Evapotranspiration Methods compared on a Sierra Nevada Forest Ecosystem

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Abstract Evapotranspiration, as a major component in terrestrial water balance and net primary productivity models, is often difficult to measure and predict. This study compared five potential evapotranspiration models applied to a ponderosa pine forest ecosystem at an Ameriflux site in Northern California. The Ameriflux sites are research forests across the United States, Canada, Brazil, and Costa Rica with towers measuring carbon, water, and energy fluxes out of the ecosystems.   The evapotranspiration models ranged from simple temperature- and solar radiation-driven equations to physically-based combination approaches and included reference surface and surface cover-dependent algorithms. For each evapotranspiration models, results were compared against mean daily latent heat from half-hourly measurements recorded on a tower above the forest canopy. All models calculate potential evapotranspiration and thus overpredicted values from the summer seasons of 1997 and 1998. Development of a soil moisture function to connect potential with actual evapotranspiration resulted in significant improvement on three of the five models. A modified Priestley-Taylor method performed well given its relative simplicity.

Introduction

The terrestrial water cycle has become increasingly important in understanding climate, plant community dynamics, carbon and nutrient biogeochemistry, and the structure and function of aquatic ecosystems. The necessity of understanding terrestrial water cycles has been accelerated by climate change, particularly due to CO_2-induced greenhouse warming (Houghton et al. 1990; GCIP-GEWEX 1993; IGP-BAHC 1993; Watson 1995; Kaczmarek et al. 1996). Global change is of direct relevance to human society and has begun to play a role in the overall environmental policy-making process.

Evapotranspiration, as an important component of the terrestrial water cycle, represents more than 60% of precipitation inputs at the global scale (Korzoun et al. 1978; L'vovich and White 1990). Through links between stomatal conductance, carbon exchange, and water use efficiency in plant canopies (e.g. Raich et al. 1991; McGuire et al. 1992; Woodward and Smith 1994; Sellers et al. 1996) evapotranspiration serves as a regulator of key ecosystem processes. The reduction of evapotranspiration through widespread land cover change may lead to an overall diminishing of the water cycle, including the recycling of precipitation and generation of runoff (Shukla et al. 1990; Durbridge and Henderson-Sellers 1993; Lean et al. 1995).

Differences in the treatment of evapotranspiration are prominent among both climate and terrestrial ecosystem models (Shuttleworth 1991; VEMAP Members 1995). Many water-balance models in the literature lack a sound evapotranspiration technique, and they often account for evapotranspiration with little biophysical justification. The reason for this gap is due to the fact that evapotranspiration has always been difficult to measure, especially on an ecosystem spatial scale. The method by which evapotranspiration is measured requires a tower above the canopy to record water fluxes out of the forest ecosystem. Inasmuch as the majority of moisture supplied by precipitation returns to the atmosphere as evapotranspiration, and since evapotranspiration is one of the most difficult processes to evaluate in hydrologic analysis, estimates are generally considered to be a significant source of error in streamflow simulation.

Several methods for estimating evapotranspiration have been introduced in the literature. Vörösmarty et al. (1998) tested and compared 11 methods on various watersheds in a global-scale water balance model. The primary objective of my study is to compare a similar set of potential evapotranspiration methods that are commonly employed in global-scale water balance

and terrestrial net primary production models. The methods include surface-dependent methods developed by Shuttleworth and Wallace (1985), Monteith (1965), Priestley and Taylor (1972), McNaughton and Black (1973), and the reference-surface method by Penman (1948). While Vörösmarty et al. worked on a global scale, I assess these methods at a forest ecosystem-scale using input data from a tower at the Blodgett Forest Research Station in California.

