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Pan Evaporation and Potential Evapotranspiration Trends in South Florida

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by

Wossenu Abtew, Jayantha Obeysekera and Nenad Iricanin

Restoration Sciences Department

South Florida Water Management District

3301 Gun Club Road

West Palm Beach, FL 33406

Pan evaporation and potential evapotranspiration trends in South Florida

Wossenu Abtew[1], Jayantha Obeysekera[2] and Nenad Iricanin[1]

[1]Restoration Sciences Department, South Florida Water Management District, 3301 Gun Club Road, West Palm Beach, FL 33406, U.S.A. E-mail

[2]Hydrology and Environmental Systems Modeling Department, South Florida Water Management District, 3301 Gun Club Road, West Palm Beach, FL 33406, U.S.A.

Abstract:

Literature reports of declining trends in pan and lake evaporation warrants studying the case for every region and its implications for water management. If true, the constant rates of decline reported in some literature are alarming, especially when projected with time and the possible changes in the environmental energy balance. Data from nine pan evaporation sites in South Florida were evaluated to see if there is a trend and if the quality of the data is sufficient for such analysis. The conclusion is that pan evaporation measurements are prone to too many sources of errors to be used for trend analysis. This condition is demonstrated in South Florida and in other regions by differences in magnitude and direction between spatially related pan stations and unexplainable observations. Also, potential evapotranspiration was estimated with the Penman method and the Simple method (Abtew Equation). Both cases indicated no decline in evapotranspiration for the period of analysis. Based on the decline in humidity and the increasing trend in vapor pressure deficit for the short period of analysis, 1992 to 2009, it appears that South Florida is experiencing increase in evaporation and evapotranspiration at this time assuming no systematic error in the weather stations' observations.

KEY WORDS evaporation; evapotranspiration; pan evaporation, trends in evaporation, South Florida

INTRODUCTION

Evaporation from open water surfaces and evapotranspiration (ET) from vegetated surfaces has always been challenging to measure or estimate. In recent years, evaluation of trends in pan evaporation has been introduced into climate change discussions. Results indicating both decreasing and increasing trend in pan evaporation have been published as shown in the following literature review. It appears that pan evaporation data are being used without sufficient qualification of data quality. Evaporation measurement with a pan is a crude measurement subject to many potential errors including pan environment bias, operator's bias, rainfall estimation on the pan, reading error, data recording error, etc. Experiments in South Florida showed that pan evaporation measurement error occurs due to the difference in sampling rainfall events by the rain gauge, with smaller surface area, and the pan with larger area (Gunderson, 1989).

Based on pan evaporation data (1945 to 1990) analysis from the eastern and western United States, Europe, Middle Asian and Siberian regions of the former Soviet Union, a significant decline of pan evaporation was reported (Peterson et al., 1995). The largest change reported was 97 mm increase in a warm season (May-September) for the western United States during the past 45 years and the study suggested that a feature of recent climate change includes a decrease in potential evaporation (ET_p). The decrease in pan evaporation was attributed to a decrease in the diurnal temperature range and an increase in low cloud cover. Acknowledging the decline in pan evaporation in the northern hemisphere, Roderick and Farquhar (2005) evaluated pan data in New Zealand. Their conclusion was that since 1970, pan evaporation declined at a rate of 2 mm yr^{-1} resulting in 60 mm decline in annual pan evaporation at the end of 30 years. A suggestion was made that the cause may be global warming. Six of the nineteen pans showed an increase in evaporation although not statistically significant. Six of the remaining thirteen pans showed statistically significant decline in evaporation. A later study acknowledged that retrofitting of pans with bird guards could cause a decline in pan evaporation (Gifford et al., 2007). After applying a 7 percent correction for the bird guards, the study still reported a decline of 3 mm yr^{-1} in pan evaporation. Also, the study reported that the rate of evaporation decline for lakes has been 2-4 mm yr^{-1} since the 1950s. It was also pointed out that spatial and temporal variations in pan evaporation were observed. A follow-up analysis reported the decreasing trend within the range of 1 mm to 4 mm yr^{-1}, with an average of 2 mm yr^{-1} translating to a change of -4.8 Wm^{-2} in energy terms in 30 years (Roderick et al., 2009). This decline in energy was compared to the change in energy at the top of the atmosphere due to doubled levels of carbon dioxide (~3.7 Wm^{-2}) reported by the Intergovernmental Panel on Climate Change (IPCC). Jun and Hideyuk (2004) reported that pan evaporation is in a declining trend throughout Japan for all seasons, based on 34 years of pan evaporation data from 13 sites. The cause for the few exceptional stations not following the trend was attributed to local urbanization influence. Stated factors for declining pan evaporation were increasing vapor pressure deficit and increasing terrestrial evapotranspiration.

Based on an analysis of four meteorological variables in the Yangtze Basin of China, a decreasing trend of reference evapotranspiration was reported (Xu et al., 2006). Pan evaporation for the corresponding period was also reported having a decreasing trend. Out of the four meteorological parameters analyzed, air temperature and relative humidity showed an increasing trend while wind speed and net radiation showed a declining trend. The decrease in solar radiation was suggested to be most likely from a decrease in global radiation and may also be due to pollution. The study also cites reports of decreasing mean cloud amount over China. The increase in air temperature was reported to be consistent with global warming reports. A study of India's pan evaporation and $ET_{p,}$ between 1961 and 1992, showed decreasing trends in all seasons (Chattopadhyay and Hulme, 1997). A decline of 1 mm yr^{-1} was reported for the premonsoon and monsoon seasons over the 32-year study period. The study hypothesized the cause to be increasing humidity in the lower troposphere over tropical oceans. The same study applied six General Circulation Models (GCM) to predict future climate change impacts on ET_p over India. The results from the three GCM experiments showed an increase in ET_p over most parts of India. In GCM model results analysis for Australia, Whetton et al. (1993) suggested an ET_p increase of 2-4 percent per degree of regional warming. Based on modeling of climate change impacts on Finland water resources, annual potential evapotranspiration is projected to increase by 6, 13, and 23 percent by the years 2020, 2050 and 2100, respectively (Vehviläinen and Huttunen, 1997). The basis of the projection was the linear relationship of pan evaporation and air temperature.

Analysis of trends of gross evaporation (Meyer's Formula) over Canada for a 30, 40 and 50-year period, produced varying trends of gross evaporation and pan evaporation with generally June, July, October and annual evaporation producing significant decreasing trends (Hersch and Burn, 2005). Comparison with pan evaporation revealed many similar results mostly indicating no trend for either gross or pan evaporation. A study of trends in evaporation and surface cooling in the Mississippi River basin revealed an increasing trend in evaporation, increasing trend in precipitation, a cloud-related decrease in surface net radiation, and a decrease in pan evaporation due to evaporative and radiative cooling of the land and lower atmosphere (Milly and Dunne, 2001). The increase in evaporation was attributed to an increase in precipitation. A study on the trend of reference evapotranspiration in the Northeast Arid Zone of Nigeria (1961-1991) showed a decline in annual rainfall, a 1.5 ^{o}C increase in air temperature and an increasing trend in reference evapotranspiration, although not significant (Hess, 1998). Analysis of evaporation measurements (1964-1998) in the central coastal plains of Israel showed a small but statistically significant increase in pan evaporation from screened Class A pans (Cohen et. al., 2002). Total open evaporation and reference evapotranspiration estimated with the Penman Combination equation did not show change. The study hypothesized the decrease in evaporation reported by other studies from other areas is from global dimming rather than an increase in the rate of atmospheric moisture cycling due to global warming. The study acknowledged the decrease in the radiation balance term but pointed out that it was compensated by the increase in the aerodynamic term.

