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# A comparison of models for estimating potential evapotranspiration for Florida land cover types

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SUMMARY

We analyzed observed daily evapotranspiration (DET) at 18 sites having measured DET and ancillary climate data and then used these data to compare the performance of three common methods for estimating potential evapotranspiration (PET): the Turc method (Tc), the Priestley–Taylor method (PT) and the Penman–Monteith method (PM). The sites were distributed throughout the State of Florida and represent a variety of land cover types: open water (3), marshland (4), grassland/pasture (4), citrus (2) and forest (5). Not surprisingly, the highest DET values occurred at the open water sites, ranging from an average of 3.3 mm d$^{-1}$ in the winter to 5.3 mm d$^{-1}$ in the spring. DET at the marsh sites was also high, ranging from 2.7 mm d$^{-1}$ in winter to 4.4 mm d$^{-1}$ in summer. The lowest DET occurred in the winter and fall seasons at the grass sites (1.3 mm d$^{-1}$ and 2.0 mm d$^{-1}$, respectively) and at the forested sites (1.8 mm d$^{-1}$ and 2.3 mm d$^{-1}$, respectively). The performance of the three methods when applied to conditions close to PET (Bowen ratio $\leqslant 1$) was used to judge relative merit. Under such PET conditions, annually aggregated Tc and PT methods perform comparably and outperform the PM method, possibly due to the sensitivity of the PM method to the limited transferability of previously determined model parameters. At a daily scale, the PT performance appears to be superior to the other two methods for estimating PET for a variety of land covers in Florida.



## Introduction

During the past few decades, many hydrologic models have been developed to simulate water flow in the subsurface, utilizing different techniques to couple the atmospheric evaporative demand with the resulting extractions of evapotranspiration from the canopy and subsurface. A commonly used approach to determine the water lost to the atmosphere is to specify the potential evapotranspiration (PET) within the model and use soil moisture, water-table depth, and/or canopy characteristics to estimate the actual evapotranspiration. Examples of such hydrologic models are MODFLOW-2000, a widely-used model for simulation of ground-water flow (Harbaugh et al., 2000) and the MIKE SHE (Danish Hydraulic Institute, 1998) and HEC-HMS (US Army Corps of Engineers, 2000) watershed models. Potential evapotranspiration (PET), rather than actual evapotranspiration (AET), is a common input for hydrologic models because it offers an upper limit to evapotranspirative water losses. PET is a function of available energy, vapor pressure gradient and vegetation type. AET, on the other hand, is subject to the aforementioned processes as well as to variations in soil type, rooting depth and available soil moisture, all of which are highly heterogeneous in both space and time. Acs (2005) found that simulation of actual transpiration was very sensitive to the consistency of soil hydrophysical data. Furthermore, hydrologic models are most often applied predictively, to evaluate the implications of hypothetical scenarios and management strategies, for which AET would be unknown. Hence for hydrologic modeling purposes, PET is a more robust input parameter than AET and the data layers necessary to estimate it are more readily available. For this reason, this paper compares three common methods for estimating PET.

In estimating PET, a clear definition of the "best" method for computation is not evident and the method choice is often subjective. Verstraeten et al. (2008) presented a comprehensive overview of the scientific literature on methods for estimating PET and stated that the selection of one method from the many is primarily dependent on the objectives of the study and the type of data available. For example, Weiß and Menzel (2008) compared the Priestley–Taylor (PT) method, two methods based on the Penman–Monteith (PM) equation and the Hargreaves method, a temperature-based method for estimating PET in a global-scale hydrologic model. Finding no AET available for validation of these methods, they reported that the PT results were closest to avail-

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able pan evaporation data. Oudin et al. (2005a) tabulated a total of 23 methods for PET estimation using a variety of micrometeorological input data. Their study compared the impact of these PET methods on four rainfall–runoff models for 308 watershed models and suggests that temperature-based PET estimates perform as well as or better than more physically-based PET methods. Vörösmarty et al. (1998) compared the performance of 11 different PET functions ranging from simple temperature-driven equations to physically-based approaches that incorporated land cover and reported similar findings. However, Oudin et al.'s study removed systematic biases by scaling using the Penman PET estimates prior to use in the rainfall–runoff models. Two approaches have been used to evaluate the utility of various PET methods: (1) relative performance of PET methods in hydrologic modeling and (2) comparisons of computed PET with empirical ET measurements. For this study, we chose the latter approach to evaluate the performance of PET models for a variety of land cover types across the state of Florida.

Experimental data have been widely used to compare the relative performance of PET methods. In the southeastern United States, several studies have compared methods. Yoder et al.'s (2005) grass lysimeter study in the humid Southeast found that the FAO-56 Penman–Monteith equation gave the best results, but that the Turc equation was a reasonable, less complex alternative. Sumner and Jacobs (2005) studied a nonirrigated pasture site in Florida, USA, and found that both Penman–Monteith and a modified Priestley–Taylor methods required seasonal calibration parameters. Jacobs et al. (2002, 2004) studied a wet prairie community in Central Florida, USA, and found that a calibrated Penman–Monteith model gave good results for PET, that the Priestley–Taylor and the Penman models overestimated PET, and that the uncalibrated, simpler Turc and Makkink methods performed nearly as well as the Penman–Monteith method. Abtew and Obeysekera (1995) and Abtew (1996) found that the Penman–Monteith method was well suited to estimate evapotranspiration from cattails (*Typha domingensis*), mixed marsh vegetation, and an open water/algae system, but that calibrated simpler radiation-based models also provided reasonable estimates. Lu et al. (2005) compared mean annual water budget-inferred ET values for 36 forested watersheds in the southeastern United States to PET computed by six methods and concluded that the three best methods were the Priestley–Taylor, Turc, and Hamon PET methods; of these, the Priestley–Taylor approach was recommended where radiation data are available.

While these site specific studies provide insight to individual landuses and climates, a challenge to conducting PET intercomparison studies for heterogeneous regions is that coincident ET measurements under "potential" conditions seldom are available across a region for representative landuses. The recent emergence of eddy covariance instrumentation has significantly expanded the breadth of evapotranspiration measurements. Temporal dynamics of water and energy fluxes are measured across seasons and years by routinely deploying one or more eddy covariance towers at numerous sites including the AmeriFlux and FLUXNET networks, which include more than 120 separate flux sites in the United States (Law et al., 2002). Additionally, a number of experiments have provided evapotranspiration measurements across heterogeneous landscapes including the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) Project, OASIS (Observations At Several Interacting Scales) (Leuning et al., 2004), and SMACEX (2002 Soil Moisture-Atmosphere Coupling Experiment; Crow et al., 2005) among others. These data sets are typically for short periods (seasonal), under non-potential conditions, and have not been analyzed using commonly available PET estimation methods.

The objective of this study was to characterize the relative strengths and weaknesses of selected PET models across a range of land covers common in the southeastern United States and to select one PET model for use in Florida. The approach was to use existing models and model parameters as determined from the literature to estimate PET and then to compare model estimates with observed daily evapotranspiration (DET) measured at 18 sites in Florida. A unique aspect of this research is that the 18 sites used in this intercomparison have continuous measurements of evapotranspiration and ancillary climate data over comparable time periods, which allowed us to assess and compare model errors across sites, across land uses and across seasons.

## Methods

### *Data collection sites*

The 18 sites used in the intercomparison study were distributed throughout the State of Florida and represent a variety of land cover types: open water (3), marshland (4), grassland/pasture (4), citrus (2) and forest (5). Fig. 1 shows the locations of these sites. For each site, Table 1 lists the location and dominant land cover, as well as, the methodology used to measure ET, the measurement period, and the data-collecting agency. Data were collected by several agencies (University of Florida (UF), US Geological Survey (USGS), and the Smithsonian Environmental Research Center (SERC)) using a variety of micrometeorological techniques. These techniques included: (1) a standard eddy covariance (EC) approach as outlined by Powell et al. (2005), (2) an energy-budget corrected eddy covariance (EBEC) approach as outlined by Sumner and Jacobs (2005), (3) an energy-budget Bowen ratio approach using exchange arm sensors (EBBR_1) as outlined by German (2000), and (4) an energy-budget Bowen ratio approach using water-to-air temperature and vapor pressure differentials (EBBR_2) as outlined by Sumner and Belaineh (2005). Evapotranspiration values derived from these techniques represented either half-hour or daily composites.