Methods

   Evapotranspiration methods   Five potential evapotranspiration models of increasing complexity were tested under two classes of land surface speciation (Shuttleworth 1991; Federer et al. 1996). Reference-surface evapotranspiration is defined as evaporation that would result from a specific land surface, referred to as a "reference crop." Surface-dependent evapotranspiration is defined as the evaporation that would occur from any of a variety of designated land surfaces. For the Priestley-Taylor model, the simplest of the five, cover dependency is defined solely by albedo:

$$\text{Total evapotranspiration} = 1.26\Delta A/(\Delta + \gamma)$$

where Δ is the differential of saturated vapor pressure versus temperature, A is total available energy, and γ is the psychrometric constant. The "α value" of 1.26 is given as a constant by Priestley and Taylor, but this value has been determined to be a function of soil moisture (Flint and Childs 1991).

   The McNaughton-Black model is defined as follows:

$$\text{Total evapotranspiration} = c_p\rho D/\gamma r_{cs}$$

where c_p is specific heat at constant pressure, ρ is air density, D is vapor pressure deficit, and r_{cs} is bulk stomatal resistance of the canopy.

   The Penman model is defined as follows:

$$\text{Total evapotranspiration} = (\Delta A + 73.64 \rho_w \gamma (1 + 0.54u)D)/(\Delta + \rho)$$

where ρ_w is water density, and u is wind speed.

For the Shuttleworth-Wallace model, the evaporation from the soil, λE_s, and the transpiration from the canopy, λE_c, are derived from the Penman-Monteith combination equations:

$$\lambda E_s = (\Delta A_s + \rho c_p D_0 / r_{sa}) \ / \ (\Delta + \gamma(1 + r_{ss}/r_{sa}))$$

$$\lambda E_c = (\Delta(A - A_s) + \rho c_p D_0 / r_{ca}) \ / \ (\Delta + \gamma(1 + r_{cs}/r_{ca}))$$

where A_s is available soil energy, and D_0 is vapor pressure deficit in the canopy; r_{sa}, r_{ss}, and r_{ca} are all aerodynamic resistances. D_0 is derived from the Ohm's law electrical analog for the vapor pressure and temperature difference between the canopy and the reference height above the canopy where fluxes out of the vegetation are measured. D_0 is a function of the measurable vapor pressure deficit at the reference height, D:

$$D_0 = D + (\Delta A - r_{aa} \lambda E_c (\Delta + \gamma)) \ / \ \rho c_p$$

and D can thus be substituted for D_0 into the combination equations. The total evaporation from the crop, λE, for the Shuttleworth-Wallace model is the sum of the Penman-Monteith combination equations with D substituted in for D_0:

$$\lambda E = C_c PM_c + C_s PM_s$$

where PM_c describes evaporation from the closed canopy, and PM_s describes evaporation from the bare substrate. The new Penman-Monteith equations have the form:

$$PM_c = \frac{(\Delta A + (\rho c_p D - \Delta r_{ca} A_s)/(r_{aa} + r_{ca}))}{(\Delta + \gamma(1 + r_{cs}/(r_{aa} + r_{ca})))}$$

$$PM_s = \frac{(\Delta A + (\rho c_p D - \Delta r_{sa}(A - A_s)/(r_{aa} + r_{sa}))}{(\Delta + \gamma(1 + r_{ss}/(r_{aa} + r_{sa}))}$$

The coefficients C_c and Cs are resistance combination equations:

$$C_c = 1/(1 + R_c R_a/(R_s(R_c + R_a)))$$

$$C_s = 1/(1 + R_s R_a/(R_c(R_s + R_a)))$$

where

$$R_a = (\Delta + \gamma)r_{aa}$$

$$R_s = (\Delta + \gamma)r_{sa} + \gamma r_{ss}$$

$$R_c = (\Delta + \gamma)r_{ca} + \gamma r_{cs}$$

The evapotranspiration models described above calculate potential evapotranspiration rather than actual evapotranspiration. Potential evapotranspiration is defined as the evapotranspiration flux from the ecosystem under well-watered soil—at, or close to, field capacity. I derived actual evapotranspiration from potential evapotranspiration using a soil water function:

$$\lambda E_{actual} = f(\phi)*\lambda E$$

where the soil water function is:

$$f(\phi) = \text{Soil moisture at 20 cm / Field capacity}$$

Field capacity was empirically determined as 39%. Parameters used in each method are compared in Table 1.

