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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