Roderick et al. (2009) compiled literature review of average trends of pan evaporation from many regions (United States, Former Soviet Union, India, China, Australia, Thailand, New Zealand, Tibetan Plateau, Israel, Turkey, Canada, Kuwait, Ireland and U.K.). The study cited variation in pan size and environment. Mostly, trends showed declining evaporation ranging from -0.70 mm yr^{-1} (Thailand) to -12 mm yr^{-1} (India). Five out of 22 literature papers reviewed reported an increasing trend from 0.8 mm yr^{-1} (Ireland) to 13.6 mm yr^{-1} (Kuwait). Analysis of Australian pan evaporation data for the period 1975-2004 was reported to have a declining trend and suggested the cause could be change in wind speed (Rayner, 2007). A term "pan evaporation paradox" has been introduced to express the conflicting observation of global temperature increase and reported declining trends in pan evaporation. Rayner's attempt to correlate a decline in wind speed to evaporation pan decline did not provide consistent results. He raised the possibility that pan evaporation decline and wind speed trend changes may be due to changes in the local environment surrounding the observation stations. Szilagyi et al. (2001) acknowledged the conclusion that pan evaporation has been documented as decreasing in the last 50 years. An attributed cause was the increase in cloud cover associated with climate change. The study concludes that at the same time, over the conterminous United States, actual annual evapotranspiration has increased at a rate of 3 percent. The reason was attributed to an increase in precipitation during the same period. A study of regional evapotranspiration across the United States concluded that actual evaporation has decreasing and an increasing trend depending on the region (Hobbins et al., 2001). According to the study, most of Florida, including South Florida, has an increasing trend in actual evapotranspiration. A follow-up study of trends in pan evaporation and actual evapotranspiration across the conterminous United States showed that pan evaporation had an increasing trend in South Florida (Hobbins and Ramirez, 2004). A study on pan evaporation trends in the United States reported that pan evaporation had a decreasing trend in most regions except the southeast where the trend was increasing for the period 1948 to 1998. The study also showed that precipitation for the warm season increased for all regions except the south east ranging from 3.6 mm to 13.6 mm per decade. The southeast, including all of Florida, was reported with precipitation decline of 8.4 mm per decade (Lawrimore and Peterson, 2000).

The purpose of this study is to evaluate current trends of pan evaporation and potential evapotranspiration in South Florida along with trends of meteorological variables that control the rate of evaporation. This study will provide a starting point for prediction of the impact of climate change on evapotranspiration in South Florida

SOUTH FLORIDA CLIMATE

The temperature in South Florida increases from the north to the south. A 1955 study reported that the average annual temperature ranges from 22.22 ^{o}C in the Upper Kissimmee to 23.89^{o} C at the tip of the peninsula and 25 ^{o}C at Key West (Parker et al., 1955). Record minimum temperatures reported at the time ranged from -7 ^{o}C in the Upper Kissimmee River basin to -3.33 ^{o}C to -2.22 ^{o}C along the southern tip of the peninsula and about 4.44^{o} C along the Florida Keys. Recent observations of air temperature at weather stations (Figure 1) for five representative stations from north to south show minimum temperature of -2.8 ^{o}C to a maximum of 39 ^{o}C (Table 1). The region is humid with average humidity of 80 percent. Wind speed is relatively low with an average 2.8 m s^{-1}.

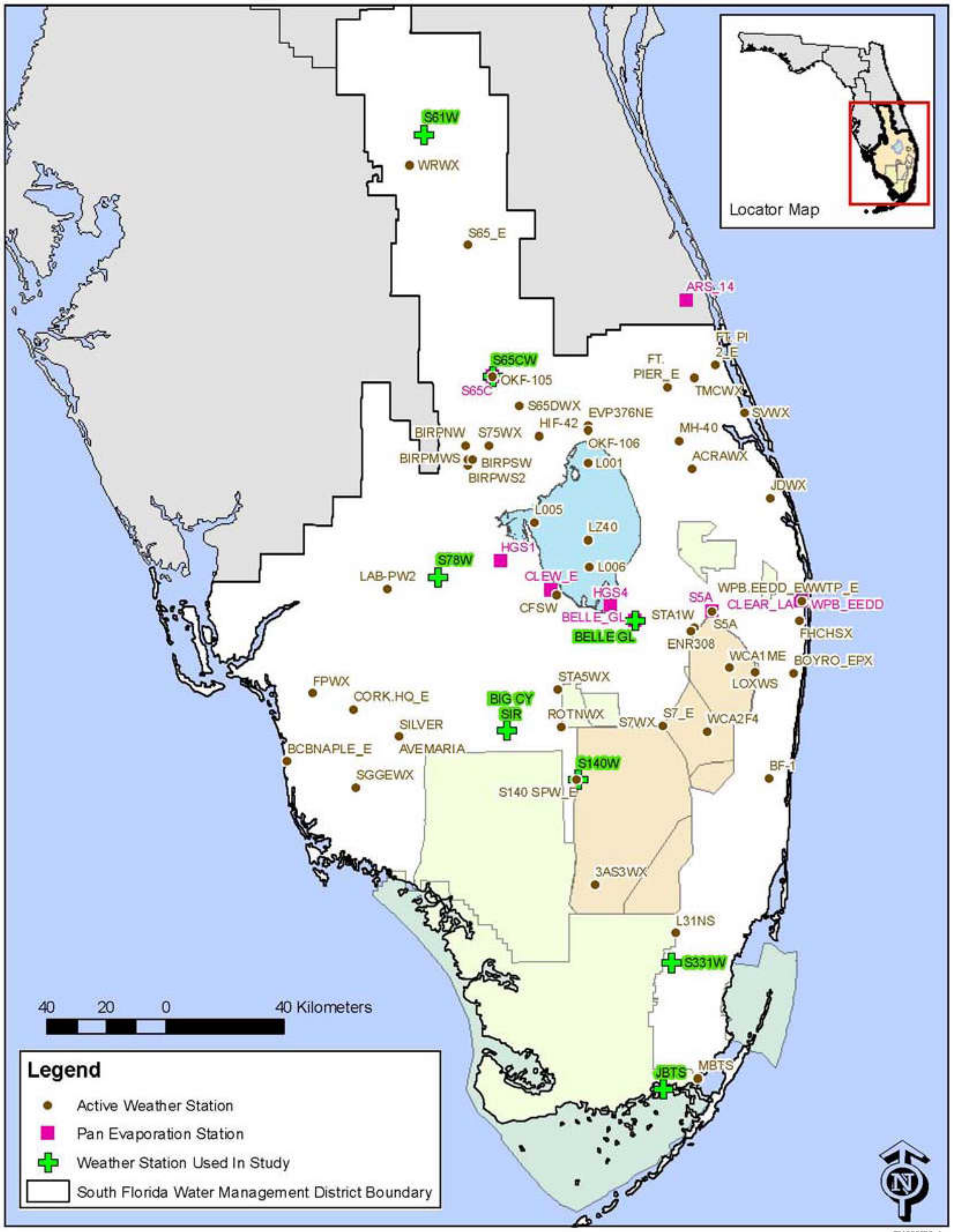

Figure 1. Weather stations and pan evaporation sites in South Florida.

Table 1. Recent air temperature records from north to south in South Florida.