	Priestley-Taylor	McNaughton-Black	Penman	Penman-Monteith	Shuttleworth-Wallace
Δ	√		√	√	√
A	√		√	√	√
γ	√	√	√		√
c_p		√		√	√
ρ		√	√	√	√
D		√	√	√	√
r_{cs}		√		√	√
ρ_w			√		
u			√		√
r_{ca}				√	√
r_{sa}					√
r_{ss}					√
A_s					√

Table 1. Comparison of the complexity of each model in terms of quantity of parameters required.

Site description Data were gathered during the summers of 1997 and 1998 at Blodgett Forest Research Station (38°53´42.9´´N, 120°37´57.9´´W, 1315 m), a research forest of the University of California, Berkeley. The forest consisted of 6 year-old trees dominated by ponderosa pine. The canopy also included individuals of Douglas fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), giant sequoia (*Sequoiadendron giganteum*), incense-cedar (*Calocedrus decurrens*) and California black oak (*Quercus kelloggii*).   The major understory shrubs were manzanita (*Arctostaphylos* spp.) and *Ceonothus* spp. In 1997, about 25% of the ground area was covered by shrubs, 30% by conifer trees, 2% by deciduous trees, 7% by forbs, 3% by grass and 3% by stumps. The forest area was in a stage of rapid growth, as exhibited by the large (30-35%) increase in leaf area index (LAI) between the 1997 and 1998 growing seasons.   The site is characterized by a Mediterranean climate with an average annual precipitation of 163 cm, the majority of which falls between September and May, and almost no rain in the summer. The soil is a fine-loamy, mixed, mesic, ultic haploxeralf in the Cohasset series whose parent material was andesitic lahar (Goldstein et al. 2000).

Measurements Infrastructure for the canopy scale flux measurements consisted of a 10 m measurement tower (Upright Inc.). From 1 June to 10 September 1997 and from 1 May to 30 October 1998, fluxes of CO_2, H_2O, and sensible heat were measured by the eddy covariance method.   Environmental parameters such as wind speed and direction, air temperature and

humidity, net and photosynthetically active radiation, soil temperature, soil moisture, soil heat flux, rain, and atmospheric pressure were also monitored. A system to measure the vertical profiles of CO_2 and H_2O was added in 1998. The data acquisition system was separated in two parts: (1) a fast response system which monitored data at high frequency (up to 10 Hz) used to calculate eddy covariance, with raw data stored in 30 min data sets; and (2) a slow response system which monitored environmental parameters and stored 30 min averaged data (Goldstein et al. 2000).

Wind velocity and temperature were measured at 10 Hz with a three-dimensional sonic anemometer (ATI Electronics Inc., Boulder, CO) mounted 5 m above the canopy. CO_2 and H_2O mixing ratios were measured with an infrared gas analyzer (IRGA, LICOR model 6262, Lincoln, NE). Fluxes of CO_2, H_2O, and sensible heat between the forest and the atmosphere were determined by the eddy covariance method (Goldstein et al. 2000). This method quantifies vertical fluxes of scalars between the forest and the atmosphere from the covariance between vertical wind velocity and scalar fluctuations averaged over 30 min periods (e.g. Shuttleworth et al. 1984; Baldocchi et al. 1988; Wofsy et al. 1993; Moncrieff et al. 1996). Environmental parameters were recorded on a CR10X datalogger (Campbell Scientific Inc., Logan, UT). Two soil moisture probes were buried horizontally at 10 and 20 cm depth; rain gauge and barometric pressure devices (Campbell Scientific Inc., Logan, UT) were located one mile away. Total (all-sided) LAI was estimated using two techniques that resulted in similar estimates, (1) the LI-2000 (Li-Cor Inc., Lincoln, NE), and (2) scaling from leaf-level determination using the measured geometry of trees.

