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Testing DRAINMOD-FOREST for predicting evapotranspiration in a mid-rotation pine plantation ☆

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A B S T R A C T

Evapotranspiration (ET) is a key component of the hydrologic cycle in terrestrial ecosystems and accurate description of ET processes is essential for developing reliable ecohydrological models. This study investigated the accuracy of ET prediction by the DRAINMOD-FOREST after its calibration/validation for predicting commonly measured hydrological variables. The model was tested by conducting an eight year simulation of drainage and shallow groundwater dynamics in a managed mid-rotation loblolly pine (*Pinus taeda* L.) plantation located in the coastal plain of North Carolina, USA. Modeled daily ET rates were compared to those measured in the field using the eddy covariance technique. In addition, the wavelet transform and coherence analysis were used to compare ET predictions and measurements on the time–frequency domain. Results showed that DRAINMOD-FOREST accurately predicted annual and monthly ET after a successful calibration and validation using measured drainage rates and water table depth. The model under predicted ET on an annual basis by 2%, while the Nash–Sutcliffe coefficient of model predictions on a monthly basis was 0.78. Results from wavelet transform and coherence analysis demonstrated that the model reasonably captured the high power spectra of ET at an annual scale with significantly high model-data coherency. These results suggested that the calibrated DRAINMOD-FOREST collectively captured key factors and mechanisms controlling ET dynamics in the drained pine plantation. However, the global power spectrum revealed that the model over predicted the power spectrum of ET at an annual scale, suggesting the model may have under predicted canopy conductance during non-growing seasons. In addition, this study also suggested that DRAINMOD-FOREST did not properly capture the seasonal dynamics of ET under extreme drought conditions with deeper water table depths. These results suggested further refinement to parameters, particularly vegetation related, and structures of DRAINMOD-FOREST to achieve better agreement between ET predictions and measurements in the time–frequency domain.

1. Introduction

Computer models are useful tools for studying hydrological, biogeochemical, and physiological processes and understanding their interactions in forest ecosystems (Tian et al., 2013). One of the essential components in modeling forest ecosystems is quantifying evapotranspiration (ET) (Vose et al., 2011; Jasechko et al., 2013). ET is a process that transports water from earth surface to atmosphere, during which water changes from liquid (or snow) to gaseous phase. It is a dominant component of the water balance in forest and other terrestrial ecosystems (Vorosmarty et al., 1998; Jung et al., 2010; Fisher et al., 2011) and inherently interacts with carbon cycling (Law et al., 2002; Mahecha et al., 2010), biogeochemical (Lohse et al., 2009) and physiological processes (Fisher et al., 2011). Quantifying ET is thus essential for both hydrological models (Zhou et al., 2006; Vose et al., 2011) and ecosystem models (Vorosmarty et al., 1998; Vose et al., 2011). However, accurate prediction of ET dynamics is still a challenge

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because of its inherent complexity (Lettenmaier and Famiglietti, 2006; Dietze et al., 2011; Fisher et al., 2011; Wang and Dickinson, 2012; Polhamus et al., 2013).

Existing forest hydrology models usually estimate ET as a function of soil water availability and potential evapotranspiration (PET), which is driven by meteorological data and/or plant characteristics (Fisher et al., 2005). Traditionally forest hydrology modeling studies have focused on predicting discharge, and/or soil water dynamics under different climate conditions and/or management practices (Dai et al., 2010; Amatya and Jha, 2011; Kuras et al., 2012; Ellis et al., 2013; Cristea et al., 2014) and have largely ignored model performance for simulating ET dynamics. This has been generally accepted under the assumption that a model could accurately estimate the ET given a good estimation of other generally available hydrological variables such as flow, water table depth, and soil moisture. This assumption is most likely valid for simulations on long time scales (e.g. annually), but may be problematic for simulating shorter temporal dynamics (seasonally, monthly, weekly or daily). The calibration and application of a model without testing its capability of simulating ET dynamics may result in "getting the right answer for wrong reasons" (Kirchner, 2006).

The lack of model testing against ET measurements may be attributed to the lack of functionality for some models, or, more often, lack of independent field ET measurements. For instance, most forest hydrology models treat plants as a static component (Arora, 2002; Mendez-Barroso et al., 2014). This assumption reduces the complexity of a model, but could lead to bias/errors in hydrological predictions both seasonally (van den Hurk et al., 2003) and inter-annually (Tang et al., 2012). With the advance of techniques in experimentally estimating ET in forest ecosystems (Wilson et al., 2001; Williams et al., 2004; Baldocchi, 2014), more and more researchers have realized the importance of field measurements for improving model accuracy in predicting ET dynamics (Wang et al., 2009; Dietze et al., 2013). Several forest ecosystem modeling studies have attempted to test their models using more detailed water flux/energy measurements from eddy covariance (Baldocchi and Wilson, 2001; Kramer et al., 2002; Baker et al., 2003; Falge et al., 2005; Morales et al., 2005; Sun et al., 2008; Williams et al., 2009; Emanuel et al., 2010; Mahecha et al., 2010; Chen et al., 2013; Vargas et al., 2013). The eddy covariance data have proven to be useful for improving the accuracy of process-based models for estimating the water balance (Santaren et al., 2007), although the uncertainties of ET estimation from eddy flux measurements are well recognized (Oishi et al., 2008; Wang and Dickinson, 2012).