### *Observed evapotranspiration*

Net and solar radiation, temperature, humidity and wind speed observations were made at 30-min increments at all sites except the open water sites, Reedy Lake and Indian River Lagoon. At the open water sites, observations were made at a daily resolution because of the uncertainty associated with the 30-min storage term. Daily values were computed by compositing the 30-min values. When energy-budget eddy covariance (EBEC) or exchange-arm energy-budget Bowen ratio (EBBR_1) measurements were not available for a particular 30-min increment, ET was estimated using a modified Priestley–Taylor method (4). When standard eddy covariance (EC) measurements were not available, ET was estimated using a combination of linear interpolation and ET-to-net radiation relations (Falge et al., 2001). We acknowledge that the use of a modified Priestley–Taylor method for gap-filling some ET data could bias the selection of the best PET estimation model towards the PT method, however most missing values occurred during nighttime or during periods of rainfall when ET values would be low. To minimize the effect that the gap-filling model might have on our analysis, we selected only those days having ET measurements for 80% or more of the 30-min increments. These were considered "good" observations for the purpose of this study. For the water-to-air temperatures and vapor pressure differentials energy-budget Bowen ratio method (EBBR_2), the resolution of ET measurements was daily, rather than 30-min, and missing values were estimated using a mass-transfer approach. Table 2 summarizes the total number of days for which ET was measured

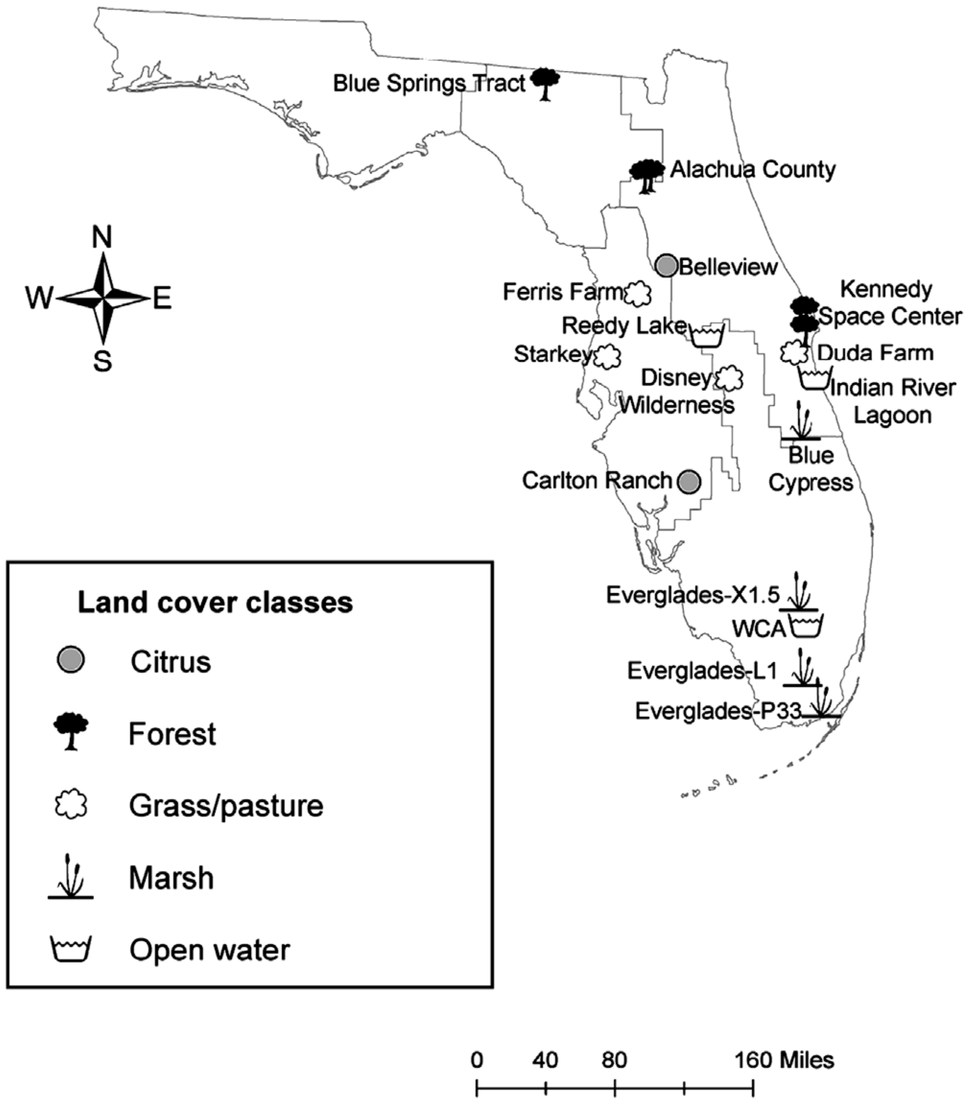


**Fig. 1.** Location and generalized land cover type for the 18 data collection sites throughout Florida.

**Table 1**
Land cover, data source, experimental methodology, location, and period of record for each study site.

| Site | Land cover | Data source | Method[a] | Longitude (decimal degrees) | Latitude (decimal degrees) | Time period |
|---|---|---|---|---|---|---|
| Alachua (Donaldson) | Forest (immature pine) | UF | EBEC | −82.1633 | 29.7548 | January 1999–June 2003 |
| Alachua (Austin Cary) | Forest (mature pine) | UF | EC | −82.2188 | 29.7381 | July 2000–June 2002 |
| Kennedy Space Center | Forest (scrub oak) | SERC | EC | −80.6715 | 28.6086 | March 2000–March 2003 |
| Kennedy Space Center | Forest (slash pine) | SERC | EC | −80.6709 | 28.4583 | March 2002–February 2003 |
| Blue springs tract | Forest (pine) | USGS | EBEC | −83.1969 | 30.5067 | January 2003–December 2004 |
| Belleview | Citrus | UF | EBEC | −82.0000 | 29.0000 | July 2004–July 2005 |
| Carlton ranch | Citrus | USGS | EBEC | −81.7731 | 27.1783 | May 2004–May 2005 |
| Disney wilderness | Grass | USGS | EBEC | −81.4002 | 28.0488 | July 2000–January 2006 |
| Duda farm | Grass | USGS | EBEC | −80.776 | 28.274 | Jun 2000–May 2005 |
| Ferris farm | Grass | USGS | EBEC | −82.2762 | 28.7613 | January 2003–February 2005 |
| Starkey | Grass | USGS | EBEC | −81.6132 | 28.4161 | April 2003–December 2004 |
| Blue cypress | Marsh | USGS | EBEC | −80.7114 | 27.6953 | January 2001–April 2005 |
| Everglades L1 | Marsh (25% cover) | USGS | EBBR_1 | −80.7022 | 25.6164 | November 2000–October 2003 |
| Everglades P33 | Marsh (95% cover) | USGS | EBBR_1 | −80.5294 | 25.3597 | January 1996–October 2003 |
| Everglades X1.5 | Marsh (85% cover) | USGS | EBBR_1 | −80.7381 | 26.2583 | January 2002–October 2003 |
| Indian River Lagoon | Open water | USGS | EBBR_2 | −80.5761 | 28.0561 | January 2002–January 2004 |
| Reedy Lake | Open water | USGS | EBBR_2 | −82.5592 | 28.2253 | December 2001–October 2005 |
| WCA | Open water | USGS | EBBR_2 | −80.6695 | 25.9736 | August 2002–July 2005 |

[a] EC denotes a standard eddy covariance method. EBEC denotes an energy-budget corrected eddy covariance approach as outlined by Sumner and Jacobs (2005). EBBR_1 denotes an energy-budget Bowen ratio approach using exchange arm sensors as outlined by German (2000). EBBR_2 denotes an energy-budget Bowen ratio approach using water-to-air temperature and vapor pressure differentials as outlined by Sumner and Belaineh (2005).

**Table 2**
Number of days of daily actual ET observations, the number "good" observations and the number of days in which the Bowen ratio ($\beta$) was less than or equal to 1.

| Site | Land cover | Number of observations | | |
|---|---|---|---|---|
| | | Daily | Good | $\beta \leqslant 1$ |
| Alachua (Austin Cary) | Forest (mature pine) | 723 | 606 | 320 |
| Alachua (Donaldson) | Forest (immature pine) | 2373 | 1110 | 931 |
| Kennedy Space Center | Forest (oak) | 1474 | 1189 | 765 |
| Kennedy Space Center | Forest (pine) | 358 | 302 | 272 |
| Blue springs Tract[a] | Forest (pine) | 731 | 676 | 0 |
| Belleview | Citrus | 365 | 365 | 294 |
| Carlton ranch | Citrus | 380 | 211 | 171 |
| Disney wilderness | Grass | 2004 | 559 | 371 |
| Duda farm | Grass | 1684 | 967 | 826 |
| Ferris farm | Grass | 790 | 202 | 81 |
| Starkey | Grass | 630 | 310 | 188 |
| Blue cypress | Marsh | 2071 | 1001 | 982 |
| Everglades L1 | Marsh (25% cover) | 1058 | 621 | 613 |
| Everglades P33 | Marsh (95% cover) | 2800 | 1007 | 996 |
| Everglades X1.5 | Marsh (85% cover) | 555 | 167 | 157 |
| Indian River | Open water | 746 | 680 | 674 |
| Reedy Lake | Open water | 1416 | 1264 | 1264 |
| WCA | Open water | 1089 | 341 | 341 |

[a] Because none of the data at this site had $\beta < 1$, all "good" data were analyzed.

and the number of days considered to be good. It was necessary to relax this criterion for some of the sites (i.e., the Everglades and Disney Wilderness sites) where ideal measuring conditions were difficult to maintain. For instance, at the Disney Wilderness site, more than 30% of the 30-min measurements were gap-filled due to wind direction with inadequate fetch, excessive misalignment of sonic anemometer, or obscured hygrometer windows. The remote location of the Everglades sites made instrument maintenance difficult (Ed German, US Geological Survey, written communication, April 2006). Also presented in Table 2 are the number of days for which the Bowen ratio ($\beta$ = daily average sensible heat ($H$) divided by daily average latent heat (LE)) was less than unity, signifying days in which energy was primarily partitioned to LE (and hence, ET), rather than to $H$. We used this threshold as an indicator of potential evapotranspiration conditions; this is discussed in greater detail in "Characterization of potential evapotranspiration conditions".