Systematic errors associated with the eddy covariance method include time lags between wind and scalar data due to travel through sampling tube and instrument response time, damping of high frequency fluctuations by the closed-path IRGA and travel through the sampling tube, sensor separation between wind and scalar measurements (Rissman and Tetzlaff 1994), and inability of the sonic anemometer to resolve fine-scale eddies in light winds (Goulden et al. 1996; Moncrieff et al. 1996). Generally, these type of errors result in the underestimation of flux (Leuning and King 1992). The inability of the sonic anemometer to resolve the vertical wind occurs mainly at night as the fluctuations become dominated by small, high frequency eddies (Goulden et al. 1996) use $u^* < 0.17$ m s^{-1} as the threshold for reliable measurements). The inability of the sonic anemometer to resolve fine-scale eddies in light winds (e.g. during night)

produced systematic errors in the sensible heat flux to correct the CO_2 and H_2O fluxes. Thus, although daytime turbulence was strong enough to produce reliable measurements, the calmer conditions during nigh rendered the nighttime flux measurements less reliable (Goldstein et al. 2000). I corrected for outliers (greater than three standard deviations from the mean) and missing data points (via interpolation or backup sensors), and I evaluated the evapotranspiration models using daytime (5am – 9pm) averages because nighttime measurements were unreliable.

Results

For all potential evapotranspiration models, simulated evaporation compared reasonably well with measured evapotranspiration at the beginning of the summer season (Figure 1). As the soil moisture decreased below field capacity throughout the summer all methods tended to overpredict evapotranspiration. The Penman method performed poorly overall and dramatically overpredicted evapotranspiration. Shuttleworth-Wallace, Penman-Monteith, and McNaughton-Black all resulted with similar trends and magnitudes; Penman-Monteith tended to estimate an intermediary value with McNaughton-Black giving slightly greater estimates and Shuttleworth-Wallace giving slightly lower estimates. The Priestley-Taylor method, however, performed well given its relative simplicity. The Priestley-Taylor method performed particularly well in 1998 with the original α value of 1.26, when soil moisture was higher than in 1997.
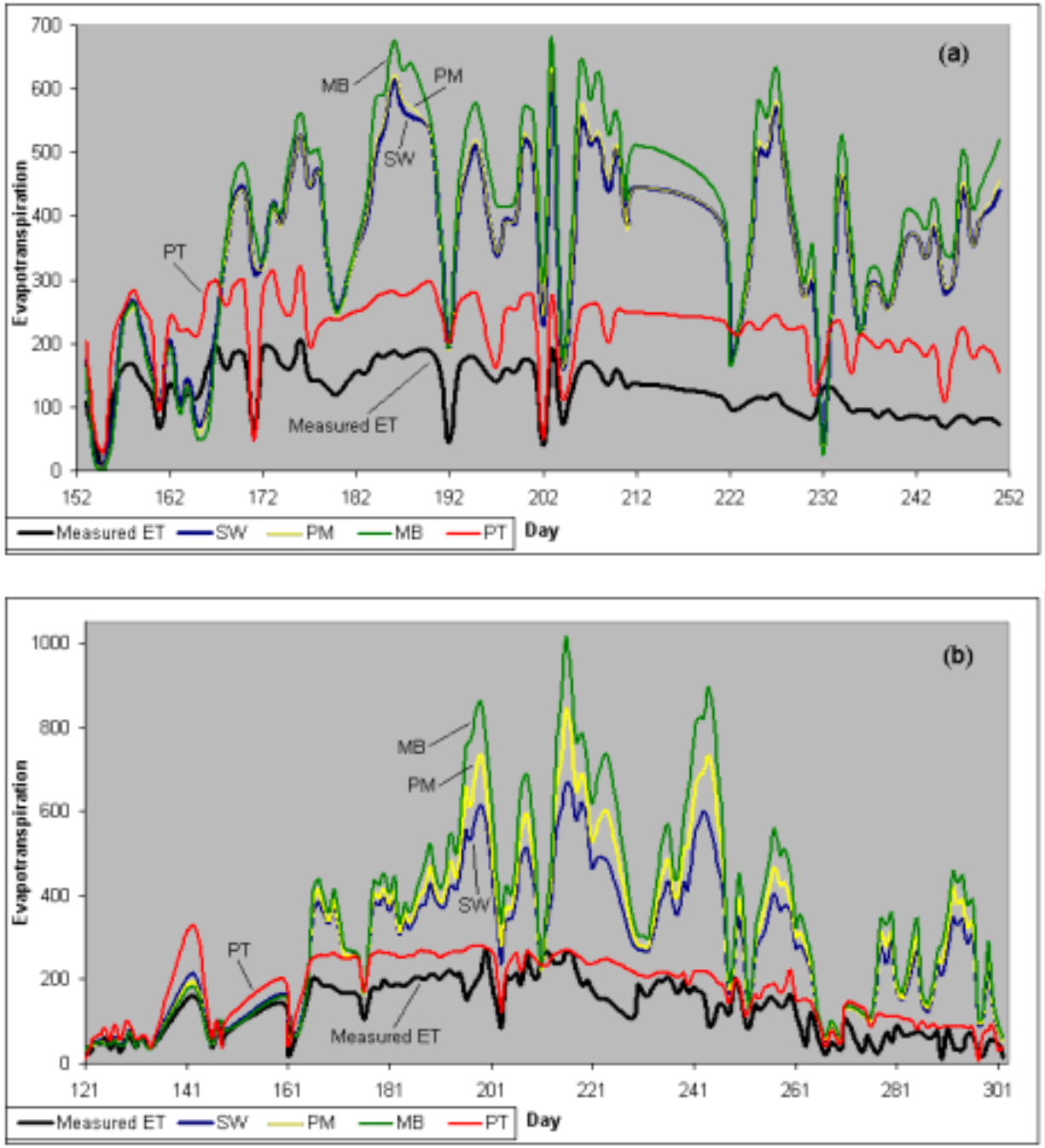
Figure 1. Potential evapotranspiration without soil moisture function for (a) 1997 and (b) 1998. Shuttleworth-Wallace (SW), Penman-Monteith (PM), and McNaughton-Black (MB) all have similar trends and magnitudes, whereas Priestley-Taylor (PT) comes closest to measured evapotranspiration (Measured ET). All methods overpredict Measured ET. Penman method excluded due to extreme overprediction.