ET dynamics is controlled by physical, biological, and physiological processes that vary on multiple temporal scales including hourly, daily, seasonally, and inter-annually (Baldocchi et al., 2001; Katul et al., 2001; Law et al., 2002). Accurately capturing the temporal variations of ET at various temporal scales and time location (time and frequency domain) is as equally important as precisely quantifying the magnitude of ET. This information is critical for improving model responses to various environmental drivers with different frequencies (Mahecha et al., 2010; Dietze et al., 2011; Stoy et al., 2013). Wavelet coherence analysis is a useful tool to evaluate the association relationship between two non-stationary time series at the time–frequency domain. It has been traditionally applied to evaluate the relationship between different geophysical processes and other environmental factors (Grinsted et al., 2004; Labat, 2005; Vargas et al., 2010; Guan et al., 2011; Carey et al., 2013; Ding et al., 2013; Ouyang et al., 2014). Recently, wavelet coherence analysis techniques have been used for diagnosing model errors and improving model performance in predicting the timing and magnitude of hydrological events (Salerno and Tartari, 2009; Schaefli and Zehe, 2009; Liu et al., 2011), and simulating net ecosystem exchanges and/or energy balance by ecosystem models (Williams et al., 2009; Mahecha et al., 2010; Dietze et al., 2011; Wang et al., 2011; Stoy et al., 2013; Vargas et al., 2013).

DRAINMOD-FOREST (Tian et al., 2012a) is a field scale, process-based, and integrated forest ecosystem model for simulating water, soil carbon (C) and nitrogen (N) cycling, and forest growth in lowland areas with poorly drained soils. The model has been successfully applied to simulate long-term hydrological and biogeochemical processes in artificially drained pine plantations (Tian et al., 2012a,b). A global sensitivity analysis demonstrated the critical role of ET simulation in affecting the predictions of other hydrological and water quality variables (Tian et al., 2014). However, like many other forest hydrological models, DRAINMOD-FOREST and its predecessors have not yet been explicitly tested for simulating ET dynamics because of the limited data available for previous applications. The goal of this study was to evaluate the accuracy of ET predictions of DRAINMOD-FOREST after calibration and validation with commonly measured hydrological variables (drainage and water table depth) from a managed loblolly pine (*Pinus taeda L*) plantation in southeastern United Sates. In addition to traditional methods for evaluating model performance (Moriasi et al., 2007; Bennett et al., 2013), this study utilized wavelet coherence analysis to diagnose potential model errors in predicting ET dynamics on the time and frequency domain. Calibrating DRAINMOD-FOREST to achieve the best agreement between ET predictions and measurements is beyond the scope of this study.

2. Materials and methods

2.1. Study site

The study site is a mid-rotation loblolly pine plantation (35°48′N, 76°40′W), located in the lower coastal plain at the Plymouth County of North Carolina in the southeastern United States. The area is approximately 90 ha and is artificially drained with parallel ditches that are spaced 90 m apart and 0.9–1.30 m deep. The study site is nearly flat and has naturally poorly drained soils with a ground elevation less than 8 m above sea level. Mean annual precipitation during the study period from 2005 to 2012 was 1185 mm (Fig. 1A), about 9% lower than the long-term (1945–2010) average precipitation (1308 ± 201 mm) (Domec et al., 2010). Months from June to October have higher mean monthly precipitation with greater year to year variability due to highly variable convective, tropical, and hurricane events (Fig. 1B). The study period included two consecutive dry years (2007 and 2008) with about 30% less annual precipitation compared to the long-term mean (Fig. 1). The long-term mean air temperature is 15.5 °C and changes from about 6 °C in January to about 25 °C in July and August (Fig. 1B).

The site was planted with loblolly pine in 1992 after the previous pine stand was commercially clear cut. The tree density was about 635 trees ha^{-1} from 2005 to 2009. The stand basal area was 25.1 m^2 ha^{-1} in 2005, and 34.2 m^2 ha^{-1} in August of 2009. The study site was thinned by about 58% in August 2009, after which the basal area reduced to 14.9 m^2 ha^{-1}. Soil in the study site is classified as Belhaven Series (i.e., loamy mixed dysic thermic Terric Haplosaprists) with high organic content (20–95%) in the top 50 cm and sandy loam underneath (Diggs, 2004). A more detailed description of the study site can be found in Domec et al. (2010) and Sun et al. (2010).

2.2. Data collection

Several meteorological variables were continuously measured above the canopy, including relative humidity and air temperature (HMP45AC; Vaisala, Helsinki, Finland), photosynthetic photon flux

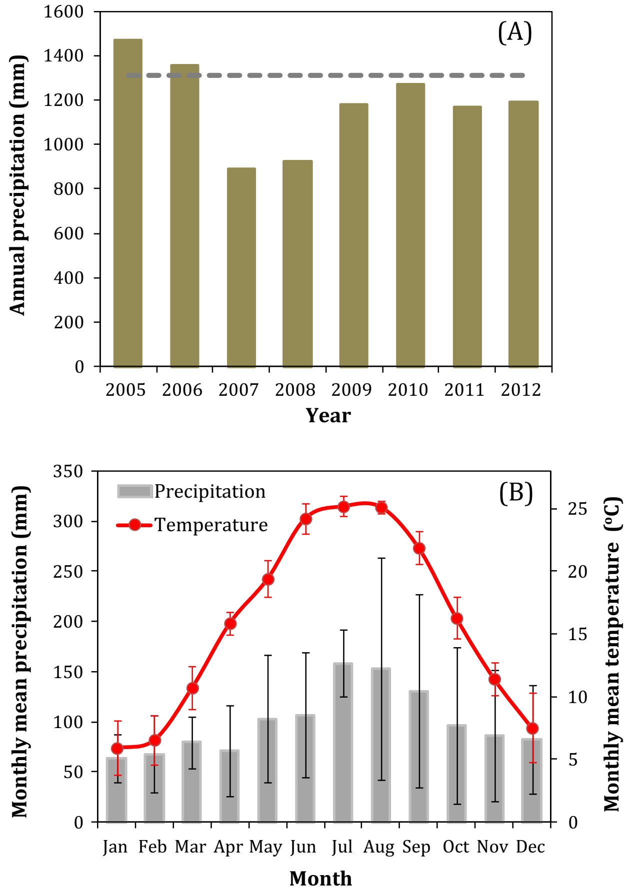

Fig. 1. Climate condition in the study site; (A) Annual total precipitation; (B) Monthly mean temperature and precipitation during the 2005–2012 study period. Dashed line in represents 65-year mean annual precipitation; Error bars are standard deviations.