### *Potential evapotranspiration models*

Potential evapotranspiration (PET) models generally rely on micrometeorologic data such as air temperature, radiation, wind speed and humidity. Of the great variety of PET models, three equations were chosen for evaluation in this study: the Penman–Monteith (PM) method (Penman, 1948; Monteith, 1965), the Priestley–Taylor (PT) method (Priestley and Taylor, 1972), and the Turc (Tc) method (Turc, 1961). These three equations span the spectrum in data requirements from the complex PM method (requiring net radiation, soil/canopy heat flux, air temperature, humidity, and aerodynamic and surface resistance) to the less data-intensive PT method (requiring net radiation, soil/canopy heat flux, and air temperature) to the simple Tc method (requiring air temperature and solar radiation). Generally, the more complicated and physically-based PET methods give the best results, but at the expense of greater data and model parameter requirements.

The Tc radiation method, developed in western Europe for regions where the relative humidity is greater than 50%, expresses PET as

$$\lambda\rho_w \mathrm{ET}_o = 0.369\frac{T_{avg}}{T_{avg}+15}(2.06R_s + 50) \tag{1}$$

where $\mathrm{ET_o}$ is the potential evapotranspiration (mm day$^{-1}$), $\lambda$ the latent heat of vaporization (here held constant at 2.451 MJ kg$^{-1}$), $\rho_w$ the density of water (kg m$^{-3}$), $R_s$ the daily solar radiation (W m$^{-2}$), and $T_{avg}$ the mean daily air temperature (°C).

The PT method uses the concept of the theoretical lower limit of evaporation from a wet surface as the "equilibrium" evaporation to estimate PET where

$$\lambda\rho_w \mathrm{ET}_o = \alpha\frac{\Delta}{\Delta+\gamma}(R_n - G) \tag{2}$$

where $\Delta$ is the slope of the saturation vapor pressure temperature curve, $\gamma$ is the psychrometric constant, $R_n$ is the net radiation (W m$^{-2}$), and $G$ is the soil/canopy heat flux (W m$^{-2}$). Priestley and Taylor (1972) showed that for conditions of minimum advection with no edge effects, $\alpha$ = 1.26. Here $G$ is assumed to equal zero over the course of a day. The parameters $\Delta$ (in kPa °C), $\lambda$ (MJ kg$^{-1}$) and $\gamma$ (in kPa °C) were computed as

$$\Delta = \frac{4098e_s}{(237.3+T_{\min})^2} \tag{3}$$

$$\lambda = 2.501 - 0.0002631 \cdot T_{avg} \tag{4}$$

$$\gamma = \frac{c_p P}{\varepsilon\lambda}\times 10^{-3} = 0.0016286\frac{P}{\lambda} \tag{5}$$

where $e_s$ is the saturated vapor pressure (in kPa), $c_p$ is the specific heat of moist air (=1.013 kJ kg$^{-1}$ °C$^{-1}$), P is atmospheric pressure (set equal to 101.3 kPa) and $T_{\min}$ is the minimum daily temperature (in °C), respectively. Saturated vapor pressure was computed as

$$e_s = 0.6108\exp\left(\frac{17.27T_{\min}}{237.3+T_{\min}}\right) \tag{6}$$

The Penman–Monteith model is an extension of the Penman equation for application to vegetated surfaces through the introduction of plant specific resistance factors and is given as

$$\lambda\rho_w \mathrm{ET}_o = \frac{\Delta(R_n - G) + \rho_a c_p D/r_a}{\Delta + \gamma(1 + r_s/r_a)} \tag{7}$$

where $D$ is the vapor pressure deficit of the air (in kPa), $\rho_a$ is the mean air density (kg m$^{-3}$), $r_s$ the bulk surface resistance (s m$^{-1}$), and $r_a$ the aerodynamic resistance (s m$^{-1}$). The mean air density, $\rho_a$, was computed using

$$\rho_a = 3.486\frac{P}{275+T_{avg}} \tag{8}$$

where $P$ was set equal to a constant value of 101.3 kPa and $T_{avg}$ was the average daily temperature (in °C). The vapor pressure deficit, D, was computed as $e_s - e$, where $e$ is the observed daily vapor pressure. The aerodynamic resistance was computed using Monin–Obukhov similarity

$$r_a = \frac{\ln[(z_u - d)/z_{om}]\ln[(z_e - d)/z_{ov}]}{k^2 u} \quad (9)$$

where $u$ is the wind speed (in m s$^{-1}$) and $z_u$ is the height at which the wind speed was measured, $z_e$ is the height of the vapor pressure/relative humidity instrument, $d$ is the displacement height (approximated as $0.67h_c$, where $h_c$ is the average vegetation height), $z_{om}$ is the roughness height for momentum, $z_{ov}$ is the roughness height for water vapor (approximated as $0.1z_{om}$) and $k$ is von Karman's constant (0.41). We used literature values for $z_{om}$, because using a relationship between $z_{om}$ and canopy height is not appropriate for all land cover types. Height of wind measurement ($z_u$), height of vapor pressure/relative humidity measurement ($z_e$) and average canopy height ($h_c$) were obtained from the metadata for each site or from the personnel responsible for collecting the data. The terms $z_u$ and $z_e$ were assumed to be equal unless otherwise noted.

For open water sites, the PM (Eq. (7)) aerodynamic term was estimated following Shuttleworth (1993):

$$\text{Open water aerodynamic term (in mm d}^{-1}) = \frac{\gamma}{\Delta + \gamma}\frac{6.43(1 + 0.536u)D}{\lambda} \quad (10)$$

which incorporates the $r_a$ formulation for open water as

$$r_a = \frac{4.72[\ln(z_m/z_o)]^2}{1 + 0.536u} \quad (11)$$

where $z_m$ is a standardized measurement height of 2 m and $z_o$ = 0.00137 m.

The PM parameters used in this analysis are presented in Table 3. Also included in Table 3, for comparison purposes, are "at-site" $r_s$ values made available for the Alachua County and Kennedy Space Center forested sites. A range of $r_s$ estimates for wetlands and for pine forest sites were available from published studies in Florida (Abtew, 1996; Abtew et al., 1995; Jacobs et al., 2002; Powell et al., 2005). Breuer et al.'s (2003) extensive compilation of published vegetation parameters was used to estimate surface resistance. For grass/pasture sites, we computed $r_s$ using the functions developed by Sumner and Jacobs (2005):

$$g_s = f(D)g_{\max}(R_n) \quad (12)$$

$$f(D) = -0.166\ln(D) + 0.235 \quad (13)$$

$$g_{\max} = 5.39 \times 10^{-5}R_n + 0.0033 \quad (14)$$

where $g_s$ is bulk surface conductance (in m s$^{-1}$), $D$ is vapor pressure deficit (in kPa) and $g_{\max}$ is the maximum bulk surface conductance. Bulk surface resistance for grass ($r_s$, in s m$^{-1}$) is the reciprocal of $g_s$. Average bulk surface resistance for the grass/pasture sites, calculated for each site, ranged from 284 to 319 s m$^{-1}$ (see Table 3), which is consistent with published values. The published value of $r_s$ for marsh/wetland vegetation is 55 s m$^{-1}$ and $r_s$ for open water is zero. For marsh and wetland sites, $r_s$ was computed as a weighted average based on the proportion of vegetated area and open water area.

### *Model error estimation*

Model estimated ET values were compared to the observed values using standard statistics and regression analysis. Mean absolute error (MAE) and root mean squared error (RMSE) were computed as

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}|ET_{\text{mod},i} - ET_{obs,i}| \quad (15)$$

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(ET_{\text{mod},i} - ET_{obs,i})^2} \quad (16)$$

**Table 3**
Penman–Monteith parameters used for each site.

| Site | Land cover | Bulk canopy resistance (s m$^{-1}$) | Humidity height (m) | Wind height (m) | Canopy height (m) |
|---|---|---|---|---|---|
| Alachua (Donaldson)[a] | Forest (immature pine)[b] | 500 | 15 | 15 | 10 |
| | At-site | 274 | – | – | – |
| Alachua (Austin Cary)[a] | Forest (mature pine) | 500 | 32 | 32 | 22 |
| | At-site | 245 | – | – | – |
| Kennedy Space Center[c] | Forest (oak) | 322 | 3.5 | 3.5 | 1.5 |
| | At-site | 157 | – | – | – |
| Kennedy Space Center[c] | Forest (pine) | 500 | 18 | 18 | 13 |
| | At-site | 105 | – | – | – |
| Blue springs Tract[d] | Forest (pine) | 500 | 8.5 | 8.5 | 6 |
| Belleview | Citrus | 500 | 6.65 | 7.28 | 5.5 |
| Carlton ranch[a] | Citrus | 500 | 6.4 | 6.4 | 5 |
| Disney wilderness | Grass | 288 | 1.2 | 3.6 | 0.4 |
| Duda farm | Grass | 284 | 1.1 | 2.7 | 0.1 |
| Ferris farm[e] | Grass | 319 | 1.9 | 3.3 | 0.1 |
| Starkey[f] | Grass | 299 | 1.4 | 2.2 | 0.35 |
| Blue cypress | Marsh | 55 | 2 | 3 | 2.1 |
| Everglades L1[g] | Marsh (25% cover) | 14 | 2.13 | 2.13 | 0.8 |
| Everglades P33[g] | Marsh (95% cover) | 52 | 2.35 | 2.35 | 1.7 |
| Everglades X1.5[d] | Marsh (85% cover) | 47 | 2.74 | 2.74 | 1.5 |
| Indian River[h] | Open water | 0 | 4.6 | 4.6 | – |
| Reedy Lake[a] | Open water | 0 | 1.9 | 1.9 | – |
| WCA | Open water | 0 | 3.2 | 3.7 | 0 |