With the soil moisture function, Shuttleworth-Wallace ($r^2 = 0.45$ in 1997; $r^2 = 0.68$ in 1998), Penman-Monteith ($r^2 = 0.42$ and 0.65), and McNaughton-Black ($r^2 = 0.37$ and 0.61) all performed well with similar trends and magnitudes. The soil moisture function performed well across both the dry season of 1997 and the relatively wet season of 1998 (Figure 2 and 3). Determination of α based on soil moisture resulted in an improved Priestley-Taylor method ($r^2 = 0.74 - 0.84$) as well. The empirical α function was determined as:

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α = 0.3 + 0.04(Soil moisture at 20 cm)
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where it was found that $\alpha = 0.73$ in 1997 and $\alpha = 0.94$ in 1998.

Discussion

Shuttleworth-Wallace, Penman-Monteith, and McNaughton-Black resulted in similar simulations due to the connection of their equations. McNaughton-Black, which excludes any effect from the soil, is a simplification of Penman-Monteith, whereas Shuttleworth-Wallace, which expands upon the soil layer, is derived from the Penman-Monteith equations. Hence, the simulations revealed that Penman-Monteith tended to give an intermediate result between those three models. Shuttleworth-Wallace, specifically, is designed for sparse crops where vegetation is not dense. At the Blodgett Ameriflux site, the canopy is dense and the substrate does not significantly affect evapotranspiration. Thus, the Shuttleworth-Wallace model reduced back to the Penman-Monteith model and gave only slightly better results. In the relatively wet season of 1998, Shuttleworth-Wallace resulted in a more accurate simulation than in 1997 because the greater soil moisture lead to greater soil evaporation. Still, the soil was not a significant factor at this site and thus the McNaughton-Black model, which neglects the soil, yielded similar results. The success of Priestley-Taylor, given its relative simplicity, shows that this simple model may be more effective than the complex models by Shuttleworth-Wallace, Penman-Monteith, and McNaughton-Black under dense canopy conditions.