density (LI-190; LI-COR, INC), and precipitation (TE-525; Campbell Scientific, Logan, UT). These data were recorded at a 30-min interval using data loggers (CR1000 and CR5000, Campbell Scientific, Logan, UT). While this study site was previously instrumented for drainage measurements (Diggs, 2004), flow data were only available during the second half of the study period (2009–2012). Flow rates were determined from stage measurements above a V-notch weir. Water table depth was recorded at 1-h intervals with a WL40 pressure transducer (Global Water, Port Orange, FL) installed in monitoring wells (220 cm deep) located between two drainage ditches and less than 15 m from the eddy flux towers.

Canopy latent heat (λE) fluxes were measured using an open-path infrared gas analyzer (LI-7500; LI-COR, Inc.) and a three-dimensional sonic anemometer (CSAT3; Campbell Scientific, Logan, UT) that was installed on an eddy covariance tower, located in the middle of the stand. The 30-min mean fluxes of H_2O were calculated as the covariance of vertical wind speed and the concentration of H_2O, representing the total ET. Data quality was judged by criteria including atmospheric stability and flux stationarity during periods of well-developed turbulence as reported previously (Noormets et al., 2008). Spurious or incomplete half-hourly data resulting from system malfunction or environmental disturbance were screened. Gaps in 30-min ET data were filled using empirical monthly correlations between observed ET and Food and Agriculture Organization PET (Noormets et al., 2010; Sun et al., 2010). Detailed description of ET measurements and gap filling methods were reported previously (Noormets et al., 2010; Sun et al., 2010).

2.3. Brief description of DRAINMOD-FOREST model

DRAINMOD-FOREST (Tian, 2011; Tian et al., 2012a) is an integrated, process-based field-scale model for simulating hydrology, soil C and N dynamics, and forest growth in drained forest lands under silvicultural and water management practices. It was developed by linking a modified forest growth model (Landsberg and Waring, 1997) to the hydrologic model DRAINMOD and the modified soil C and N model DRAINMOD-N II. The model has been used for simulating long-term hydrological and biogeochemical responses of forest to various management practices (Tian et al., 2012a, 2013).

The hydrological component, DRAINMOD (Skaggs, 1978; Skaggs et al., 1999), calculates a water balance at the soil surface and along a soil column midway between two parallel drains on an hourly basis. At each time step, the model simulates key hydrological processes such as infiltration, ET, subsurface drainage, surface runoff, subirrigation, deep and lateral seepage, water table fluctuation and soil water distribution in the vadose zone. The soil C and N component, DRAINMOD-NII simulates detailed N transformation processes including atmospheric deposition, application of mineral N fertilizers and organic N sources, plant uptake, N mineralization/immobilization, nitrification, denitrification, ammonia volatilization, and mineral N losses via vertical seepage to an underlying aquifer, lateral subsurface drainage, and surface runoff (Youssef et al., 2005). Recently, DRAINMOD-NII was modified for simulating DON leaching losses from both drained agricultural and forest ecosystems and was incorporated into the DRAINMOD-FOREST model to simulate the long-term nitrogen export dynamics from several loblolly pine plantations (Tian et al., 2013).

The forest growth component is based on the 3-PG model (Landsberg and Waring, 1997), which simulates net primary production using radiation use efficiency and allocates fixed C to different tree components (leaf, stem and root) using species dependent allometric relationships. Photosynthetic processes of the forest canopy are constrained by air temperature and the availability of soil water and mineral N. The model also simulates the effects of commonly used forest management practices including N fertilizer application, thinning, pruning, harvesting, site preparation, and regeneration on C and N cycling in forest ecosystems. Carbon inputs to forest floor from foliage litterfall are estimated as a function of leaf longevity, and fine root turnover is quantified based on fine root lifespan.

The three components inherently interact with each other to represent the interactions occurring among the simulated processes. Predicted foliage litterfall and root turnover are used to update OM pools simulated by DRAINMOD-N II. The leaf area index (LAI) predicted by the forest growth model is a critical variable for estimating rainfall interception and ET. The plant growth model and modifications to the original hydrology model for simulating rainfall interception, ET, and Penman–Monteith based potential ET are described in Tian et al. (2012b). DRAINMOD-FOREST model has been calibrated and validated for predicting water table fluctuation, subsurface drainage fluxes, mineral N export, dissolved organic nitrogen losses, and tree growth for drained loblolly pine plantations under limited and intensive water management and silvicultural management practices (Tian et al., 2012a, 2013).