Weather Station	Period of Record	Air Temperature (°C)		
		Mean	Minimum	Maximum
S61W	01/12/92-12/31/09	22.0	-1.8	37.8
S65CW	01/11/92-12/31/09	22.1	-2.6	39.0
BELLE GL	01/02/92-12/31/09	22.6	-2.8	36.7
S140W	01/11/92-12/31/09	22.8	-1.5	37.7
S331W	01/08/94-12/31/09	23.4	0.6	38.4

South Florida receives an average of 134 cm rainfall annually, spatially varying from 113 cm to 164 cm. Temporal variation of annual rainfall ranges from 74 cm to 229 cm. The wet season from June through October accounts for 66 percent of the annual rainfall. The number of rainy days and cloud cover affects rates of evaporation. Spatial average evaporation from open water bodies, evapotranspiration from wetlands, evapotranspiration from lakes and potential evapotranspiration in South Florida is estimated to be 134.5 cm yr^{-1} (Abtew et al., 2003). Monthly average model estimated average evaporation or potential evapotranspiration based on 22 weather stations (1988-2002) is shown in Figure 2a. Figure 2b depicts monthly mean difference between rainfall and evaporation. Generally, rainfall in the summer exceeds potential evapotranspiration potential evapotranspiration exceeds rainfall in winter and spring months.

The model used to estimate potential evapotranspiration is the Simple (Abtew) method, Equation 1, also cited as Abtew Equation and Simple (Abtew) Equation in published literature (Abtew, 1996; Xu and Singh, 2000; Abtew et al., 2003; Delclaux and Coudrain, 2005; Oudin et al., 2005; Shoemaker and Sumner, 2006; Melesse et al., 2009; Zhai et al., 2009):

$$ET = K_1 \frac{Rs}{\lambda} \qquad (1)$$

Where ET is daily evapotranspiration from wetland or shallow open water or potential evapotranspiration (mm d^{-1}), Rs is solar radiation (MJ m^{-2} d^{-1}), λ is latent heat of vaporization (MJ kg^{-1}), and K_1 is a dimensionless coefficient (0.53).

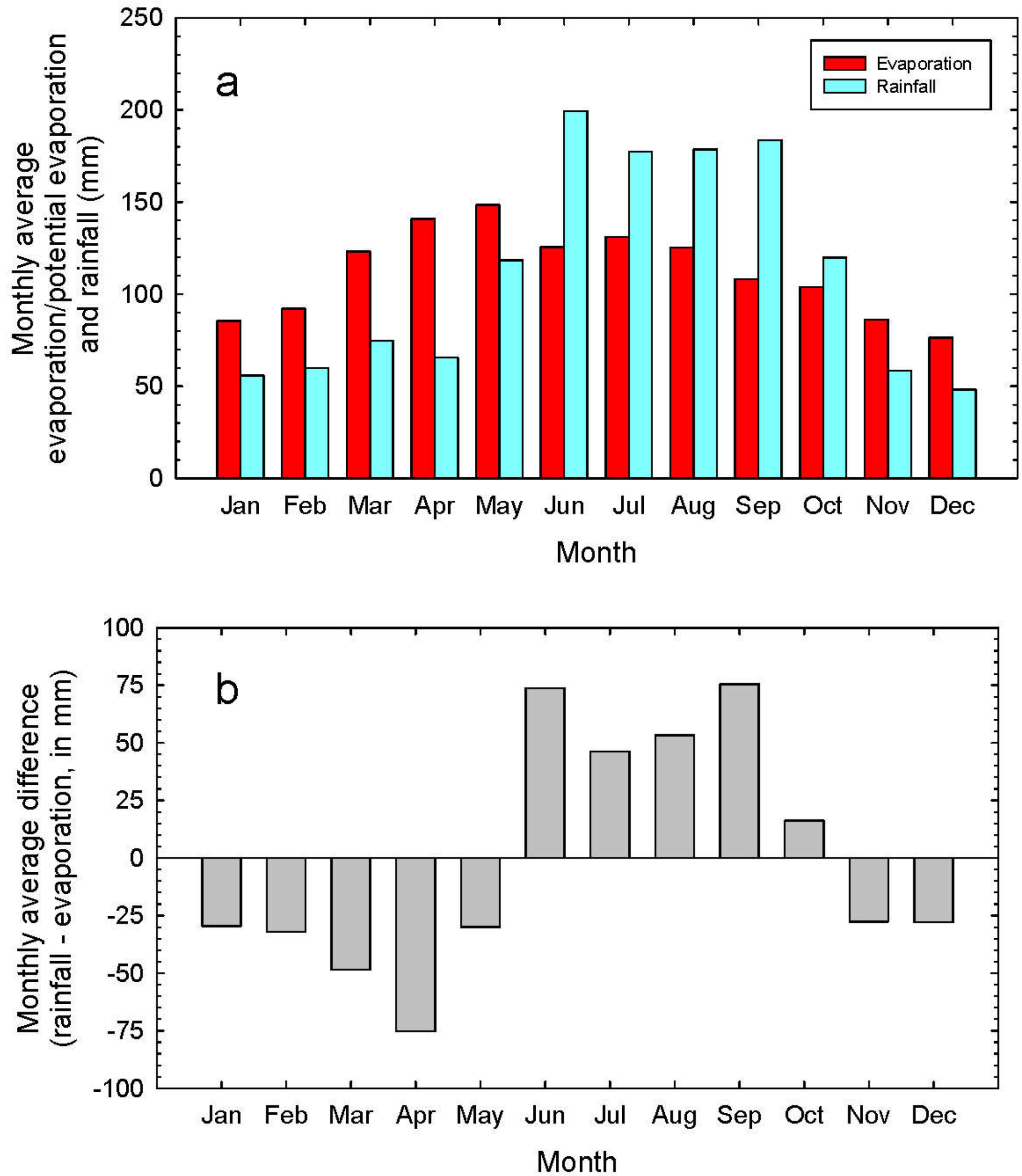

Figure 2. District wide monthly average evaporation or potential evapotranspiration and rainfall (a) and monthly differences between rainfall and evaporation (b).

Pan Evaporation

The most common and probably the oldest method of measurement or estimation of open evaporation of water is the use of the evaporation pan. Various types of pans are used in different parts of the world. A common pan is the Class A evaporation pan of the National Weather Service in the United States. The pan is 120.7 cm in diameter and 25 cm in depth. Water is added or removed to maintain water level at 5 cm from the rim. The pan is usually accompanied with a rain gauge to factor out the contribution of rainfall to the depth of water in the pan. In some cases, a partial or full-scale weather station may accompany pan evaporation stations (Figure 3b). Variations between pans include setup and the pan environment. The sunken Colorado pan is square in shape (100 cm x 100 cm), 50 cm deep, buried in the ground to a depth of 45 cm. Pan setups vary from a wooden platform at the base and bird guard (Figure 3a, http://en.wikipedia.org/wiki/Pan_evaporation) to an elevated stand (Figure 3b, Pathak, 2007). The process of acquiring evaporation estimates from a pan can be presented with a mass balance equation, Equation 2.

$$E_{pan} = D_{t-1} - D_t + R - L \pm \varepsilon \qquad (2)$$

Where D_t is current day depth of water in the pan; D_{t-1} is previous day depth of water; R is rainfall over the pan; L is other losses such as bird or animal consumption and ε is errors. Sources of error in monitoring evaporation with an open outdoor pan include environmental factors such as location, wind flow obstruction, advective heat sources or losses in the area surrounding the pan, height of pan, bird guard, rate of windblown sediment accumulation, and frequency of cleanup. Bird guard was acknowledged for lowering evaporation rates. In an Australian case a correction factor (7 percent) has been applied to correct for the effect of bird guard (Gifford et al., 2007). The accuracy of change in water level measurement through water level reading or measurement of volume of replacement water to fill the pan to previous day level, are also major sources of error. The training and discipline of pan evaporation operators probably accounts for significant variations in pan evaporation data in close locations. Measurement of rainfall contribution to the pan is another potential source of error.