The soil moisture function plays a key role in deriving actual evapotranspiration from potential evapotranspiration. Potential evapotranspiration assumes that the soil is at field capacity and will overpredict evapotranspiration under drier soil. In both years, the potential evapotranspiration methods performed well at the beginning of the summer season when soil

moisture was still high from the spring rains. But, as soil moisture declined throughout the summer, potential evapotranspiration subsequently overpredicted.
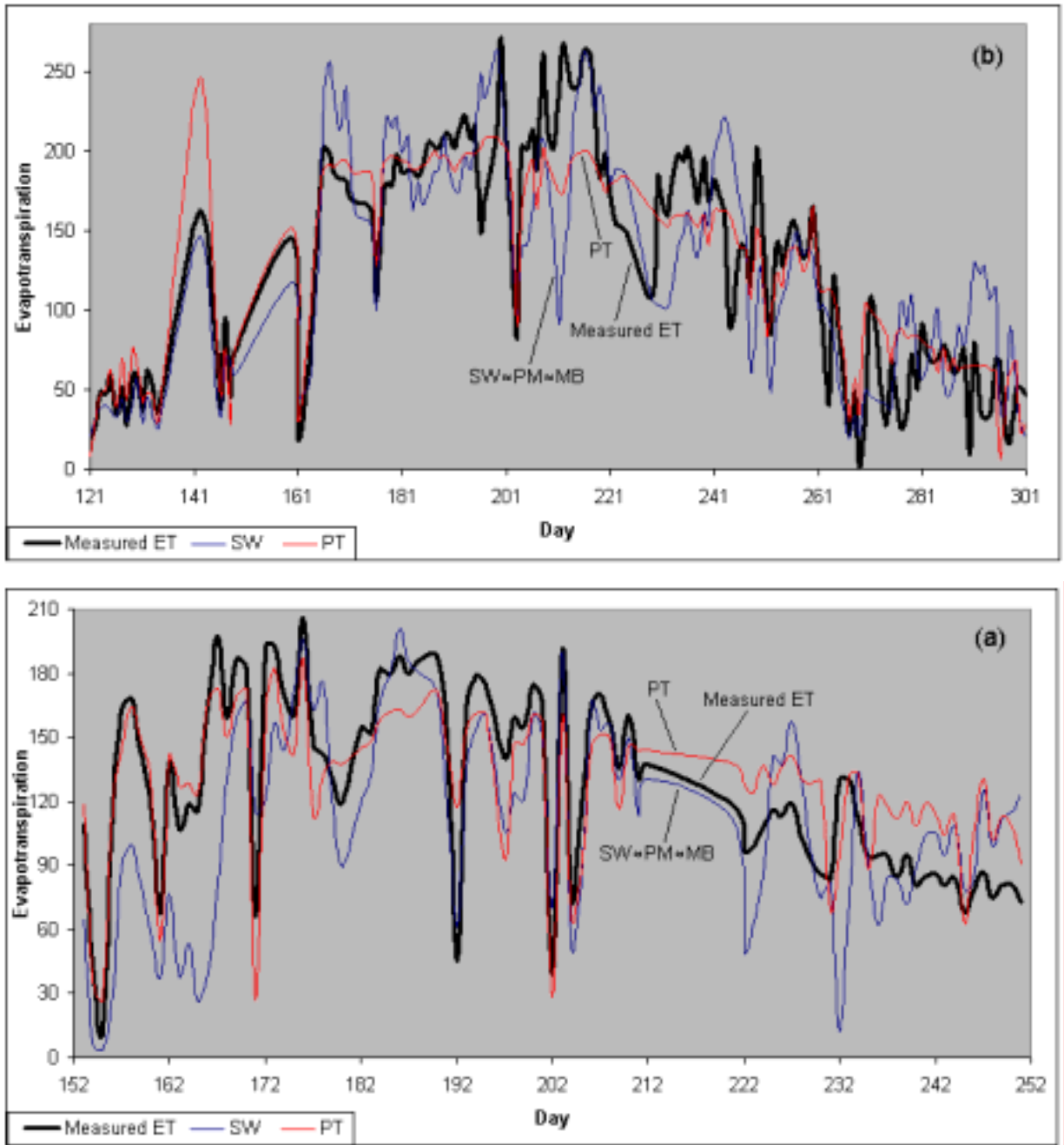