[a] Used wind speed measurement height for $Z_u$ and $Z_e$.
[b] Canopy height varied from 9.1 to 11 m due to growth of immature pine stand.
[c] Parameters based on communication from Tom Powell, Kennedy Space Center.
[d] Parameters based on communication from Trey Grubbs, USGS.
[e] Average height of grass 8–12 cm, per Sumner and Jacobs, 2005.
[f] Max height is 0.5 m, mowed to 0.2 m twice a year. Used average height.
[g] Parameters based on communication from Ed German, USGS.
[h] Anemometer height above water varied. Used average height for $Z_u$ and $Z_e$.

**Table 4a**
Average seasonal net radiation, Bowen ratio and evapotranspiration by site and by land cover type.

| | Net radiation (W m$^{-2}$) | | | | Bowen ratio | | | | Observed daily ET (mm d$^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Win | Spr | Sum | Fall | Win | Spr | Sum | Fall | Win | Spr | Sum | Fall |
| *Forest* | | | | | | | | | | | | |
| Alachua (imm pine) | 72 | 156 | 142 | 73 | 0.5 | 1.1 | 0.4 | 0.2 | 1.3 | 1.9 | 2.9 | 2.0 |
| Alachua (mature pine) | 102 | 175 | 172 | 106 | 1.2 | 1.4 | 0.9 | 0.9 | 2.7 | 4.2 | 3.6 | 2.6 |
| KSC[a] (slash pine) | 92 | 169 | 157 | 107 | 0.4 | 0.3 | 0.4 | 0.4 | 1.5 | 2.5 | 3.1 | 2.6 |
| KSC[a] (scrub oak) | 95 | 167 | 151 | 95 | 0.9 | 0.8 | 0.4 | 0.0 | 1.6 | 2.6 | 3.1 | 2.0 |
| Average | **90** | **167** | **155** | **95** | **0.7** | **0.9** | **0.5** | **0.4** | **1.8** | **2.8** | **3.2** | **2.3** |
| *Citrus* | | | | | | | | | | | | |
| Belleview | 72 | 139 | 127 | 83 | 1.3 | 0.6 | 0.2 | 0.4 | 1.4 | 3.8 | 4.1 | 2.7 |
| Carlton Ranch | 111 | 178 | 179 | 120 | 1.1 | 0.7 | 0.3 | 0.6 | 1.9 | 3.8 | 4.8 | 2.8 |
| Average | **91** | **158** | **153** | **101** | **1.2** | **0.7** | **0.2** | **0.5** | **1.7** | **3.8** | **4.4** | **2.8** |
| *Grass* | | | | | | | | | | | | |
| Disney wilderness | 85 | 159 | 152 | 93 | 1.3 | 0.9 | 0.4 | 0.7 | 1.4 | 3.0 | 4.1 | 2.3 |
| Duda farm | 83 | 151 | 143 | 90 | 0.8 | 0.7 | 0.4 | 0.4 | 1.8 | 3.4 | 4.3 | 2.6 |
| Ferris farm | 68 | 135 | 131 | 81 | 2.4 | 0.9 | 0.7 | 1.4 | 0.8 | 2.5 | 2.9 | 1.3 |
| Starkey | 93 | 168 | 154 | 93 | 2.3 | 0.8 | 0.4 | 1.2 | 1.1 | 3.2 | 3.6 | 1.9 |
| Average | **82** | **153** | **145** | **89** | **1.7** | **0.8** | **0.5** | **0.9** | **1.3** | **3.0** | **3.7** | **2.0** |
| *Marsh* | | | | | | | | | | | | |
| Blue cypress | 102 | 111 | 168 | 109 | 0.5 | 0.3 | 0.3 | 0.3 | 2.4 | 4.8 | 4.5 | 3.0 |
| Everglades L1 | 105 | 161 | 152 | 112 | 0.4 | 0.4 | 0.2 | 0.3 | 2.9 | 4.1 | 4.4 | 3.6 |
| Everglades P3 3 | 102 | 166 | 148 | 100 | 0.5 | 0.5 | 0.3 | 0.2 | 2.5 | 4.2 | 4.4 | 3.5 |
| Everglades X1.5 | 113 | 163 | 148 | 121 | 0.6 | 0.6 | 0.3 | 0.3 | 3.0 | 3.7 | 4.4 | 3.2 |
| Average | **106** | **167** | **154** | **110** | **0.5** | **0.5** | **0.3** | **0.3** | **2.7** | **4.2** | **4.4** | **3.3** |
| *Open Water* | | | | | | | | | | | | |
| Indian River Lagoon | 108 | 173 | 160 | 113 | 0.1 | 0.1 | 0.1 | 0.1 | 3.5 | 5.3 | 4.8 | 4.2 |
| Reedy Lake | 98 | 178 | 168 | 96 | 0.2 | 0.1 | 0.1 | 0.2 | 2.8 | 5.2 | 5.1 | 3.4 |
| WCA | 105 | 166 | 141 | 104 | 0.1 | 0.1 | 0.1 | 0.1 | 3.4 | 5.5 | 4.5 | 3.7 |
| Average | **104** | **173** | **156** | **104** | **0.1** | **0.1** | **0.1** | **0.1** | **3.3** | **5.3** | **4.8** | **3.8** |

[a] KSC denotes Kennedy Space Center.

where $ET_{\mathrm{mod},i}$ and $\mathrm{ET}_{\mathrm{obs},i}$ are the modeled and observed *ET* values, respectively, for each day *i* and *n* is the number of days per site. MAE and RMSE are aggregate indicators of model performance whereas regression statistics (slope, intercept, $R^2$) are indicators of how well the models predict ET on a daily basis.

**Table 4b**
Coefficient of variability of net radiation, Bowen ratio and evapotranspiration by site and land cover type.

| | Net radiation (W m$^{-2}$) | | | | Bowen ratio | | | | Observed daily ET (mm d$^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Win | Spr | Sum | Fall | Win | Spr | Sum | Fall | Win | Spr | Sum | Fall |
| *Forest* | | | | | | | | | | | | |
| Alachua (imm pine) | 0.53 | 0.26 | 0.31 | 0.45 | 1.50 | 1.03 | 1.32 | 1.71 | 0.48 | 0.38 | 0.39 | 0.49 |
| Alachua (mature pine) | 0.28 | 0.26 | 0.22 | 0.31 | 0.95 | 0.43 | 0.30 | 0.53 | 0.78 | 0.55 | 0.53 | 0.71 |
| KSC[a] (slash pine) | 0.38 | 0.24 | 0.29 | 0.36 | 2.37 | 6.68 | 2.22 | 1.22 | 0.55 | 0.42 | 0.50 | 0.50 |
| KSC[a] (scrub oak) | 0.40 | 0.23 | 0.34 | 0.39 | 1.32 | 0.90 | 1.09 | 27.91 | 0.56 | 0.41 | 0.48 | 0.59 |
| Average | **0.40** | **0.25** | **0.29** | **0.38** | **1.54** | **2.26** | **1.23** | **7.84** | **0.59** | **0.44** | **0.47** | **0.57** |
| *Citrus* | | | | | | | | | | | | |
| Belleview | 0.58 | 0.40 | 0.37 | 0.42 | 0.61 | 0.65 | 0.60 | 0.93 | 0.43 | 0.32 | 0.33 | 0.39 |
| Carlton ranch | 0.32 | 0.23 | 0.27 | 0.26 | 0.42 | 0.72 | 0.56 | 0.46 | 0.27 | 0.25 | 0.20 | 0.33 |
| Average | **0.45** | **0.32** | **0.32** | **0.34** | **0.51** | **0.68** | **0.58** | **0.70** | **0.35** | **0.29** | **0.26** | **0.36** |
| *Grass* | | | | | | | | | | | | |
| Disney wilderness | 0.39 | 0.24 | 0.27 | 0.35 | 0.49 | 0.49 | 0.40 | 0.67 | 0.44 | 0.29 | 0.19 | 0.38 |
| Duda farm | 0.41 | 0.26 | 0.32 | 0.37 | 0.57 | 0.55 | 0.43 | 0.66 | 0.34 | 0.30 | 0.21 | 0.32 |
| Ferris farm | 0.41 | 0.25 | 0.31 | 0.39 | 0.43 | 0.30 | 0.34 | 0.41 | 0.53 | 0.25 | 0.32 | 0.44 |
| Starkey | 0.33 | 0.16 | 0.21 | 0.33 | 0.43 | 0.45 | 0.27 | 0.75 | 0.47 | 0.24 | 0.19 | 0.53 |
| Average | **0.39** | **0.23** | **0.28** | **0.36** | **0.48** | **0.45** | **0.36** | **0.62** | **0.44** | **0.27** | **0.23** | **0.42** |
| *Marsh* | | | | | | | | | | | | |
| Blue cypress | 0.29 | 0.20 | 0.22 | 0.29 | 0.60 | 0.42 | 0.43 | 0.48 | 0.32 | 0.21 | 0.22 | 0.28 |
| Everglades L1 | 0.33 | 0.25 | 0.34 | 0.37 | 0.43 | 0.60 | 0.33 | 0.43 | 0.28 | 0.23 | 0.27 | 0.31 |
| Everglades P3 3 | 0.34 | 0.25 | 0.32 | 0.35 | 0.43 | 0.34 | 0.48 | 0.61 | 0.39 | 0.22 | 0.24 | 0.36 |
| Everglades X1.5 | 0.27 | 0.27 | 0.31 | 0.32 | 0.30 | 0.46 | 0.32 | 0.37 | 0.19 | 0.20 | 0.18 | 0.26 |
| Average | **0.31** | **0.24** | **0.30** | **0.33** | **0.44** | **0.46** | **0.39** | **0.47** | **0.30** | **0.21** | **0.23** | **0.30** |
| *Open water* | | | | | | | | | | | | |
| Indian River Lagoon | 0.31 | 0.28 | 0.34 | 0.34 | 3.52 | 0.45 | 0.30 | 2.50 | 0.53 | 0.33 | 0.31 | 0.41 |
| Reedy Lake | 0.42 | 0.26 | 0.28 | 0.38 | 1.35 | 0.47 | 0.29 | 0.74 | 0.49 | 0.27 | 0.29 | 0.34 |
| WCA | 0.37 | 0.27 | 0.31 | 0.33 | 0.82 | 0.97 | 0.59 | 0.57 | 0.38 | 0.25 | 0.29 | 0.30 |
| Average | **0.37** | **0.27** | **0.31** | **0.35** | **1.89** | **0.63** | **0.40** | **1.27** | **0.46** | **0.28** | **0.30** | **0.35** |