2.4. Model calibration, parameterization, and validation

DRAINMOD-FOREST requires three groups of model parameters: hydrologic, soil C and N, and vegetation (Tian et al., 2012a). In this study, we evenly divided the study period into calibration (2009–2012) and validation (2005–2008) periods. The simulation was initialized following strategies described by Tian et al. (2012a). Initial water table level was defined according to field measurements and biomass stock was estimated based on tree measurements including height, LAI, diameter (Sun et al., 2010). We calibrated the model by comparing model predictions of water table depth and drainage flux to field measurements following the procedure described by Tian et al. (2012a). Since no flow data were available during the validation period, we only validated the model performance using water table depth data collected from 2005 to 2008. The C and N parameters and the vegetation parameters were taken from the previous model applications of DRAINMOD-FOREST in the same region (Tian et al., 2012a,b). Drainage system and calibrated model parameters characterizing this study site are summarized in Table 1.

2.5. Model performance and error diagnosis using wavelet coherence analysis

Several statistical measures including Nash–Sutcliffe coefficient (NSE), mean absolute error (MAE) and percent bias (PBIAS) were used as goodness-of-fit indices to assess model performance (Moriasi et al., 2007; Bennett et al., 2013). These conventional model performance indices provide an aggregate view of agreements between modeled and measured results; however, they are limited with respect to information needed for diagnosing when and at what temporal scales the model fails or succeeds. Therefore, conventional model evaluation methods have difficulty diagnosing the underlying causes of the lack of agreement between models and measurements.

To better diagnose model errors in simulating ET dynamics, we used wavelet transform techniques and wavelet coherence analysis to evaluate the correlation between measured and modeled ET. The wavelet transform partitions the variance of the time series into both frequency and time domain by varying the width of the mother wavelet (Torrence and Compo, 1998; Grinsted et al., 2004). Given a time series $X = \{x_n, n = 1, 2, \ldots\ldots, N)\}$ with a uniform time step of δt, its wavelet transform $W_n^X(s)$ at time τ and scale s can be written as:

$$W_n^X(s) = \sum_{n=1}^{N-1} x_n \psi^*\left(\frac{n-\tau}{s}\right)\delta t$$

where ψ is the mother wavelet function, $*$ denotes the complex conjugate. In this study, the Morlet wavelet function was chosen for the wavelet transform:

$$\psi(n) = \pi^{-1/4} e^{-i\omega_0 n} e^{(-n^2/2)}$$

where i is the imaginary complex number, ω_0 is dimensionless frequency and equals 6 in this study to provide a balance between time and frequency localization.

The cross wavelet transform ($W_n^{XY}(s)$) was used to illustrate common locations with high power of two non-stationary time series X and Y. It can be written as:

$$W_n^{XY}(s) = W_n^X(s) W_n^{Y*}(s)$$

The wavelet coherency ($R^2(s)$) was further calculated to quantify a statistical relationship between the two non-stationary time series on the time and frequency space, and is defined as:

$$R^2(s) = \frac{\left|S\left(s^{-1} W_n^{XY}(s)\right)\right|^2}{S\left(s^{-1}|W_n^X(s)|^2\right) \cdot S\left(s^{-1}|W_n^Y(s)|^2\right)}$$

where S is a smoothing operator; W_n^{XY} is the cross-wavelet spectrum of time series of X and Y. The wavelet coherence resembles the traditional correlation coefficient but localized in time frequency domain. The value of wavelet coherence ranges from 0 to 1, with 0 suggesting no correlation, and 1 indicating perfect linear relation at a particular time and frequency between two time series. It is worthy to note that high coherence between two wavelet spectra reflect similar oscillations occurring in each series at the frequency of interest, but does not indicate correlation at high power as is revealed by the cross wavelet transform. The method used for quantifying statistical significance level of the wavelet coherence and detailed description of wavelet coherence analysis can be found elsewhere (Torrence and Compo, 1998; Grinsted et al., 2004).

Following the suggestion of Torrence and Compo (1998) and Grinsted et al. (2004), we applied zero padding strategy to avoid errors occurring at the beginning and end of the wavelet power spectrum for finite-length time series. The zone with edge effects is called the "cone of influence" (Torrence and Campo 1998) and the spectral information in the zone lacks accuracy and should be interpreted with caution. The wavelet coherence analysis was carried out using a free Matlab-software package (WTC-R15), provided by the Proudman Oceanographic Laboratory of the Natural Environment Research Council (NERC-UK) (Grinsted et al., 2004). This software was used to construct the cross wavelet transform from two time series, exposing their common power and relative phase in time–frequency space. The package also calculates the coherency and provides corresponding information on significance. Since this continuous wavelet transform and cross wavelet analysis require continuous time series without gaps, gap filled ET measurements were used for this study. To minimize effects of data points from gap-filling, the wavelet analyses were only conducted for a period from 2005 to 2009, when the eddy covariance measurements had high quality with minimal missing data (Sun et al., 2010; Domec et al., 2012b).

Table 1
Drainage system characteristics and calibrated parameters for DRAINMOD-FOREST.