In evaluating historical records of pan data, factors such as relocation of the pan (Figure 4), changes in measuring gauges and changes in operators have to be considered as factors influencing observations of evaporation. Historical pan evaporation data are usually plagued with outliers, gaps and data of questionable quality. Variations in pan evaporation data within relatively small distances indicate the challenges of acquiring consistent observations from pans. Comparison of pan evaporation data around Lake Okeechobee in South Florida resulted in pan coefficients ranging from 0.64 to 0.95 demonstrating that each pan is influenced by local environment and operations (Abtew, 2001). The wide range of pan coefficients tends to overemphasize the shortcoming of pan data (Maidment, 1993).

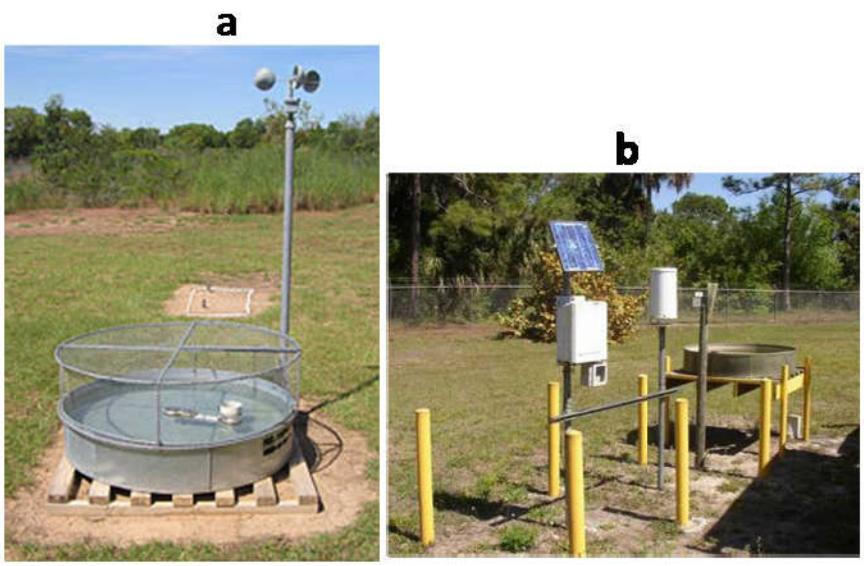

Figure 3. Evaporation pan with elevated bird guard (a) and with elevated platform (b).

Figure 4 Relocation of an evaporation pan site in South Florida.

Pan evaporation data from South Florida were analyzed to see if the data quality is sufficient to determine evaporation trends. A total of nine pan evaporation sites with varying length of record from 1916 to 2009 were used for analysis (Figure 1). Seven sites are presented independently and data were combined from two sites (HGS1 and HGS4). Sites WPB.EEDD, CLEAR LA, CLEW, HGS1 and HGS4 had monthly data and data were used for analysis for years where data were available for all 12 months. The remaining sites had daily values where in all cases maximum daily outliers were estimated to a maximum of 8.9 mm day^{-1} evaporation. Missing data less than a week were estimated mainly by interpolation. Months and years with too many missing days were excluded. In many cases where several daily data were available as a cumulative value on the last day of record, the values were redistributed equally for each day of accumulation. The mean pan annual evaporation for all sites was 156 cm. with a standard deviation of 18.5 cm. Maximum annual record was 210 cm at site CLEW (1977) and the minimum record was 119 cm at site HGS1 (1929). These ranges of records reflect the challenges of acquiring good quality pan evaporation observations rather than actual variation in the phenomenon in a sub-region. Provided water is available for evaporation and the site environment and operation is similar, the annual variation in evaporation at a site due to changes in meteorological parameters should not be as large as recorded at these sites. Probably these challenges are common at pan evaporation sites at other parts of the world. Even if there was no error in observations, the role of the microclimate and environment differences between sites could produce varying results. The distance between pan evaporation sites used in this study is shown in Table 2.

Table 2. Distances between evaporation pans (km).

Station	**Station**								
	WPB.EEDD	BELLE GL	ARS I4	S5A	S65C	CLEAR LA	CLEW	HGS1	HGS4
WPB.EEDD		56.8	108.8	30.6	129.2	0.2	85.1	102.9	64.9
BELLE GL	56.8		109.7	26.3	95.5	56.7	30.3	49.8	9.8
ARS I4	108.8	109.7		105.5	70.6	108.7	108.2	108.3	106.6
S5A	30.6	26.3	105.5		108.7	30.4	55.1	73.6	34.6
S65C	129.2	95.5	70.6	108.7		129	74.8	62.3	87.1
CLEAR LA	0.2	56.7	108.7	30.4	129		84.9	102.7	64.8
CLEW	85.1	30.3	108.2	55.1	74.8	84.9		19.7	20.8
HGS1	102.9	49.8	108.3	73.6	62.3	102.7	19.7		40.1
HGS4	64.9	9.8	106.6	34.6	87.1	64.8	20.8	40.1	

The eight set of annual pan evaporation data from the nine sites showed both decreasing and increasing trends. Sites with decreasing trends of pan evaporation are shown in Figure 5a with Figure 5b showing comparative statistics; median, mean, 25th percentile, 75th percentile, 2 standard deviations above and below the median, and outliers. Figure 5c shows sites with increasing pan evaporation trends and Figure 5d shows the comparative statistics. The differences in median, mean and spread is characteristics of a meteorological parameter that has high spatial and temporal variation. Theoretically, evaporation should not vary spatially and temporally so much as the meteorological variables such as solar radiation does not vary so much on yearly basis. Sites WPB.EEDD (1916-1928) and CLEAR LA (1965-1976) are 0.2 km apart. As shown in Table 3, the mean evaporation for WPB.EEDD was 143 cm compared to

171.5 cm for site CLEAR LA. Site CLEW has a range of 86 cm, too high for evaporation. Detail statistics is presented in Table 3 for all sites.