[a] KSC denotes Kennedy Space Center.

## Results and discussion

### *Daily observations*

Before comparing PET models, we evaluated the characteristics of the climate and ET observations to be used for the intercomparison. Tables 4a and 4b present the site averages and coefficients of variability (CV), respectively, of observed net radiation ($R_n$), the Bowen ratio ($\beta$ and DET statistics by season for all 18 sites. $R_n$ represents the total available energy that is partitioned between LE and $H$. The CV is computed as the standard deviation divided by the average, which allows for the comparison of variability within and between sites. These statistics were also averaged over the five general land cover classes: forest (4 sites), citrus (2 sites), grass (4 sites), marsh (4 sites) and open water (3 sites). LE and $H$ measurements were not available for the Blue Springs Tract site in northern Florida, hence data from this site were not included. In order to eliminate the effect of low-end latent heat measurements (which resulted in anomalously high Bowen ratios and low values of ET), days in which observed latent heat was less than 5 W m$^{-2}$ were excluded. Seasons were demarcated by the Julian day (JD) of their calendar start and end dates (winter: December 21 through March 20 (JD 355-79); spring: March 21 through June 20 (JD 80-171); summer: June 21 through September 20 (JD 172-263); and fall: September 21 through December 20 (JD 264-354)).

In general, the highest daily average $R_n$ was observed during spring, whereas the lowest average $\beta$ and highest average DET occurred during the summer (see Table 4a). Summer is generally considered to be the wet season in Florida. However, at the open water sites, maximum $R_n$ and DET occurred within the same season (spring). At these sites, DET was presumably limited only by the available energy. This is further supported by the fact that the $\beta$ estimates at the open water sites were consistently low (0.1–0.2) throughout the year. These results suggest that in most cases, variations in moisture availability is an important determinant of spatial variations in DET across Florida. Not surprisingly, the highest DET values also occurred at the open water sites, ranging from an average of 3.3 mm d$^{-1}$ in the winter to 5.3 mm d$^{-1}$ in the spring. DET at the marsh sites was also high, ranging from 2.7 mm d$^{-1}$ in winter to 4.4 mm d$^{-1}$ in summer. The lowest average DET occurred at the grass sites in winter (1.3 mm d$^{-1}$) and fall (2.0 mm d$^{-1}$) and at the forested sites in winter (1.8 mm d$^{-1}$) and fall (2.3 mm d$^{-1}$).

From a measurement variability standpoint, marsh sites yielded the most consistent observations, with the average CV ranging from 0.24 to 0.33 for $R_n$, 0.39 to 0.47 for $\beta$ and 0.21 to 0.30 for DET (see Table 4b). At-site CV values for DET at the marsh sites ranged from a high of 0.39 to a low of 0.18. At the open water sites, the average CV was relatively low for $R_n$ (0.27–0.37), moderate for DET (0.28–0.46) and high for $\beta$ (0.40 to about 1.9). The high variability of $\beta$ at the open water sites may be due to seasonal changes in both the magnitude and direction of heat flux across the water–air boundary. At-site CV values for DET at open water sites ranged from 0.25 to 0.53. Forested sites yielded the greatest variability, with the average CV ranging from 0.25 to 0.40 for $R_n$, about 1.2 to 7.8 for $\beta$ and 0.44 to 0.59 for DET. At-site CV values for DET at the forested sites ranged from 0.38 to 0.78. A large part of this variability is likely due to the fact that the forested sites covered a variety of tree types ranging from scrub oak (height = 1.5 m) to mature pine (height = 22 m). This explanation is supported by the fact that, despite the smaller sample size, the citrus sites showed low to moderate variability, presumably due to a single tree type and a more uniform canopy height.

The timing of maximum LE flux was also found to vary by land cover type. Fig. 2a and b compares observed LE for each general land cover class (forest, citrus, grass, marsh and open water). The vertical dashed lines indicate season breaks as defined previously. The wet season in Florida typically begins around JD 160 (early June). Observed LE peaked earliest at the open water sites. The timing of the maximum LE ($LE_{max}$) at the open water sites was not easily defined (due to measurement variability) but tended to occur between JD 100 and 150. The $LE_{max}$ at the grass sites generally occurred between JD 170 and 180, whereas at the forest sites, $LE_{max}$ did not occur until after JD 200. The lag at forest sites may have been due to deeper rooting depths. The timing of $LE_{max}$ at the marsh sites was variable. At Blue Cypress, $LE_{max}$ occurred at JD 168, at Everglade L1 and X1.5, $LE_{max}$ occurred at JD 190, but at Everglade P33, $LE_{max}$ occurred at JD 210.

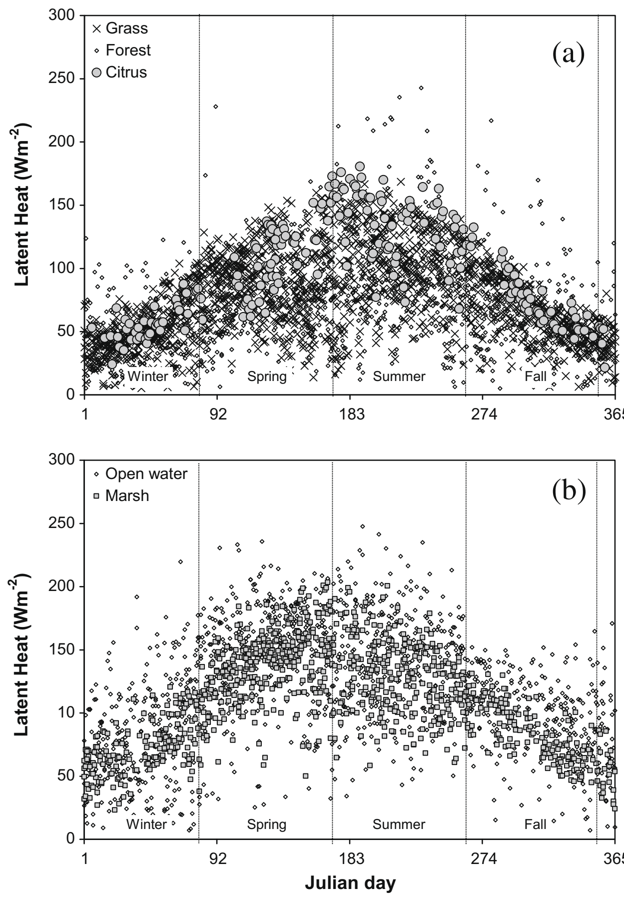


**Fig. 2.** Observed daily latent heat fluxes (in W m$^{-2}$) for each land cover type: (a) forest, citrus, and grass and (b) open water and marsh. Vertical dashed lines delineate the beginning of each season. In general, peak latent heat fluxes were lower and occurred later at grass, forest and citrus sites (upper graph) than at the marsh and open water sites (lower graph).