Figure 2. Potential evapotranspiration with soil moisture function for (a) 1997 and (b) 1998. Penman-Monteith (PM) and McNaughton-Black (MB) excluded due to similarity to Shuttleworth-Wallace (SW). The soil moisture function brought the simulations down to good approximations of measured evapotranspiration (Measured ET). Penman method excluded due to extreme overprediction.
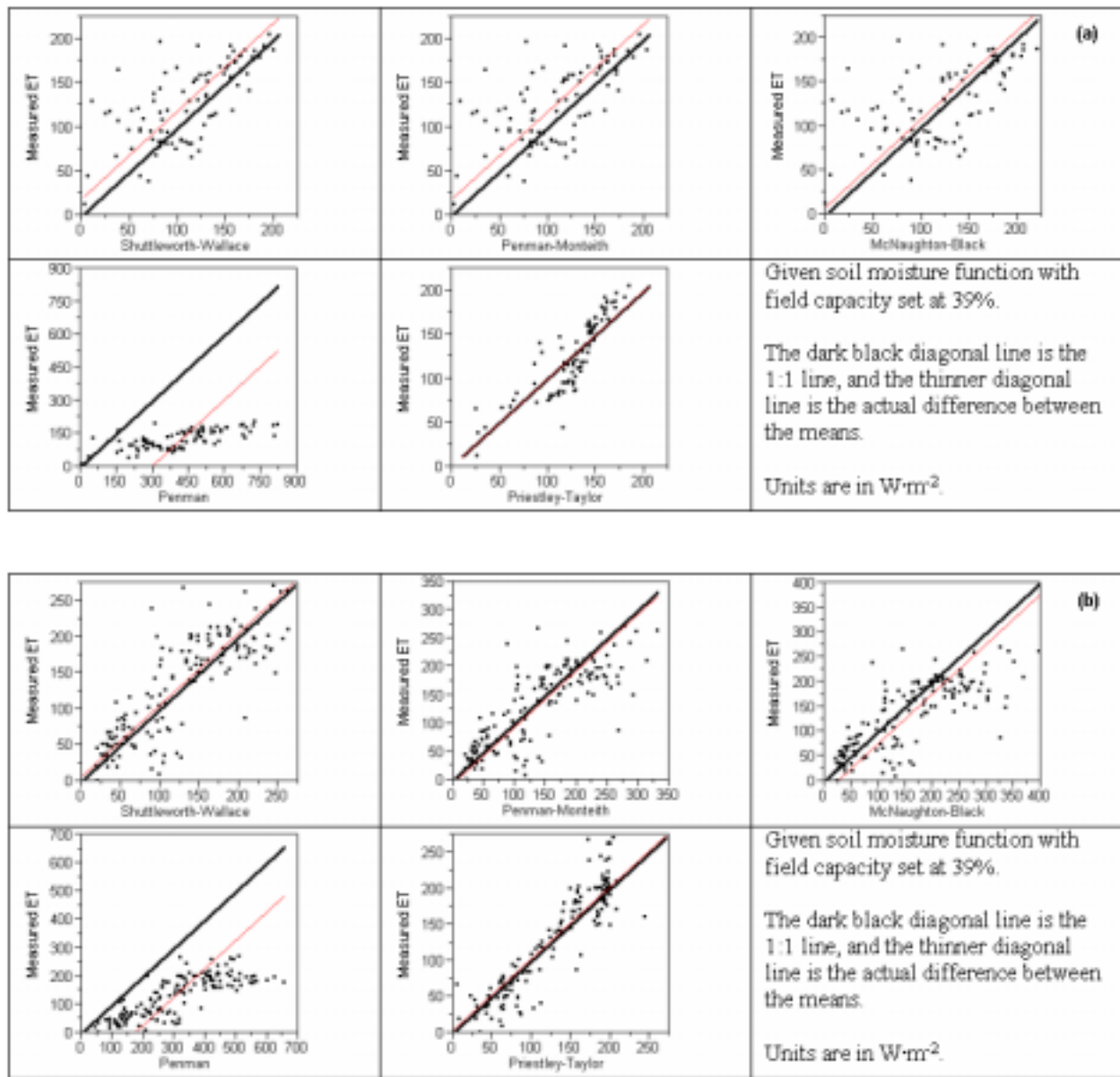
Figure 3. Simulated versus measured evapotranspiration during (a) 1997 and (b) 1998. Shuttleworth-Wallace, Penman-Monteith, and McNaughton-Black perform similarly. Penman is noticeably significantly different whereas Priestley-Taylor is not significantly different than a true difference of 0 (the 1:1 line) in both years.

