechanism multiplies the influence of rainfall variation on estuarine salinity

Salinity varies markedly across Florida Bay. Some regions like the central portions of Florida Bay exhibit hypersaline conditions most of the time because of long water residence times and the lack of surface water inflows (Lee et al., 2006). The northeastern portion of the bay, where freshwater runoff enters the system, can be either hyposaline or hypersaline. Over the period 1991-1994, for example, the range in measured salinity in extreme northeast Florida Bay was 48 psu (Frankovich and Fourqurean 1997). Tidally driven mixing with the Gulf of

Mexico also serves to ameliorate the effects of net evaporation of freshwater on salinity along the western edge of the bay. From this study, it is not obvious that spatial variability in evaporation rates contribute to the spatial variability in salinity across the bay. However, a seasonal pattern in evaporation is observed and this combined with the seasonal pattern in rainfall (Figs. 2 and 5) and runoff (Nuttle et al. 2000) most likely explains the seasonal pattern in salinity (Kelble et al. 2007).

The results of this study indicate that Florida Bay was an evaporative basin over the 33-year period of our reconstruction, with estimated evaporation exceeding measured rainfall on average by 60 cm yr^{-1} (Fig. 4). Despite these results, the long term average salinity of Florida Bay as a whole is not different from the salinity of the adjacent Gulf of Mexico. This can be explained by spatial variability in freshwater delivery to the bay and by mixing with the Gulf of Mexico. Annual estimate of freshwater runoff from the Everglades was 9 cm yr^{-1} between 1970 and 1995 (Nuttle et al. 2000). More recent estimates ranged from 10 to 25 cm yr^{-1}; from 1998 to 2004 (Kelble et al. 2007). While small in magnitude compared to the estimates of evaporation (166 cm yr^{-1}) and the measured precipitation (106 cm yr^{-1}), runoff does add to the freshwater budget. The magnitude of uncertainty and variation in evaporation as measured in this study (±9% or 15 cm) is comparable to the annual inflow of freshwater directly into the bay from the southern Everglades. Overall, the results of this study point to the need to account for variation and uncertainty in estimating all components of the water budget in estuaries.

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Table 1: Instruments, measurement errors as specified by manufacturers, and resulting uncertainty in the estimated evaporation for two methods. *Does not take into account errors in the vapor flux model at low wind speeds.

n.a.= not applicable

Variable	**Sensor**	**Measurement Error**	**Uncertainty in Estimated Evaporation**	
			Vapor Flux	**Energy Budget**
Net radiation	REBS Q7-1 net radiometer	1% for negative fluxes and up to 6% for positive fluxes at wind speeds of 7 m s^{-1}	n.a.	7%
Wind speed and direction	RM Young 5103 wind monitor	±0.3 m s^{-1}	2.5%*	n.a.
Air temperature and relative humidity	Vaisala, Inc. HMP45C temperature and relative humidity probe (shielded)	temperature: ±0.3°C over a temperature range of 0 to 40°C; relative humidity: ±2% RH (0 to 90% RH) and ±3% RH (90 to 100% RH) at 20°C	2.6% (air temperature) 4.4% (relative humidity)	0.2% (air temperature)
Water temperature	Campbell Scientific 107 temperature probe	±0.1°C over a temperature range of 24°C to 48°C	1%	0%

Table 2. Average monthly values for conditions measured at the Rabbit and Butternut sites in Florida Bay. *S.D.=standard deviation of all data 30-minute data collected throughout the year.