### *Characterization of potential evapotranspiration conditions*

Ideally, PET model results should only be compared with DET values collected on days when soil moisture is not a limiting factor (Brutsaert and Chen, 1995); however, the soil moisture content required to transition from water-limited to PET conditions is not clearly defined. Previous research in the region showed that PET can occur at soil moisture values as dry as 9% in a wet prairie (Jacobs et al., 2002). However, pine forests may not be effected by prolonged drought conditions (Gholz and Clark, 2002), but require extreme conditions before impacts are discernible (Powell et al., 2005). This transition is highly dependent on site-specific soils, vegetation, and the depth of soil moisture measurement.

For example, Powell et al. (2006) found near surface soil moisture measurement was not an adequate indicator of Florida scrub oak net ecosystem exchange of $CO_2$. Unfortunately, soil moisture measurements were either not available or too shallow to develop a consistent framework to indicate system stress across sites.

An alternate approach was applied that recognizes, under progressively more stressed conditions, the partitioning of available energy will increasingly favor *H*. The Bowen ratio ($\beta = H/\mathrm{LE}$) is a measure of this partitioning that is independent of the magnitude of the available energy. Jacobs et al. (2002) reported that the average value of $\beta$ for a Florida marsh was 0.4, but this value is expected to vary among sites. For a Florida pine forest with sufficient water supply, the Bowen ratio reached to 1.0 (Gholz and Clark, 2002). Bracho et al. (2008) found that Bowen ratios reached 1.6 and 1.2 in Florida scrub oak and pine flatwoods ecosystems, respectively, during extremely dry spring conditions and exceeded 1 when soil moisture was less than field capacity for both sites. It is recognized that Bowen ratio thresholds will likely vary across sites and that the at-site Bowen ratio variations reflect plant canopy as well as soil water availability (Bracho et al., 2008) that require further study.

In the present study, $\beta$ was found to be consistently less than one for the growing season from JD 160 to 290 (mid-June to mid-October). During the remainder of the year, $\beta$ was highly variable and frequently greater than one. For this study, PET model comparisons were performed using data collected on so-called "good" days (as defined in "Observed evapotranspiration") and then again using only good days for which $\beta$ was less than or equal to one. The purpose of the latter comparison was to test the performance of the PET models under conditions that were as close to PET as possible. We also performed the model comparison analysis for good days with $\beta$ less than or equal to 0.8 and $\beta$ less than or equal to 0.6. We found that our results were statistically equivalent; hence we present only the results for the analysis using $\beta$ less than or equal to one. The number of data points that met these conditions for each site is presented in the last column of Table 2. Both subsets of measurements (good days and good days with $\beta$ less than or equal to one) were used in our PET model comparisons.

*PET methods comparison results*

*Mean annual results*

As noted in "Characterization of potential evapotranspiration conditions", PET values were estimated for each "good" day and for each day in which $\beta$ was less than or equal to 1, using the three PET models outlined in "Observed evapotranspiration". Table 5 lists the observed daily evapotranspiration (DET) estimates as well as DET computed by the three models for all "good" days and for good days when $\beta \leqslant 1$. In general, both modeled and observed DET values were lowest for the grass, forest, and citrus sites and highest for marsh and open water sites. A noteworthy anomaly is that the literature values for the PM method underestimate the observed DET at forested sites. For these sites, the use of at-site values of surface resistance greatly improved the PM mean modeled DET values. This improvement in model performance suggests that existing surface resistance parameters for trees are not reliable for all forest communities in Florida. Fig. 3 compares PM estimates with observed DET and illustrates the improvement in model performance for forest sites when the at-site surface resistance parameter values are used. In general, the PM model shows much better agreement for the marsh and open water sites than for the other land cover classes. Seasonal variations in surface resistance are likely to be higher at the forest, grass, and citrus sites, another reason for poorer PM model performance.

Overall, the highest RMSE values are for the forested sites, followed closely by the citrus sites. The RMSE values are comparable for the grass, marsh and open water sites. Fig. 4 compares the RMSE values by site and model, grouped by land cover type. The PT method has consistently low RMSE values. Both the PT and the Tc methods perform best for the marsh and open water sites, which is consistent with the fact that these are energy-based

**Table 5**
Daily evapotranspiration (DET) estimated by the three PET models and compared with observed DET. Model estimates were computed for all "good" days and for days in which $\beta \leqslant 1$.

| Site | Daily evapotranspiration (mm d$^{-1}$) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *All "good" days* | | | | | *Days when $\beta \leqslant 1$* | | | | |
| | N | obs | Tc | PT | PM | N | obs | Tc | PT | PM |
| Alachua (imm pine) | 1110 | 2.02 | 3.12 | 3.03 | 0.94 | 931 | 2.14 | 2.99 | 2.88 | 0.93 |
| Alachua (mature pine) | 606 | 3.08 | 4.00 | 3.74 | 1.18 | 320 | 3.52 | 4.30 | 3.78 | 1.11 |
| KSC (scrub oak) | 1189 | 2.27 | 3.25 | 3.61 | 1.46 | 765 | 2.45 | 3.19 | 3.88 | 1.57 |
| KSC (slash pine) | 302 | 2.36 | – | 4.09 | 0.96 | 272 | 2.46 | – | 4.20 | 0.99 |
| Blue springs tract | 676 | 3.20 | 2.94 | 2.96 | 0.84 | 0 | – | – | – | – |
| Belleview | 365 | 3.03 | 3.17 | 2.97 | 0.83 | 294 | 3.28 | 3.25 | 3.08 | 0.88 |
| Carlton ranch | 211 | 3.48 | 3.91 | 4.31 | 1.01 | 171 | 3.77 | 3.97 | 4.51 | 1.08 |
| Disney wilderness | 559 | 2.53 | 3.45 | 3.30 | 1.62 | 371 | 3.03 | 3.67 | 3.66 | 1.84 |
| Duda farm | 967 | 3.06 | 3.81 | 3.74 | 1.95 | 826 | 3.26 | 3.81 | 3.82 | 2.00 |
| Ferris farm | 202 | 1.58 | 2.90 | 2.52 | 1.51 | 81 | 2.27 | 3.21 | 3.16 | 1.88 |
| Starkey | 310 | 2.57 | 3.65 | 3.68 | 1.89 | 188 | 3.31 | 4.19 | 4.45 | 2.33 |
| Blue cypress | 1001 | 3.98 | 3.85 | 4.16 | 4.27 | 982 | 4.03 | 3.89 | 4.20 | 4.32 |
| Everglades L1 | 621 | 3.86 | 4.13 | 4.25 | 5.48 | 613 | 3.87 | 4.12 | 4.25 | 5.46 |
| Everglades P3 3 | 1007 | 3.87 | 4.31 | 4.55 | 5.04 | 996 | 3.89 | 4.32 | 4.57 | 5.06 |
| Everglades X1.5 | 167 | 3.92 | 4.29 | 4.99 | 5.18 | 157 | 3.98 | 4.26 | 4.98 | 5.20 |
| Indian River Lagoon | 680 | 4.45 | 3.53 | 4.19 | 4.19 | 674 | 4.49 | 3.54 | 4.29 | 4.20 |
| Reedy Lake | 1264 | 4.18 | 3.43 | 4.08 | 4.31 | 1264 | 4.18 | 3.43 | 4.08 | 4.31 |
| WCA | 341 | 4.42 | 3.47 | 3.96 | 4.40 | 341 | 4.42 | 3.47 | 3.96 | 4.40 |
| All sites | | | | | | | | | | |
| Median | 11578 | 3.14 | 3.53 | 3.85 | 1.75 | 9246 | 3.52 | 3.74 | 4.08 | 2.00 |
| Mean | 11578 | 3.21 | 3.60 | 3.79 | 2.61 | 9246 | 3.43 | 3.73 | 3.99 | 2.80 |

*Notes*: *N* = number of daily observations; obs = observed daily evapotranspiration (DET); Tc = DET estimted by the Turc radiation method; PT = DET estimated by the Priestley–Taylor method; PM = DET estimated by the Penman–Monteith method; KSC = Kennedy Space Center – denotes no DET estimates.

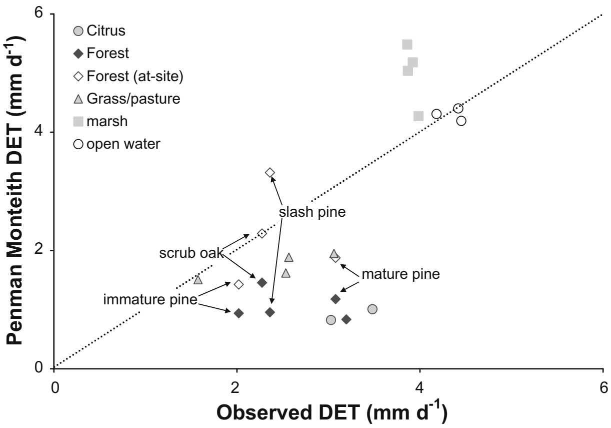


**Fig. 3.** Comparison of Penman–Monteith model estimated daily evapotranspiration (DET) with observed ET. Filled diamonds show PM estimates using regional bulk surface resistance; open diamonds show PM estimates using site-specific surface resistance. Dashed line represents 1:1 correspondence between model estimates and observed values.

methods. The PT and Tc methods performed similarly for the grass, marsh and open water sites, with RMSE values generally about 1 mm d$^{-1}$. Using the aggregate annually-averaged DET values of 2.43 mm d$^{-1}$ for the grass sites, 3.91 mm d$^{-1}$ for the marsh sites and 4.35 mm d$^{-1}$ for the open water sites, the RMSE generally ranged between 20% and 40% for these methods.