Parameters	Value			
Drainage system (Diggs, 2004b)				
Drain spacing (m)	90			
Drain depth (m)	1.1			
Depth to impermeable layer (m)	2.5			
Surface storage (cm)	15			
Kirkham's depth (cm)	10			
Effective drain radius (cm)	30			
Drainage coefficient (cm d^{-1})	5.0			
Soil physical properties				
Soil layer (cm)	0–30	30–45	45–75	60–250
Effective hydraulic conductivity (m d^{-1})	165	84	2.4	1.2
Drainable porosity	0.15	0.13	0.11	0.1
Saturated water content (cm^3 cm^{-3})	0.41	0.43	0.44	0.45
Bulk density (g cm^{-3})	1.0	1.1	1.3	1.3
Water content at wilting point (cm^3 cm^{-3})	0.18	0.21	0.22	0.24
Vegetation related parameter				
Specific leaf area (m^2 kg^{-1})	5.9			
Leaf longevity (month)	19			
Extinction coefficient	0.52			

3. Results and discussion

3.1. Model performance in simulating drainage and water table depth

As shown in the scatter plots (Fig. 2A and B) and statistical measures (Table 2), predicted daily and monthly drainage rates are in good agreement with field measurements during the model calibration period from 2009 to 2012. Predicted daily mean drainage was 1.3 ± 2.7 mm day^{-1}, which is comparable to measured value

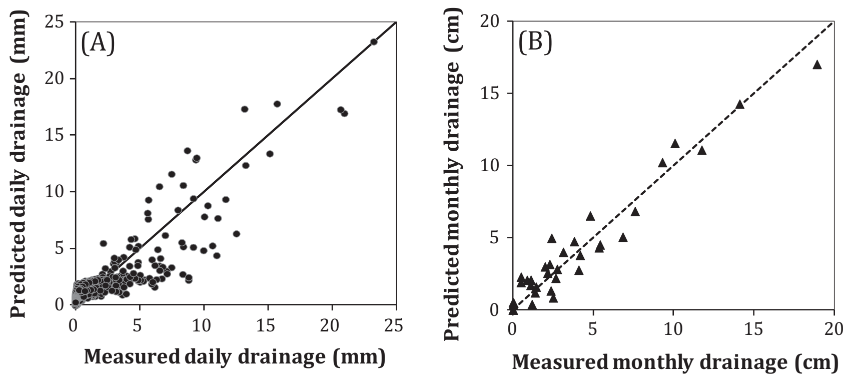

Fig. 2. Comparison between measured and predicted drainage during model calibration period from 2009 to 2012, (A): daily basis and (B): monthly basis; Solid and dashed lines are 1:1 line.

Table 2
Statistical measures of model performance for predicting daily and monthly drainage, daily water table depth (WTD) during model calibration (2009–2012) and validation periods (2005–2008).

		NSE	MAE	PBIAS (%)
Calibration	Daily drainage (mm)	0.85	0.53	13
	Monthly drainage (mm)	0.91	10.3	7
	Daily WTD (cm)	0.82	13.6	−0.3
Validation	Daily WTD (cm)	0.87	12.2	−0.3

of 1.1 ± 2.8 mm day^{-1}. Predicted monthly mean drainage was 38 ± 39 mm month^{-1}, which is comparable to measured value of 34 ± 42 mm month^{-1}. The goodness-of-fit statistics (Table 2) of drainage predictions suggested very good model predictions of daily and monthly drainage. Similarly, visual comparison (Fig. 3) and statistical measures (Table 2) showed that the model accurately predicted temporal fluctuations of water table depths on a daily basis. Predicted long-term mean water table depth was 114 ± 67 cm, comparable to the measured value of 110 ± 65 cm. The NSE and PBIAS values (Table 2) suggested very good model performance in simulating water table dynamics (Moriasi et al., 2007). Model performance measures during the calibration period exhibited lower NSE, higher MAE and PBIAS, compared to those during model validation period. However, these differences were insignificant ($p > 0.2$, $df = 4$) according to a student *t*-test, suggesting comparable model performance for predicting daily water table depth during calibration and validation periods. The slightly different model performance during calibration and validation might be attributed to post-thinning emerging understory vegetation that occurred during the calibration period (Domec et al., 2012b) and large gaps (September 2011–April 2012) of measured climate data. Overall, the model performance in predicting these hydrological variables is consistent with previous model applications in the same region (Tian et al., 2012a, 2012b).

This statistical analysis demonstrated that DRAINMOD-FOREST accurately predicted drainage dynamics and water table depth fluctuations (Table 2). Nevertheless, the scatter plots showed somewhat large discrepancies between predicted and measured daily drainage rates that were below 5 mm day^{-1} (Fig. 2A) and water table depths that were shallower than 50 cm (Fig. 3). These discrepancies between model predictions and measurements can be partially attributed to the gap-filled weather data during periods without on-site measurements, especially during the period of August of 2011 to June of 2012 when the tower was not operative. In addition, model errors in fine time scales can also be caused by the assumed hydrostatic conditions under both recharge and discharge phases and inaccurate representation of the relationship between drainage volume and water table depth in DRAINMOD-FOREST (Tian et al., 2012a).

3.2. Comparison between predicted and measured ET over different time scales

After calibrating and validating DRAINMOD-FOREST for simulating drainage and water table depth, predicted ET were compared to field measurements at various temporal scales. The model accurately predicted the inter-annual variations of ET (Table 3). Predicted annual ET varied from 903 mm in 2008 to 1170 mm in 2006, with a mean of 1018 mm over the period from 2005 to 2009. These predictions were comparable to field measurements, which ranged from 927 mm to 1226 mm, with mean annual ET of 1038 mm. Predicted rainfall interception is about 9.2% over the

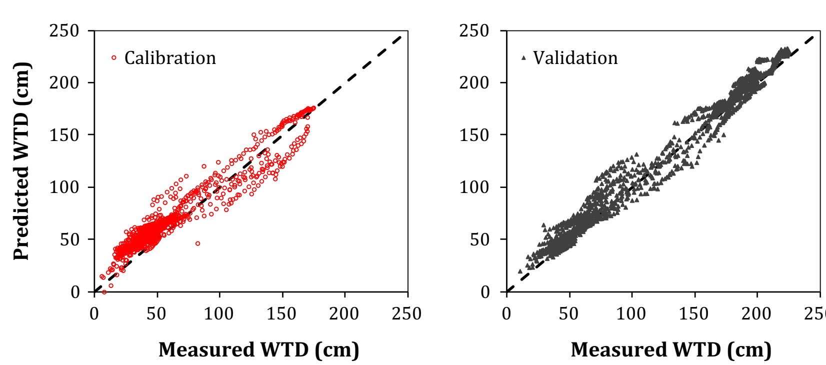

Fig. 3. Comparison between predicted and measured water table depths (WTD) during calibration and validation periods.