Parameter	**Air Temp. (°C)**	**Air Temp. (°C)**	**Water Temp. (°C)**	**Water Temp. (°C)**	**Relative Humidity (%)**	**Relative Humidity (%)**	**Wind Speed ($m\ s^{-1}$)**	**Wind Speed ($m\ s^{-1}$)**	**Net Radiation ($W\ m^{-2}$)**	**Net Radiation ($W\ m^{-2}$)**
Month	**Rabbit**	**Butternut**	**Rabbit**	**Butternut**	**Rabbit**	**Butternut**	**Rabbit**	**Butternut**	**Rabbit**	**Butternut**
Sep 2001	27.97	27.83	29.45	29.13	76.56	76.66	4.51	3.69	146	140
Oct 2001	26.05	26.21	26.38	26.30	79.83	79.11	5.88	5.61	156	116
Nov 2001	23.38	23.35	23.48	23.04	77.82	76.98	5.97	5.62	151	95
Dec 2001	22.92	22.88	23.03	22.78	79.54	78.48	5.15	5.04	102	84
Jan 2002	21.05	20.93	21.17	21.19	81.04	81.01	4.95	4.27	140	103
Feb 2002	21.12	21.62	21.94	22.46	78.19	77.59	5.18	4.98	126	113
Mar 2002	22.66	23.66	22.79	24.27	80.75	77.53	5.70	5.03	126	148
Apr 2002	25.40	25.41	26.02	26.44	71.33	70.25	5.67	5.24	154	204
May 2002	26.60	26.56	27.61	27.73	74.63	74.44	5.98	5.34	158	204
Jun. 2002	27.54	27.45	28.83	28.41	78.68	79.04	4.78	3.85	112	141
Jul 2002	28.68	28.61	30.28	29.84	74.14	75.11	3.98	3.24	151	177
Aug 2002	29.04	28.95	30.63	28.97	72.33	73.27	4.28	3.79	176	182
Average	**25.20**	**25.29**	**25.97**	**25.88**	**77.07**	**76.62**	**5.17**	**4.64**	**142**	**143**
S.D.*	**3.4**	**3.5**	**3.5**	**4.0**	**7.9**	**7.9**	**2.3**	**2.3**	**21**	**42**

LIST OF FIGURES

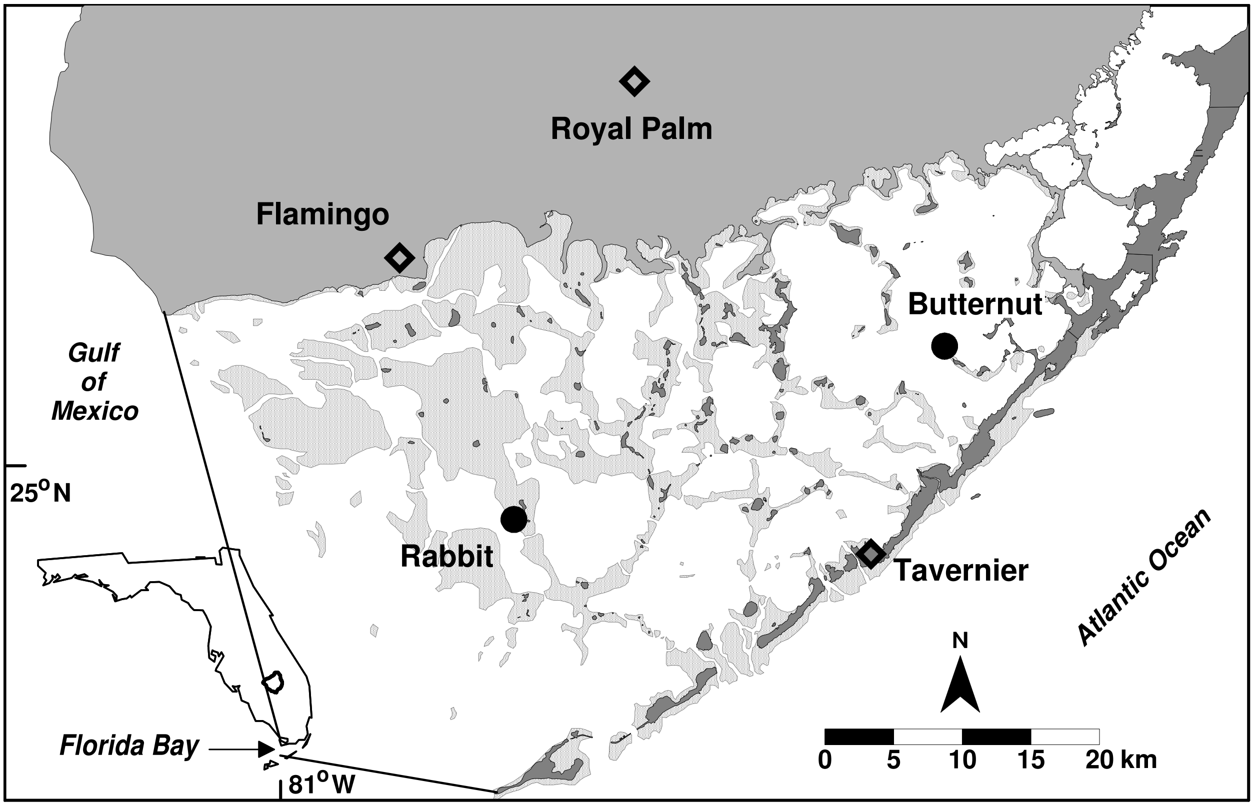
Royal Palm
Flamingo
Gulf
of
Mexico
Butternut
25° N
Rabbit
Tavernier
Atlantic Ocean
N
0 5 10 15 20 km
Florida Bay
81° W