*Average daily results*

Fig. 5 compares aggregate statistics for each of the three PET models. Filled bars illustrate statistics computed for all "good" days; hashed bars illustrate statistics for days when $\beta \leqslant 1$. Error bars represent the standard error of the mean (standard deviation divided by the square root of the sample size) for each statistic. Interestingly, when the models were applied only to days when $\beta \leqslant 1$, the performance of the Tc method improved, whereas the performance of the other two methods degraded. The PM mean MAE values were statistically different from the other methods. The Tc RMSE mean values differed significantly as compared to the other methods.

While RMSE and MAE provide an indicator of a model's ability to perform on an annual basis, regression analyses were conducted to compare model performance on an average daily basis. Ideally, the regression results would have intercepts close to zero, slopes close to one, and correlation coefficients close to one. Fig. 5 shows relatively strong correlations between measured and modeled values for all three models. However, the Tc method typically had high intercepts and relatively low slopes. The PM method had much better agreement, but with considerable variability. The PT method, with the exception of the forested sites, had the best regression relationships. We found that in both cases (all good data and data where $\beta \leqslant 1$), the Tc intercept was statistically different than the PT or PM, and the PT slope was statistically different than the Tc or PM methods. The overall (all sites) statistics shown in Fig. 5 illustrate that the PT method has slopes closest to 1. Our error analysis suggests that the PT method is superior to the other two methods for estimating DET.

Regression model residuals as a function of daily ET and day of year were examined. Fig. 6a and b shows an example of model residuals versus observed DET for a grass and a marsh site. For the grass site (Fig. 6a), the Tc and PT methods tended to overestimate DET while the PM method tended to underestimate DET. A distinct seasonality can be seen in the residuals at these sites, which is less pronounced at the marsh (Fig. 6b). The seasonality is particularly pronounced for the PM residuals with a notable bias that increases with increasing DET magnitude. This pattern can be explained by considering that the bulk surface resistance ($r_s$) is a seasonally dynamic property. However, due to limited knowledge, only a single, constant value is used in this analysis. The availability of seasonally-varying $r_s$ values would likely reduce this problem and improve performance. Residuals for the marsh site are not strongly related to ET magnitude (Fig. 6b) or day of year (not shown). There is a slight tendency to underestimate the highest values and overestimate the lowest values. The residuals also indicate that the models are relatively unbiased for these sites.

*Relative ranking of PET methods and comparison with previous studies*

Tradeoffs exist among the three models tested in this study. The PM can account for differences among vegetation, hence, it has the potential to more accurately represent PET from vegetated surfaces. However, broadly applicable PM model parameters (such

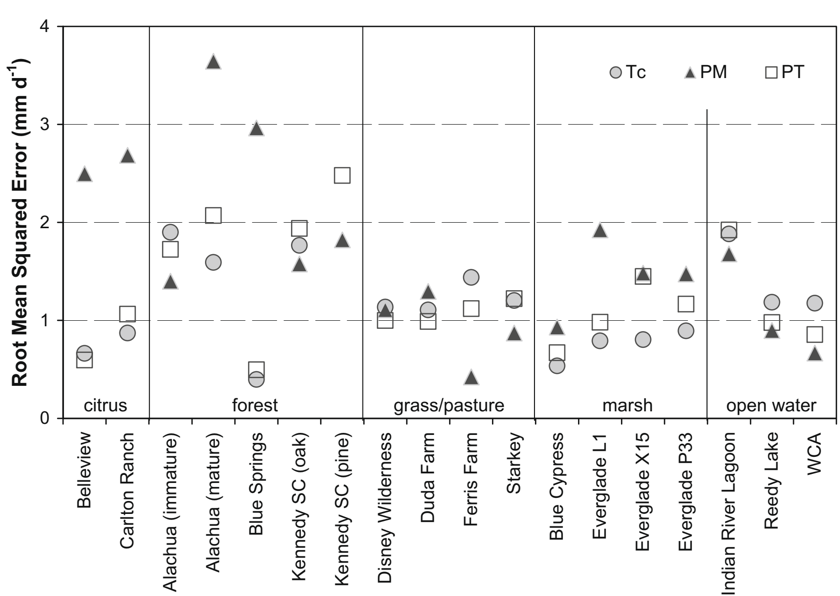


**Fig. 4.** Comparison of root mean squared error (RMSE) across models and sites. Vertical lines group results by general land cover class. Tc = Turc method; PT = Priestley–Taylor method; PM = Penman–Monteith method.

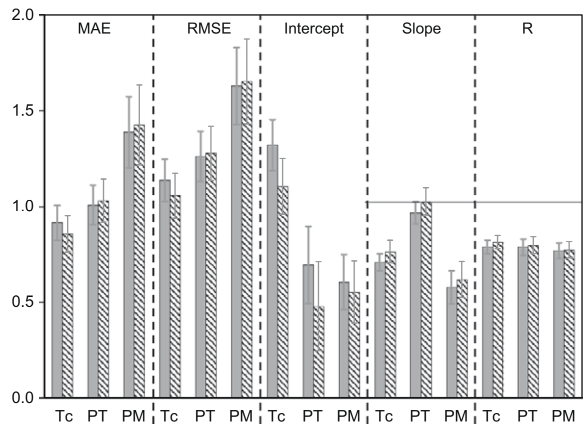


**Fig. 5.** Comparison of aggregate error statistics (in mm $d^{-1}$) and regression coefficients (Tc = Turc method; PT = Priestley–Taylor method; PM = Penman–Monteith method). Filled bars represent statistics computed on all "good" days, hashed bars represent statistic computed for days when $\beta < 1$. Mean values are represented by the heights of the bars. Error bars show the standard error of the mean. Horizontal line represents a value of 1.

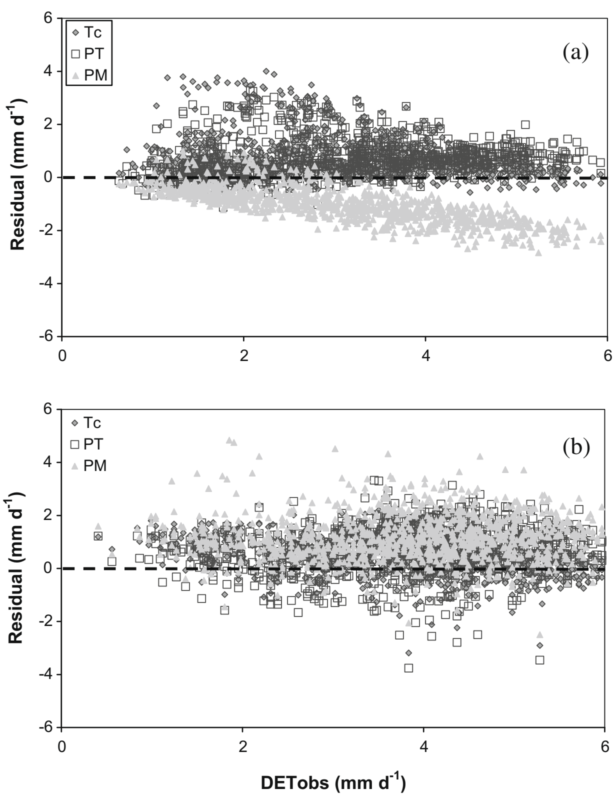


**Fig. 6.** Model residuals for two different land cover classes: (a) grass site, and (b) a marsh site. For the grass site, the PM model tended to underestimate PET and the model residuals tended to increase with the magnitude of observed DET. This was typical for most other land cover classes as well.

as surface resistance) cannot be easily or robustly estimated from routine observations. Fixed values are available for each landuse, but such parameters are difficult to defend from a biophysical perspective. This inability to characterize annual variability in surface conductance is likely the cause of the seasonality of PM residuals (Fig. 6a). On the other hand, the Tc and PT methods are energy-driven models, requiring fewer parameters; these parameters are easier to estimate from available observations.

It is particularly noteworthy that PM-estimated PET generally is substantially lower than measured DET, whereas PT and Tc PET are generally higher than measured DET (see Table 5); this bias eliminates PM PET (as formulated in this study) as an acceptable PET estimator given that PET should equal or exceed observed DET. A comparison of error statistics for the PT and Tc methods (Fig. 5) is not unambiguous, but the PT method appears to have an overall advantage over the Tc method. The relative ranking of PET methods apparent in this study is (from best to worst): PT, Tc, and PM. These results are consistent with the watershed-scale comparisons of Lu et al. (2005), who also suggested that the PT and Tc methods were preferred approaches for PET estimation in the southeastern United States. However, Lu et al. (2005) did not consider the PM method. These results contrast somewhat with the results of Oudin et al. (2005b) who ranked the PM method higher than the PT method and also higher than the more poorly-performing Tc method. However, that study scaled each PET estimates by Penman estimates and removed any systematic biases between methods, which, in the present study, is the primary liability of the PM method (i.e., PM estimates are less than measured DET). Federer et al. (1996), in performing an inter-comparison of PET methods, without the benefit of measured DET as a standard, noted that none of the methods (including PM, PT, and Tc, among others) were consistently low or high, which contrasts with the present study in which the PM generally was lower than the PT or the Tc.