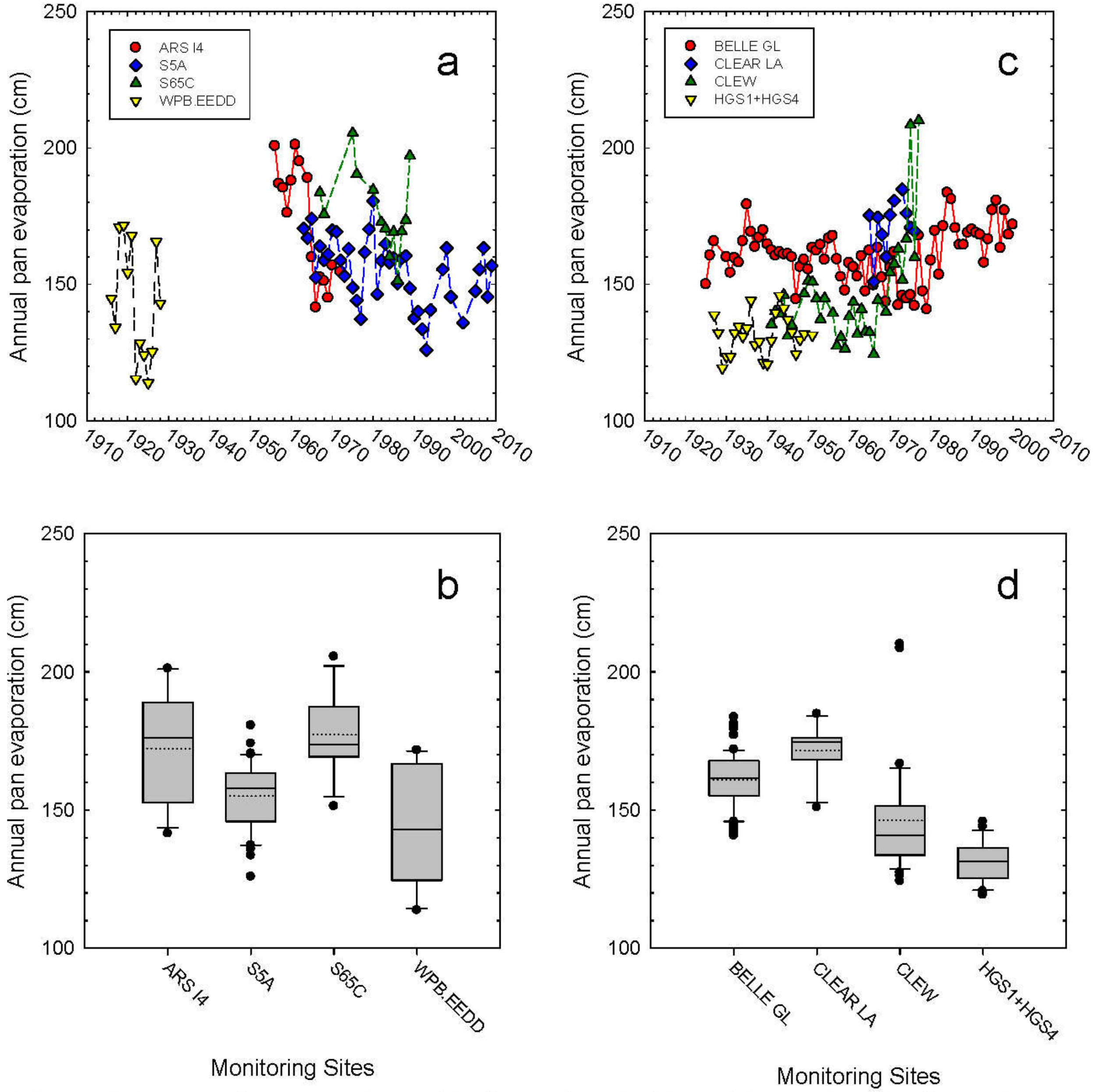

Figure 5. Evaporation pans sites with decreasing (a, b) and increasing (c, d) trends and comparative statistics (box plots). Dashed lines on the box plots indicate means and solid lines indicate medians of the pan evaporation data for each site.

Table 3. Statistics of annual pan evaporation.

Statistic	Pan Evaporation (cm)							
	ARS I4	BELLE GL	CLEAR LA	CLEW	HGS1 +HGS4	S5A	S65C	WPB.EEDD
No. of Samples	15	74	11	33	24	41	13	13
Mean	172.3	161.0	171.5	146.2	131.4	155.0	177.2	143.0
Standard Deviation	21.3	9.8	9.5	19.4	7.2	12.2	14.8	21.3
Variance	451.7	95.8	89.4	375.8	52.1	147.7	218.9	454.1
Minimum	141.5	140.8	150.9	124.3	119.3	125.9	151.4	113.8
25^{th}	153.1	155.5	168.5	134.3	126.1	146.2	169.4	124.9
Median (50^{th})	176.2	161.5	174.6	140.9	131.5	158.0	173.6	143.0
75^{th}	188.8	167.8	175.9	151.4	135.8	163.3	186.1	166.2
Maximum	201.2	183.6	184.8	210.1	145.8	180.6	205.5	171.7
Spearman's rho[1]	-0.70	0.23	0.31	0.44	0.13	-0.50	-0.39	-0.40

[1] Spearman's rho for pan evaporation vs year

Meteorology variables

Active weather stations in South Florida are shown in Figure 1; most records start in the 1990s. To minimize effort in missing data estimation and data quality evaluation, five representative weather stations located north to south were selected for meteorological data analysis. Figure 6 depict mean maximum daily (a) mean daily (c) and mean minimum daily (e) air temperature for each year for five weather stations located from north to south. Figure 6 b, d and f present comparative statistics; median, mean, 25^{th} percentile, 75^{th} percentile, 2 standard deviations above and below the median, and outliers. Figure 7 depict mean maximum daily (a) mean daily (c) and mean minimum daily (e) relative humidity for each year for five weather stations located from north to south. Figure 7 b, d and f present comparative statistics; median, mean, 25^{th} percentile, 75^{th} percentile, 2 standard deviations above and below the median, and outliers.

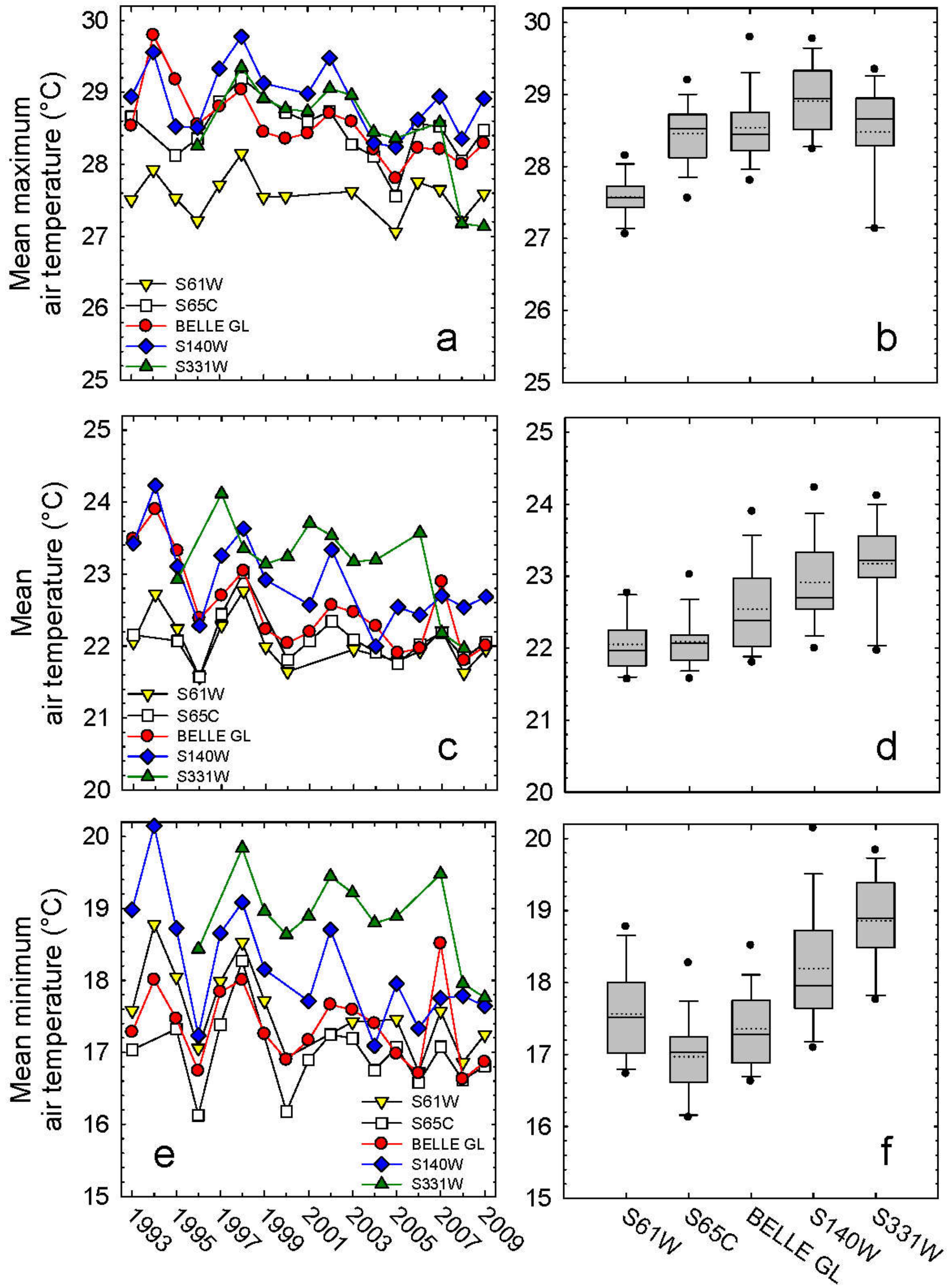

Figure 6. Mean daily maximum (a) daily mean (c) and mean daily minimum (e) air temperature at five sites. Box plots compare mean daily maximum (b) daily mean (d) and mean daily minimum (f) air temperatures between sites. Dashed lines represent the means of the data and the solid lines represent the medians of the data for each site.