Fig. 1

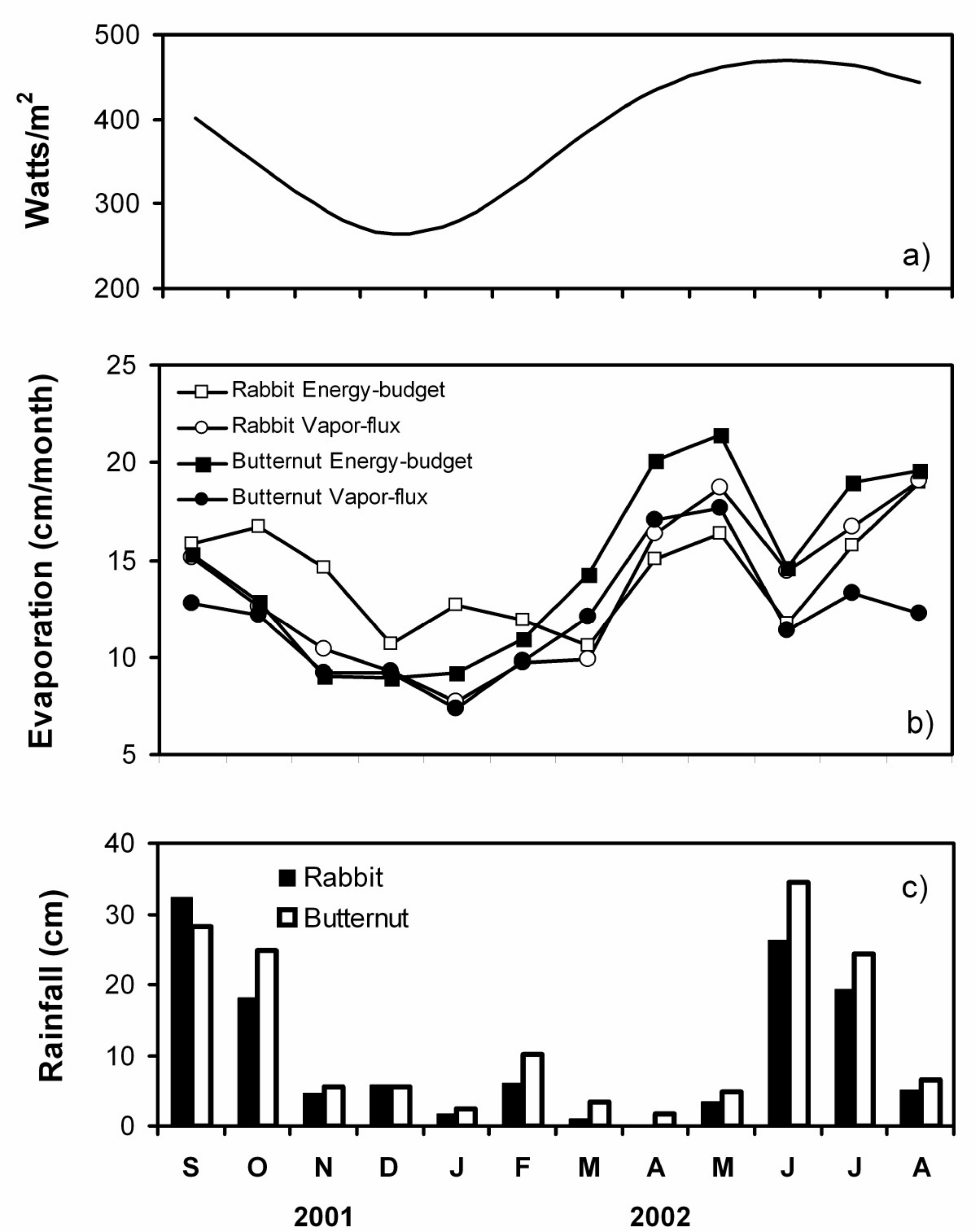
Watts/m²
500
400
300
200
a)
Evaporation (cm/month)
25
20
15
10
5
Rabbit Energy-budget
Rabbit Vapor-flux
Butternut Energy-budget
Butternut Vapor-flux
b)
Rainfall (cm)
40
30
20
10
0
Rabbit
Butternut
c)
S O N D J F M A M J J A
2001
2002