Table 3
Predicted and measured annual ET (mm yr^{-1}) from 2005 to 2009.

	2005	2006	2007	2008	2009	Mean
Measured	1024	1226	1011	927	1001	1038
Predicted	1023	1170	1027	903	969	1018
PBIAS	−0.1%	−4.5%	1.6%	−2.6%	−3.2%	−1.9%

study period, which is comparable to but lower than measured interception during the period from 2007 to 2009 (Domec et al., 2012b). As suggested by PBIAS, DRAINMOD-FOREST under-predicted annual ET in 4 of the 5 years from 2005 to 2009, though the deviation between prediction and measurement was relatively small (−1.9%). Given the accurate prediction in drainage (Fig. 2), the good model performance in predicting annual ET dynamics was expected because the hydrologic component of DRAINMOD-FOREST conducts a water balance at each time step (Skaggs et al., 2012; Tian et al., 2012a).

As illustrated in Fig. 4, DRAINMOD-FOREST reasonably captured temporal variations of daily ET dynamics. The 30-day moving average curves of predictions and measurements matched well during most of the period of simulation. Consistent with field measurements, predicted peak daily ET rates were between 6.1 and 6.7 mm day^{-1} during summer seasons. The goodness-of-fit statistics (Table 4) for monthly ET predictions were: NSE = 0.78, MAE = 13.5 mm $month^{-1}$, and PBIAS = −3.2%. Nevertheless, model predictions were not in very good agreement with field measurements on a daily basis. The goodness-of-fit statistics (Table 4) for daily ET predictions were: NSE = 0.44, MAE = 0.45 mm day^{-1}, and PBIAS = −11.6%. The largest discrepancy between predictions and measurements mainly occurred during non-growing seasons. By simply defining the non-growing season as November to February, we specifically calculated PBIAS during these periods. Results showed that the predicted mean monthly ET during the non-growing period is 23 mm, lower than field measurements (41 mm $month^{-1}$) by approximately 45%. Underestimation of ET (latent heat) during winter and spring seasons was also reported for some land surface models (Chen et al., 2013).

Evidently the model performed better simulating daily and monthly ET rates over the period from 2005 to 2008, compared to the period from 2009 to 2012 (Table 4). This is consistent with model performance of simulating water table depth (Table 2) and could be mainly caused by the disturbances and uncertainties introduced by thinning during August 2009. The thinning practice abruptly reduced canopy coverage and tree leaf area index, which induced early succession of understory species (Domec et al., 2012b). Additionally, larger model-data discrepancy during 2009 and 2012 could be due to the long-period of missing data caused by frequent failure of sensors and the lack of the eddy flux tower data from September 2011 to April 2012.

Table 4
Statistical measures of model performance for predicting daily ET through the study period. Monthly comparison was conducted based on gap filled monthly ET.

	Daily ET			Monthly ET		
	NSE	MAE (mm day^{-1})	PBIAS (%)	NSE	MAE (mm $month^{-1}$)	PBIAS (%)
2005–2008	0.62	0.45	−12.3	0.84	13.4	−2.3
2009–2012	0.24	0.42	−9.0	0.73	13.6	−3.9
Overall	0.44	0.43	−11.6	0.78	13.5	−3.2

3.3. Wavelet and wavelet coherence analysis

This study applied wavelet transform to explore the temporal dynamics of the predicted and measured ET. Fig. 5 shows the wavelet transform spectrum of measurements, predictions, and corresponding percent errors from 2005 through 2009. It illustrates that DRAINMOD-FOREST generally reproduced the dynamics of ET across different time scales. Specifically, both field measurements (Fig. 5A) and model predictions (Fig. 5B) showed: (1) significant high power spectra at an annual basis (256–512 days); and (2) very low power at periods less than 30 days, especially during winter seasons, and (3) occasionally high power at period less 8 days during summer seasons. The finding that ET typically show a strong power spectra on an annual scale is consistent with other studies (Baldocchi et al., 2001; Mahecha et al., 2010; Dietze et al., 2011; Wang et al., 2011; Vargas et al., 2013).

Fig. 5C shows that percent error has similar spectral signature as measured and predicted ET, suggesting model errors were associated the fluctuations of ET. Percent error of model predictions showed high power at period around 128 days during the first 3 years. More importantly, results showed that percent error of model predictions depicted constant strong power spectra at the annual scale through the study period. Similar spectral patterns of model residual for simulating ET dynamics were also reported for multiple ecosystem models (Dietze et al., 2011; Wang et al., 2011; Vargas et al., 2013). At shorter temporal scales (less than 8 days), it is noticeable that the locations with large power of percent error were contrast to that of measurements and mainly occurred during non-growing seasons. On the other hand, low power of percent error typically occurred during peak growing seasons (Fig. 5C), when ET measurements exhibit high power (Fig. 5A). These findings suggested that there are systematic errors of the model simulation, which is consistent with the finding that the model consistently under predicted ET during non-growing seasons (Fig. 4).