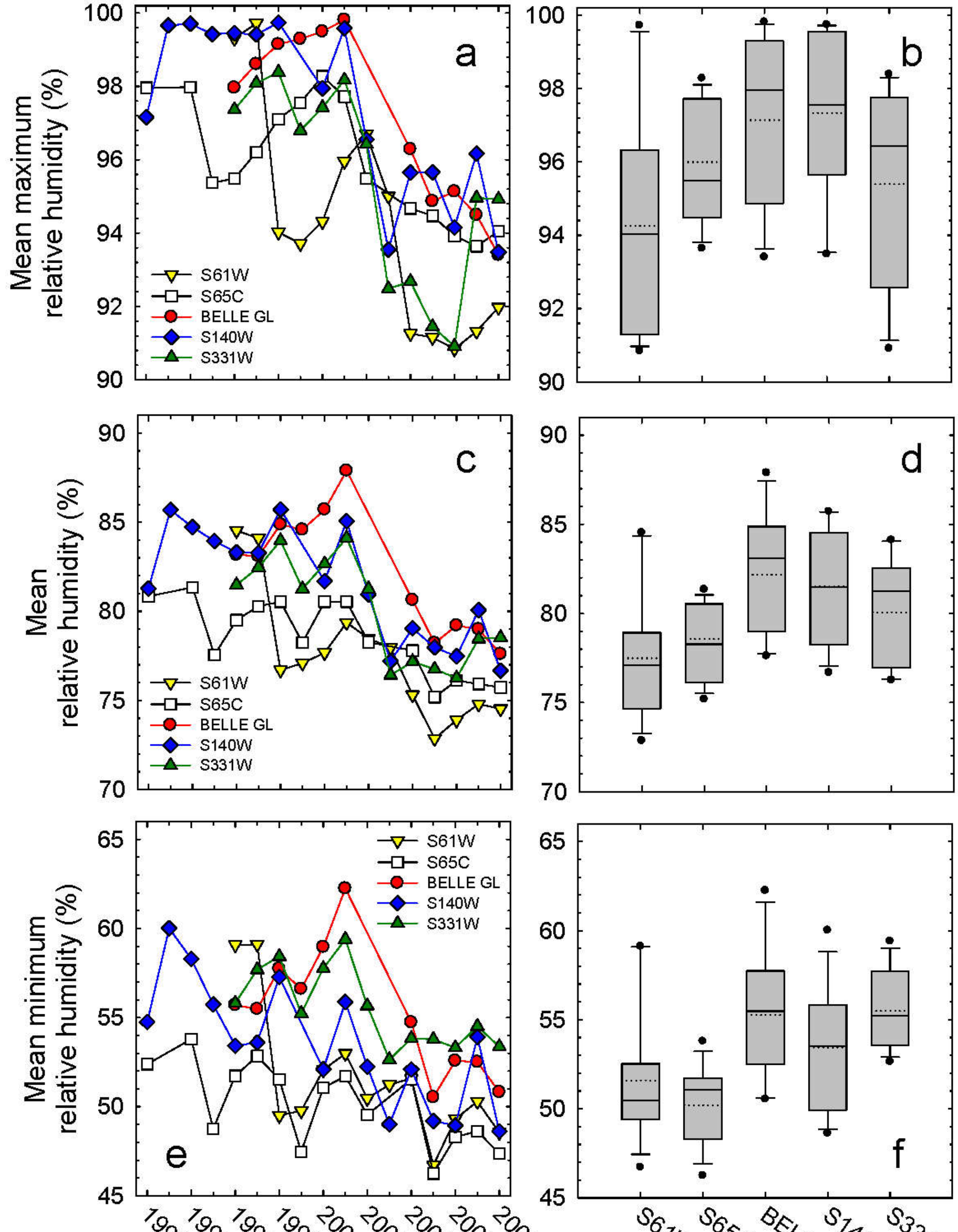

Figure 7. Mean daily maximum (a) daily mean (c) and mean daily minimum (e) relative humidity at five sites. Box plots compare mean daily maximum (b) daily mean (d) and mean daily minimum (f) relative humidity between sites. Dashed lines represent the means of the data and the solid lines represent the medians of the data for each site.

Assuming there is no systematic error in air temperature and relative humidity sensors, the short term trend of declining temperature and relative humidity is observable from the figures for the period of analysis. The declining air temperature trends are similar in pattern to what is reported by the National Climatic Data Center for Florida (http://climvis.ncdc.noaa.gov/cgi-bin/cag3/hr-display3.pl; accessed on April 21, 2010). The National Climatic Data Center reports a declining trend of -0.25 degree F per decade in annual air temperature from 1990to 2010.

Wind speed measured at 10 meter height is shown in Figure 8a and comparative statistics; median, mean, 25th percentile, 75th percentile, 2 standard deviations above and below the median, and outliers are shown in Figure 8b. Annual average wind speed varies between 2.28 m s^{-1} to 3.38 m s^{-1}. The short-term trend is significant ($p \leq 0.001$) increasing at four of the five sites. Figure 8c depicts mean vapor pressure deficit and comparative statistics; median, mean, 25th percentile, 75th percentile, 2 standard deviations above and below the median, and outliers are shown in Figure 8d. Vapor pressure deficit has significant ($p \leq 0.009$) increasing short-term trend for the period of analysis at all sites (Figure 8c). Declining relative humidity trends in Figure 7 a, c and e are reflected in the increasing trends of vapor pressure deficit. Saturation vapor pressure for the day was computed with Equation 3.

$$e_s = 0.611 \exp\left(\frac{17.27T}{T + 237.3}\right) \tag{3}$$

Where e_s is saturation vapor pressure in (kPa) and T is average air temperature (^{o}C). Mean daily vapor pressure (VPD) in kPa was computed with Equation 4.

$$VPD = e_s\left(1 - \frac{RH}{100}\right) \tag{4}$$

Where RH is daily average relative humidity in percent.