Fig. 2

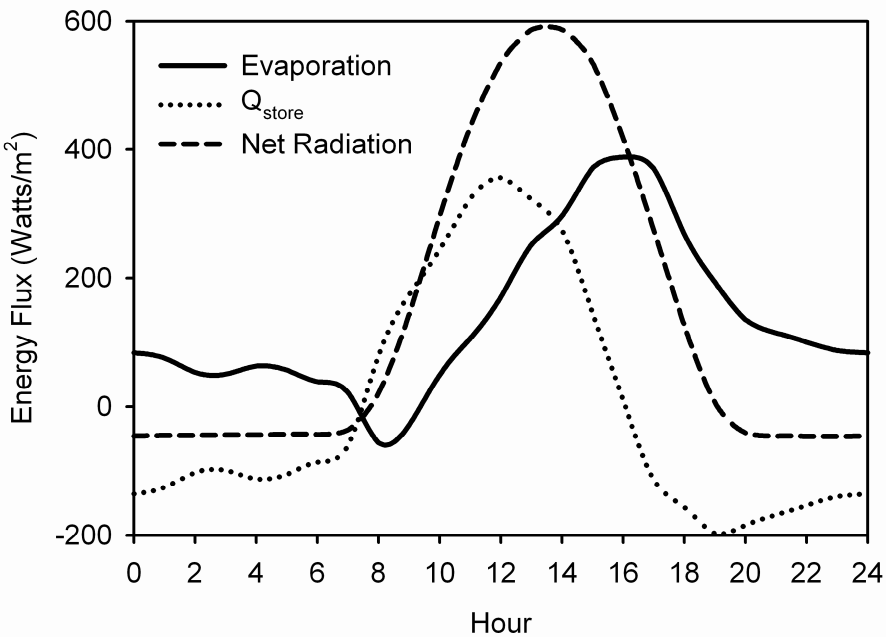
Energy Flux (Watts/m2)
600
400
200
0
-200
0 2 4 6 8 10 12 14 16 18 20 22 24
Hour
Evaporation
Qstore
Net Radiation