Fig. 6(A) showed the cross wavelet power spectrum between measured and predicted daily ET. There was significant common power in the annual band (period from 256 to 512) during the study period. Model predictions and measurements were not only

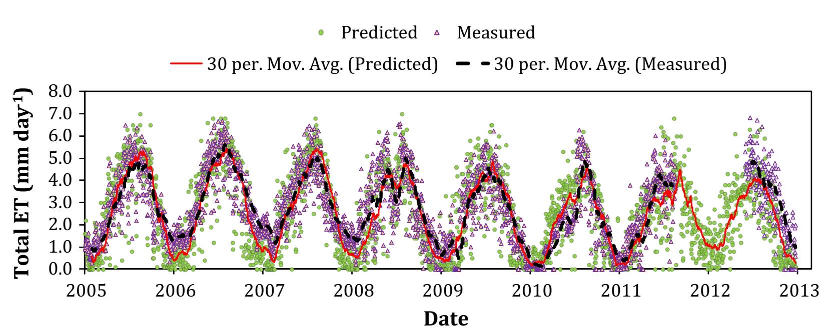

Fig. 4. Predicted and measured daily total evapotranspiration (ET) from 2005 to 2012. The dashed and solid lines are 30-day moving average curve for field measurements and model predictions, respectively.

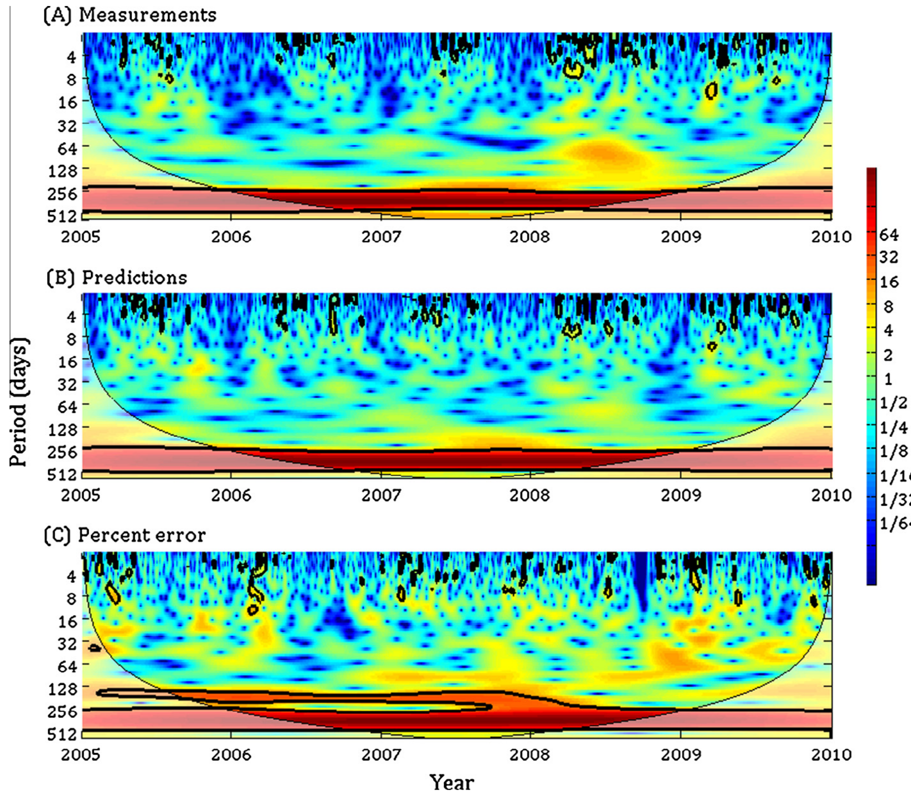

Fig. 5. Wavelet transform of daily ET rates from (A) field measurements, (B) model predictions, and (C) percent error of model simulation, which is calculated as (Prediction-Measurement) /Measurement. The faded areas outlined by black curves indicate the cone of influence (COI) regions. Areas of high spectral power are indicated by with dark red representing the highest power, while low power is indicated by dark blue representing the lowest power. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