## Summary and conclusions

The summary statistics and model residuals discussed in previous sections show strengths and weaknesses for each method. On an aggregate annual basis, MAE and RMSE statistics indicate that the Tc and PT methods appear to perform comparably and better than the PM method. The relative ranking of PET methods apparent in this study is (from best to worst): PT, Tc, and PM. Performance at a daily time scale is indicated by the values of the regression intercept and slope and the correlation coefficient, *R*. At a daily scale, the Tc intercept is much higher and statistically different than either the PT or PM statistics. The PT intercept statistics are closest to zero and slope and *R* statistics closest to 1. At a daily scale, the performance of all three methods does improve when applied to conditions close to PET ($\beta \leqslant 1$). However, probably due to the lower sample size, the improved statistics are not significantly different from those computed for all "good" data. Interestingly, *R* values for all models are nearly identical. In aggregate, the Tc and PT methods perform comparably and both outperform the PM method. But at a daily scale, the PT performance appears to be superior to the other two methods. In fact, the slope and intercept show that the Tc method significantly overestimates low DET values and underestimates high values. Hence, the PT method appears to be the best model for estimating PET in Florida.

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## References

Abtew, W., 1996. Evapotranspiration measurements and modeling for three wetland systems in South Florida. Water Resources Bulletin 32 (3), 465–473.

Abtew, W., Obeysekera, J., 1995. Lysimeter study of evaporation of cattails and comparison of 3 estimation methods. Transactions of the ASAE 38 (1), 121–129.

Abtew, W., Newman, S., Pietro, K., Kosier, T., 1995. Canopy resistance studies of cattails. Transactions of the ASAE 38 (1), 113–119.

Acs, F., 2005. On transpiration and soil moisture content sensitivity to soil hydrophysical data. Boundary-Layer Meteorology 115 (3), 473–497.

Bracho, R., Powell, T.L., Dore, S., Li, J.H., Hinkle, C.R., Drake, B.G., 2008. Environmental and biological controls on water and energy exchange in Florida scrub oak and pine flatwoods ecosystems. Journal of Geophysical Research 113, G02004.

Breuer, L., Eckhardt, K., Frede, H.-G., 2003. Plant parameter values for models in temperate climates. Ecological Modeling 169, 237–293.

Brutsaert, W., Chen, D.Y., 1995. Diagnostics of land surface spatial variability and water vapor flux. Journal of Geophysical Research – Atmospheres 100 (D12), 25595–25606.

Crow, W.T., Li, F.Q., Kustas, W.P., 2005. Intercomparison of spatially distributed models for predicting surface energy flux patterns during SMACEX. Journal of Hydrometeorology 6 (6), 941–953.

Danish Hydraulic Institute, 1998. MIKE SHE User Guide and Technical Reference Manual. DHI Software, Denmark.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, G., Clement, R., Dolman, H., Granier, A., Gross, P., Grunwald, T., Hollinger, D., Jensen, N.O., Katul, G., Keronen, P., Kowalski, A., Lai, C.T., Law, B.E., Meyers, T., Moncrieff, J., Moors, E., Munger, J.W., Pilegaard, K., Rannik, U., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. Gap filling strategies for long term energy flux data sets. Agricultural and Forest Meteorology 107 (1), 71–77.

Federer, C.A., Vörösmarty, C., Fekete, B., 1996. Intercomparison of methods for calculating potential evaporation in regional and global water balance models. Water Resources Research 32 (7), 2315–2321.

German, E. R., 2000. Regional evaluation of evapotranspiration in the Everglades. US Geological Survey Water-Resources Investigations Report 00-4217, 48 pp.

Gholz, H.L., Clark, K.L., 2002. Energy exchange across a chronosequence of slash pine forests in Florida. Agricultural and Forest Meteorology 112, 87–102.

Harbaugh, A.W., Banta, E.R., Hill, M.C., McDonald, M.G., 2000. MODFLOW-2000, the US Geological Survey modular ground-water model – user guide to modularization concepts and the ground-water flow process. US Geological Survey Open-File Report 00-92, pp. 121.

Jacobs, J.M., Mergelsberg, S.L., Lopera, A.F., Myers, D.A., 2002. Evaporation from a wet prairie wetland under drought conditions. Paynes Prairie Preserve, Florida, USA, Wetlands, 22 (2), pp. 374–385.

Jacobs, J.M., Anderson, M.C., Friess, L.C., Diak, G.R., 2004. Solar radiation, longwave radiation and emergent wetland evapotranspiration estimates from satellite data in Florida, USA. Hydrological Sciences Journal 49 (3), 461–476.

Law, B.E., Falge, E., Gu, L., Baldocchi, D.D., Bakwin, P., Berbigier, P., Davis, K., Dolman, A.J., Falk, M., Fuentes, J.D., Goldstein, A., Granier, A., Grelle, A., Hollinger, D., Janssens, I.A., Jarvis, P., Jensen, N.O., Katul, G.G., Mahli, Y., Matteucci, G., Meyers, T., Monson, R., Munger, W., Oechel, V., Olson, R., Pilegaard, V., Paw, K.T., Thorgeirsson, Valentini, R., Verma, V., Vesala, T., Wilson, K., Wofsy, S., 2002. Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation. Agricultural and Forest Meteorology 113, 97–120.

Leuning, R., Raupach, M.R., Coppin, P.A., Cleugh, H.A., Isaac, P., Denmead, O.T., Dunin, F.X., Zegelin, S., Hacker, J., 2004. Spatial and temporal variations in fluxes of energy, water vapour and carbon dioxide during OASIS 1994 and 1995. Boundary-Layer Meteorology 110 (1), 3–38.

Lu, J., Sun, G., McNulty, S.G., Amatya, D.M., 2005. A comparison of six potential evapotranspiration methods for regional use in the southeastern United States. Journal of the American Water Resources Association 41 (3), 621–633.

Monteith, J.L., 1965. Evaporation and environment. In: Fogg, G.E. (Ed.), Symposium of the Society for Experimental Biology, The State and Movement of Water in Living Organisms, Vol. 19. Academic Press, Inc., NY, pp. 205–234.

Oudin, L., Michel, C., Anctil, F., 2005a. Which potential evapotranspiration input for a lumped rainfall–runoff model? Part 1 – Can rainfall–runoff models effectively handle detailed potential evapotranspiration inputs? Journal of Hydrology 303, 275–289.

Oudin, L., Hervieu, F., Michel, C., Perrin, C., Andreassian, V., Anctil, F., Loumagne, C., 2005b. Which potential evapotranspiration input for a lumped rainfall–runoff model? Part 2 – Towards a simple and efficient potential evapotranspiration model for rainfall–runoff modeling. Journal of Hydrology 303, 290–306.

Penman, H.L., 1948. Natural evaporation from open water, bare soil, and grass. Proceedings of the Royal Society of London A 193, 120–146.

Powell, T.L., Starr, G., Clark, K.L., Martin, T.A., Gholz, H.R., 2005. Ecosystem and understory water and energy exchange for a mature, naturally regenerated flatwood in North Florida. Canadian Journal of Forest Research 35, 1568–1580.

Powell, T.L., Bracho, R., Li, J.H., Dore, S., Hinkle, C.R., Drake, B.G., 2006. Environmental controls over net ecosystem carbon exchange of scrub oak in central Florida. Agricultural and Forest Meteorology 141, 19–34.

Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Review 100, 81–92.

Shuttleworth, W.J., 1993. In: Evaporation. Handbook of Hydrology, Maidment, D. R. (Ed. in chief), McGraw-Hill, Inc. (Chapter 4).

Sumner, D., Belaineh, G., 2005. Evaporation, Precipitation, and Associated Salinity Changes at a Humid, Subtropical Estuary. Estuaries 28 (6), 844–855.

Sumner, D.M., Jacobs, J.M., 2005. Utility of Penman–Monteith, Priestley–Taylor, reference evapotranspiration, and pan evaporation methods to estimate pasture evapotranspiration. Journal of Hydrology 308, 81–104.

Turc, L., 1961. Evaluation des besoins en eau d'irrigation, évapotranspiration potentielle, formulation simplifié et mise à jour. Annales Agronmique. 12, 13–49.

US Army Corps of Engineers, 2000. Hydrologic modeling system HEC-HMS – technical reference manual. US Army COE Hydrologic Engineering Center, Davis, CA, 149 pp.

Verstraeten, W.W., Veroustraete, F., Feyen, J., 2008. Assessment of evapotranspiration and soil moisture content across different scales of observation. Sensors 8, 70–117.

Vörösmarty, C.J., Federer, C.A., Schloss, A.L., 1998. Potential evaporation functions compared on US watersheds: Possible implications for global-scale water balance and terrestrial ecosystem modeling. Journal of Hydrology 207, 147–169.

Weiß, M., Menzel, L., 2008. A global comparison of four potential evapotranspiration equations and their relevance to stream flow modelling in semi-arid environments. Advances in Geoscience 18, 15–23.

Yoder, R.E., Odhiambo, L.O., Wright, W.C., 2005. Evaluation of methods for estimating daily reference crop evapotranspiration at a site in the humid Southeast United States. Applied Engineering in Agriculture 21 (2), 197–202.