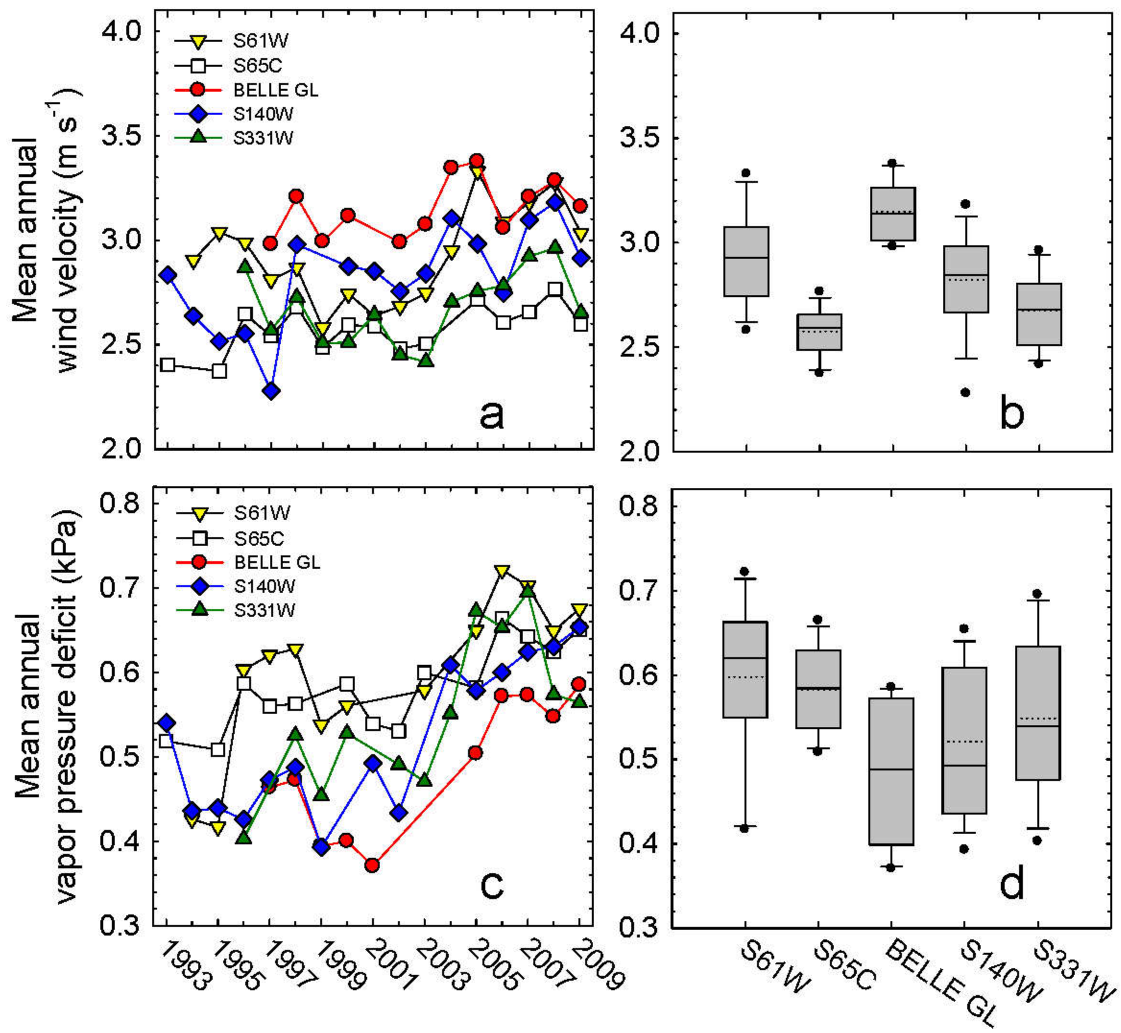

Figure 8. Mean wind speed (a) mean vapor pressure deficit (c) at five sites. Box plots compare mean wind velocity (b) and mean vapor pressure deficit (d) between sites. Dashed lines represent the means of the data and the solid lines represent the medians of the data for each site.

Although many solar radiation sites exit, most data have gaps and outliers. Figure 9 depicts annual average solar radiation from eight weather stations from 1992 to 2009. The stations are S61W, S65CW, BELL GL, S78W, BIG CY, S140W, S331W and JBTS (Figure 1). All stations may not be represented for every year as a station data was not used for a year when one or more months of data were not available. The mean solar radiation is 0.195 KW m^{-2} with a standard deviation of 0.01 KW m^{-2}. Based on Equation 1, the average annual open water evaporation, wetland evapotranspiration or potential evapotranspiration is 1,331 mm.

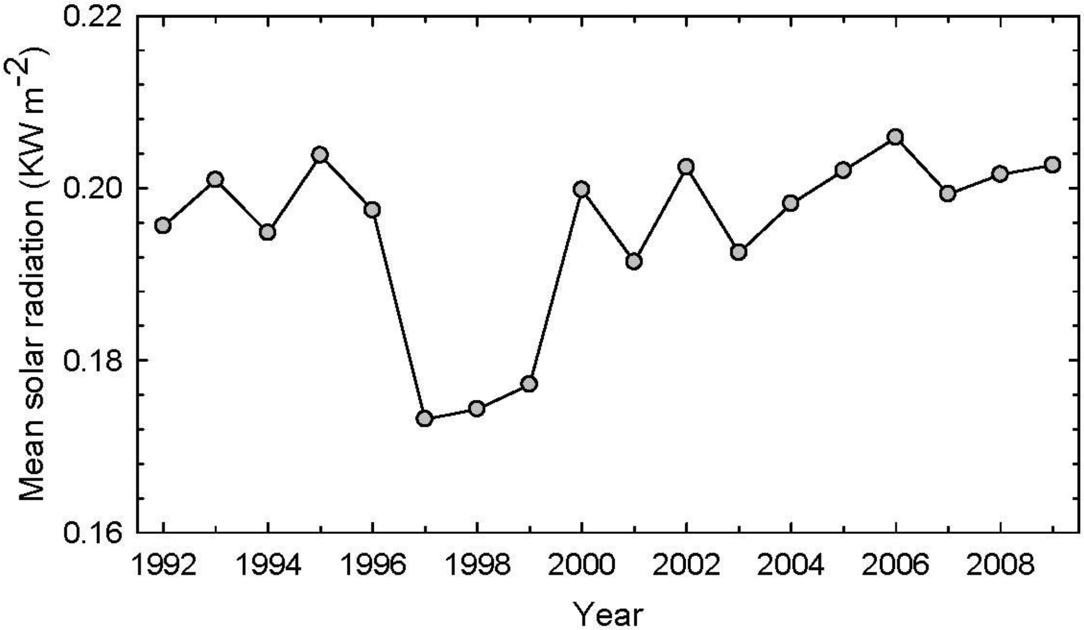

Figure 9. Annual average solar radiation from eight weather stations.

APPLICATION OF EVAPOTRANSPIRATION ESTIMATION METHODS

Penman Monteith Method

The Penman Monteith equation for computing evapotranspiration is shown in Equation 5.

$$ET = \frac{1}{\lambda}\frac{\Delta(R_n - G) + \rho c_p (e_s - e_d)\frac{1}{r_a}}{\Delta + \gamma(1 + \frac{r_c}{r_a})} \quad (5)$$

ET is evapotranspiration from vegetation (mm day^{-1}); R_n is net solar radiation (MJ m^{-2} day^{-1}); G is change in heat storage (MJ m^{-2} day^{-1}); ρ is atmospheric density (kg m^{-3}); c_p is specific heat of moist air (kJ kg^{-1} ^{o}C^{-1}); (e_s-e_d) is vapor pressure deficit (kPa); Δ is slope of vapor pressure curve (kPa ^{o}C^{-1}); γ is psychrometric constant (kPa ^{o}C^{-1}); r_a is aerodynamic resistance (s m^{-1}) and r_c is canopy resistance (s m^{-1}). Net radiation, wind speed and vapor pressure deficit are the main variables that control evaporation. Assuming no significant change in net solar radiation (R_n) and heat storage (G), the factors that influence evaporation are wind speed and vapor pressure deficit. Latent heat of vaporization (λ) in MJ kg^{-1} is defined in Equation 6 where minor change in temperature results in very little change in λ (Maidment, 1993).

$$\lambda = 2.501 - (0.00236 * T_s) \tag{6}$$

Where T_s is the surface temperature (^oC) of water or air temperature when surface is not dominated by water. Slope of vapor pressure is computed by Equation 7 (Maidment, 1993).

$$\Delta = \frac{4098 e_s}{(237.3 + T)^2} \tag{7}$$

Where e_s (kPa) is saturated vapor pressure and T is temperature (^oC). Psychometric constant is evaluated by Equation 8 (Maidment, 1993):

$$\gamma = 0.0016286 \frac{P}{\lambda} \tag{8}$$

Change in heat storage (G) in the soil is computed by Equation 9 on daily basis (FAO, 1990).

$$G = c_s d_s (T_n - T_{n-1}) \tag{9}$$

Where c_s is soil heat capacity (2100 kJ m^{-3} $^oC^{-1}$); d_s is estimated effective soil depth (0.18 m); T_n and T_{n-1} are average temperature on day n and previous day.