Fig. 3

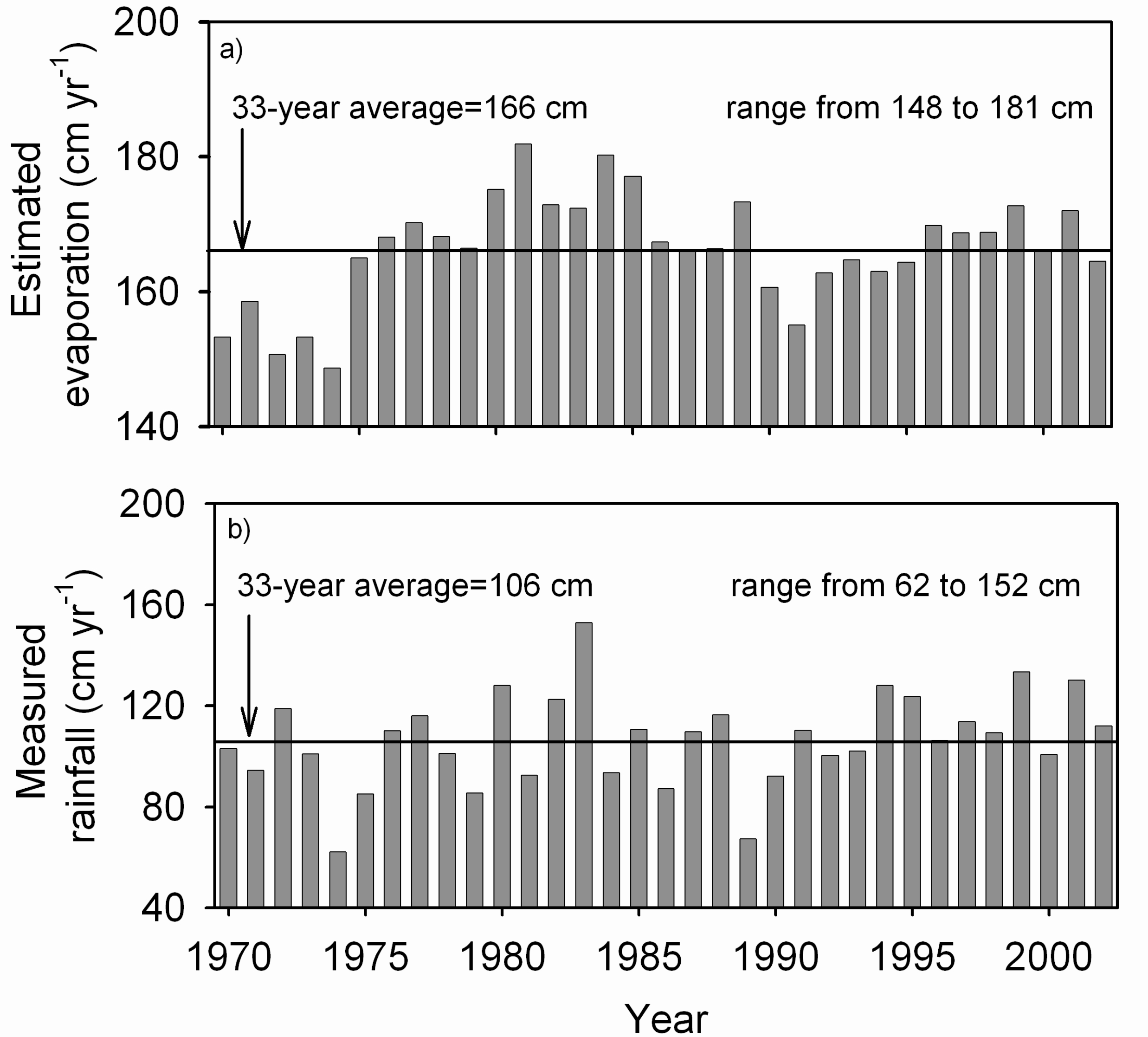
a)
33-year average=166 cm
range from 148 to 181 cm
Estimated evaporation (cm yr-1)
200
180
160
140
b)
33-year average=106 cm
range from 62 to 152 cm
Measured rainfall (cm yr-1)
200
160
120
80
40
1970
1975
1980
1985
1990
1995
2000
Year