Many ecological models use potential evapotranspiration functions on continental and global scales, and are subject to the same overprediction of actual evapotranspiration because of such assumptions. Thus, a need for relating potential to actual evapotranspiration exists in these and future models. The Priestley-Taylor method may be most applicable to continental and global models. This model is easier to parameterize than the widely used Penman-Monteith and its accuracy at Blodgett is better than the results simulated by Penman-Monteith.

Additional factors affecting the relationship between simulated and actual evapotranspiration include vegetative quality and external factors—that is, evapotranspiration may not be a simple function of temperature, radiation, vapor pressure deficit, etc. For example, ozone deposition, grazing of insects on leaves, the influence of animals such as cows on the environment, and disease are not taken into account when modeling evapotranspiration. Aside from systematic errors associated with the eddy covariance method, possible bias in the data and models include assumed values for three Shuttleworth-Wallace variables—surface resistance of the substrate, roughness length of bare substrate, and extinction coefficient of the crop for net radiation. I halved, doubled, and multiplied each parameter by a factor of 10 to test for sensitivity; nonetheless, Shuttleworth-Wallace is not highly sensitive to these parameters. Simulated evapotranspiration differed by less than 5% given the changes in these parameters. For Shuttleworth-Wallace, Penman-Monteith, and McNaughton-Black, I used a constant stomatal resistance throughout both seasons derived from the minimum and maximum values measured at the site. The models are highly sensitive to stomatal resistance and simulated evapotranspiration differed by as much as 26% at the minimum stomatal resistance and 20% at the maximum stomatal resistance. A major environmental phenomenon influencing the data was the occurrence of an El Niño event before the summer of 1998. The vegetation grew significantly and the heterogeneity across seasons allowed for ideal comparisons of the same site under different environmental conditions.

Shuttleworth-Wallace, Penman-Monteith, McNaughton-Black, Priestley-Taylor, and Penman methods for estimating evapotranspiration were compared using data from Ameriflux tower measurements at a ponderosa pine ecosystem. Vörösmarty, Federer et al., in comparing these methods on a global scale, found that the Shuttleworth-Wallace method performed best. In my study, Shuttleworth-Wallace, Penman-Monteith, and McNaughton-Black all yielded similar results; this similarity was because these models are derived from one another, and because of

the insignificant effect of the substrate on evapotranspiration. Given its relative simplicity, Priestley-Taylor performed remarkably well. As Vörösmarty, Federer et al. found, the Penman method performed poorly and is not recommended as a choice for future modeling of evapotranspiration. Integration of all the tower flux sites across the globe will be critical in determining the best possible evapotranspiration method.

Acknowledgements

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