The Penman Monteith model was applied at S331W weather station where each parameter was computed from daily measured or derived data. Because of insufficient good quality net solar radiation data (R_n), net radiation was estimated from solar radiation (R_s) with an albedo (α) of 0.23 when observed R_n data is missing or believed to be erroneous (FAO, 1990). Canopy resistance r_c was estimated to be 100 s m^{-1} (Abtew and Obeysekera, 1995). Aerodynamic roughness was computed as presented in Abtew and Obeysekera (1995) with estimated average height of 0.5 m, fraction of cover of 50 percent. The resulting monthly evapotranspiration comparative statistics from the Penman Monteith method (Equation 5) and the Simple or Abtew method (Equation 1) is depicted in Figure 10. The statistics shows median, mean, 25th percentile, 75th percentile, 2 standard deviations above and below the median, and outliers. Figure 10 also shows the seasonal distribution of evapotranspiration in South Florida. From 1994 to 2009, there were sixteen months with missing data.

Based on the analysis of the presented data, the Penman Monteith and the Simple (Abtew) methods annual average evapotranspiration estimates are 1376 and 1315 mm, respectively. Table 4 depicts monthly mean, standard deviation and inter-quartile ranges of evapotranspiration for the Penman Monteith and the Simple (Abtew) methods. The highest evapotranspiration is in May and the lowest is in December, in both cases. The Penman Monteith method shows more variance as its application requires several parameters unlike the Simple (Abtew) method

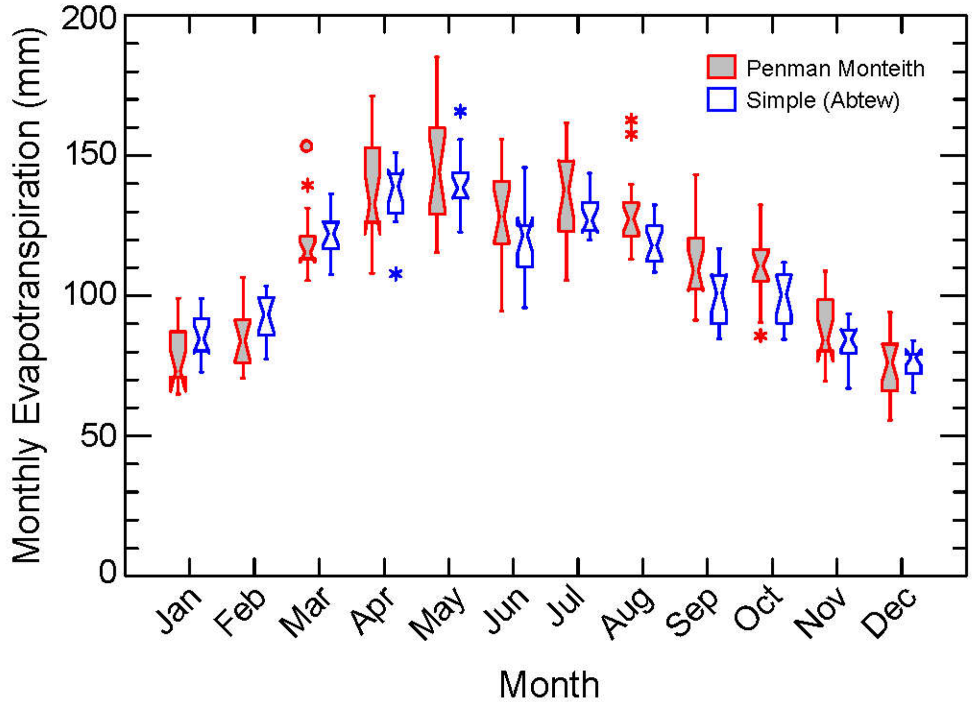

Figure 10. Notched box plots comparing the calculated evapotranspiration for the two methods over a 15-year period (1994 – 2009).

Based on the short term trends of meteorological variables, there is no reason to believe that pan evaporation or evaporation has a decreasing trend in South Florida. In the analysis of evaporation and evapotranspiration trends, the quality of the data available for analysis could influence deductions. Seasonal Kendall trend analysis on monthly evapotranspiration estimated by the Penman-Monteith and the Simple (Abtew) methods showed significant increasing trends with slopes of 0.54 ($p<0.001$) and 1.62 ($p<0.005$), respectively. Although the period of analysis (1994-2009) is short, we conclude that evaporation or evapotranspiration is not in a declining trend in South Florida.

Table 4. Monthly statistics of evapotranspiration estimates by the Penman Monteith and Simple (Abtew) methods.

Month	Penman Monteith Method			Simple (Abtew) Method		
	Mean ± SD[1]	Median	IQR[2]	Mean ± SD[1]	Median	IQR[2]
Jan	79 ± 11.4	73	17.9	86 ± 7.6	85	11.9
Feb	86 ± 11.7	84	15.4	92 ± 8.5	93	13.5
Mar	120 ± 13.7	115	11.1	122 ± 7.7	122	9.8
Apr	138 ± 18.5	133	30.1	136 ± 11.1	139	15.2
May	145 ± 19.7	144	33.1	140 ± 10.9	138	11.0
Jun	129 ± 17.0	128	22.2	118 ± 13.8	122	14.7
Jul	136 ± 15.5	138	24.8	129 ± 7.5	127	9.9
Aug	130 ± 13.8	127	11.9	119 ± 8.0	118	12.7
Sep	111 ± 14.0	109	18.1	101 ± 9.9	101	17.0
Oct	110 ± 11.4	111	11.3	99 ± 9.4	100	17.2
Nov	88 ± 12.3	84	19.7	84 ± 7.0	84	8.9
Dec	75 ± 10.9	76	16.8	76 ± 5.3	78	6.9

[1]SD = Standard deviation; [2]IQR = Interquartile Range (75th percentile - 25th percentile)

SUMMARY

The wide range of literature reports on declining trends in pan evaporation initiated this study to evaluate the case in South Florida. There are cases where similar trends are projected for lake evaporation. The consistent rates of decline reported in some papers are alarming in projecting changes in the environmental energy balance, if it holds true. Data from nine pan evaporation sites were evaluated to see if there is a consistent trend and if the quality of the data is sufficient for such analysis. The conclusion is that pan evaporation measurements are prone to too many sources of errors to be used reliably for trend analysis. This condition is demonstrated in South Florida and in other regions by pan evaporation data variation between spatially related sites. In this study, four sets of pan evaporation data showed increasing pattern while four sets of pan data showed decreasing pattern. Also potential evapotranspiration was estimated with the Penman Monteith and the Simple (Abtew) methods. Both cases indicated no decline in evapotranspiration for the period of analysis. The decline in humidity and the increasing trend in vapor pressure deficit from 1992 to 2009 appears that the region has increasing evaporation and evapotranspiration for this period. It is assumed that the weather stations used for this study did not incur systematic errors in measuring and recording meteorological parameters.

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