Fig. 4

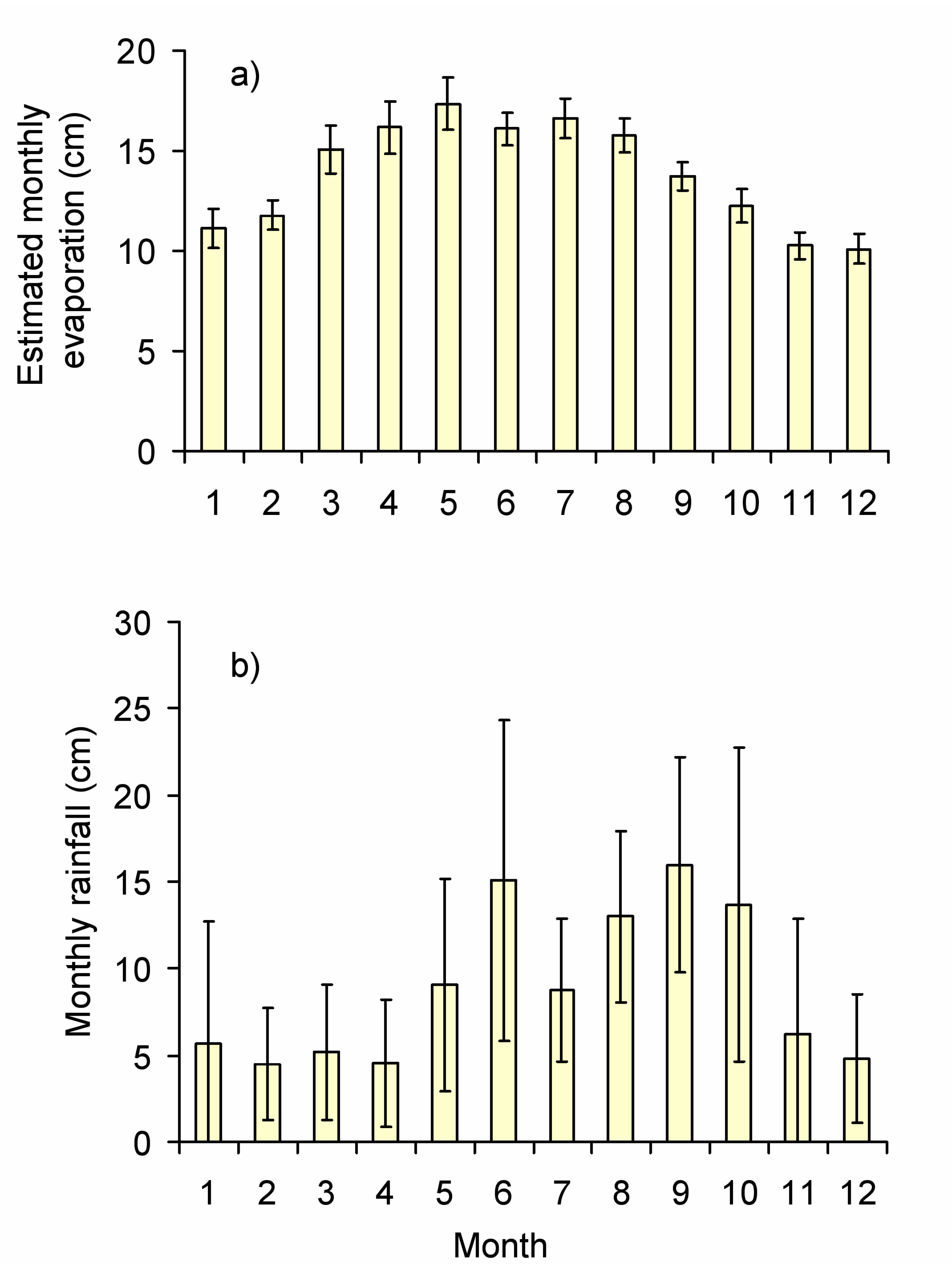
a)
Estimated monthly evaporation (cm)
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
11
12
b)
Monthly rainfall (cm)
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
11
12
Month

Fig. 5