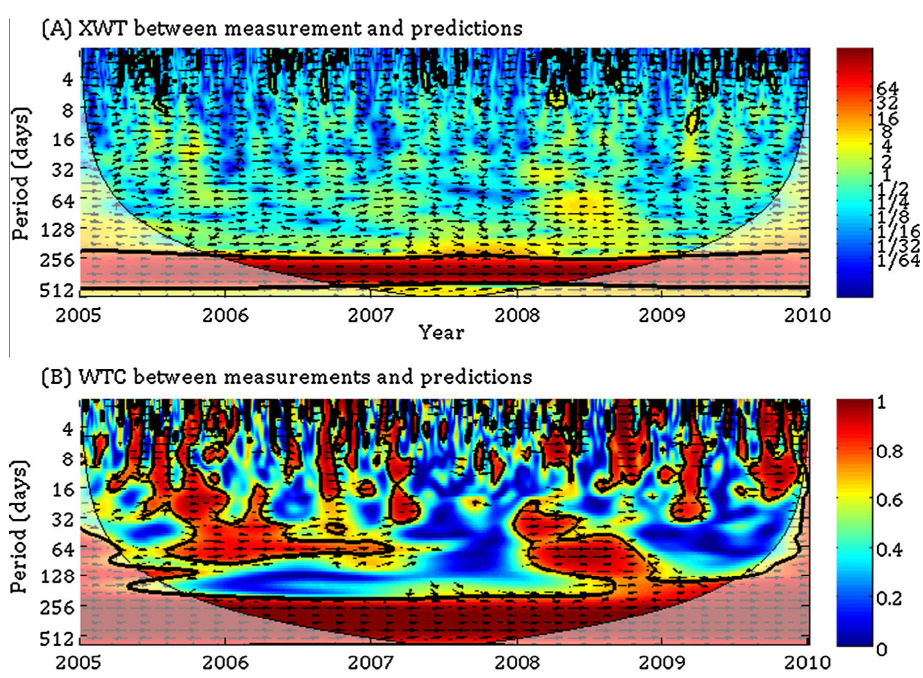

Fig. 6. (A) The cross wavelet (XWT) power spectrum (on the $\log_2$ scale) and (B) wavelet coherence (WTC) between the observed and simulated daily ET from 2005 to 2009. The shaded white areas outlined by black curves indicate the cone of influence (COI) regions. Arrows indicate the phase difference between model predictions and field measurements of the wavelet spectra (right arrows indicate series are in phase, left arrows indicate series are completely out of phase (180°), and an arrow pointing vertically upward means the second series lags the first by 90° (i.e., the phase angle is 270°). Thicker lines bounding areas of red indicate significant coherence at the 95% level against red noise. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in-phase (indicated by right arrows) in sectors with significant common power, but also across most of the area of the time–frequency domain. These findings indicated that DRAINMOD-FOREST generally captured the variations of ET in the study site over various temporal scales. Nevertheless, we noticed that (1) model predictions and field measurements were anti-phased (left arrow) at the seasonal scale (period 128–256) during the year of 2006, and predictions lead by about 45–90° (about 1.5 months) during the middle of 2007 at the same scale; (2) model predictions and measurements were out-of-phase (without clear delay or lead) at the monthly scale (period 32–64) during the second half year of 2007, as well as at monthly to seasonal scales (period 32–128) during the winter of 2009.

Fig. 6(B) illustrated the wavelet coherence between measured and predicted ET dynamics over part of the study period with high quality eddy covariance measurements. The wavelet coherence plots suggested significant correlation (areas outlined with thick dark line) between model predictions and field measurements on most areas of the time–frequency domain. However, it should be noted that the wavelet coherence reflects the timing of fluctuations but not necessarily their magnitude. In other words, wavelet coherence tests the match of temporal pattern, rather than magnitudes. It is noticeable that model predictions and field measurements were closely correlated at the annual basis (256–512 days). Additionally, strong prediction-measurement coherency occurred at monthly time scales (30–64 days) during half of the comparison period, except for years of 2007 and 2009, which is consistent with the phase interpretation of power spectrum of the cross wavelet transform (Fig. 6A). This finding revealed that the model predictions did not accurately reproduce ET fluctuations during the dry period in 2007. Moreover, there is very weak coherency between model prediction and measurements at the frequency between 2 months and 4 months (64–160 days), suggesting the model did not fully capture the ET fluctuations on a seasonal basis. There is also weak model-data coherence at daily to weekly time scales (1–16 days), especially during winter season, which is consistent with the graphical comparison and traditional statistical measures (Fig. 4).

3.4. Implications, limitations and recommendations

This study calibrated DRAINMOD-FOREST using 4-years of measured drainage and WTD data and validated the model using a separate 4-year period of measurements of WTD. Results (Figs. 2 and 3, and Table 2) showed that the model accurately predicted these traditionally measured hydrological variables. Comparisons between predicted and measured ET demonstrated that DRAINMOD-FOREST reasonably predicted annual and seasonal variations of ET (Table 3, Fig. 4). Goodness-of-fit statistics (Table 4) showed that the model, after calibration and validation for simulating drainage and WTD, could accurately predict ET at both monthly and annual scales, but not on a daily scale. The wavelet analysis provided consistent information on good model performance in simulating annual ET dynamics, as suggested by the significant and constant high coherence and perfect phase agreement between model predictions and measurements at an annual scale (256–512 days) (Fig. 6). However, wavelet analysis revealed that percent error had high power spectrum at annual scale (Fig. 5C), and predictions and measurements were occasionally out of phase (Fig. 6A) with low coherency (Fig. 6B) at monthly to seasonal scales.

It is difficult to visually compare the overall magnitude of power for predicted and measured ET from Fig. 5. Thus, we further calculated the global wavelet spectra of measurements and model predictions (Fig. 7), which illustrated that the changes of power spectrum of predicted ET closely followed that of field measurements. However, the magnitude of the power spectrum was largely different. The ratio of global power spectrum between model predictions and measurements suggested that the model over-predicted temporal variability by approximately 52% at an annual scale, and by about 18% at a seasonal scale (Fig. 7). It is also noticeable that the model over predicted ET variations by approximately 41% at weekly to monthly scales, though the magnitude of power spectra is relatively small at this scale. An over-estimation of the spectral power at annual scale of ET implied that the model overpredicted annual oscillations of ET. This was mainly attributed to under-prediction of ET during non-growing seasons (Fig. 4), which enlarged the variations of ET during each year. Since the study site typically had sufficient water supply during non-growing seasons (Domec et al., 2012b), this underestimation of ET was mainly caused by PET estimation. Under-estimation of PET during non-growing seasons was mainly caused by under-predictions of canopy conductance, which is a function of leaf area index and stomatal conductance in DRAINMOD-FOREST (Tian et al., 2012a,b). In this study, predicted minimum LAI during the non-growing season of each year ranged from 2.5 to 3.2 $m^2\ m^{-2}$, which is comparable to field measurements (Sun et al., 2010; Domec et al., 2012b). Thus, stomatal conductance was more likely under-estimated during non-growing seasons. This can be attributed to either model parameterization or model structure deficiencies in representing responses of stomatal conductance to climate conditions in non-growing seasons.

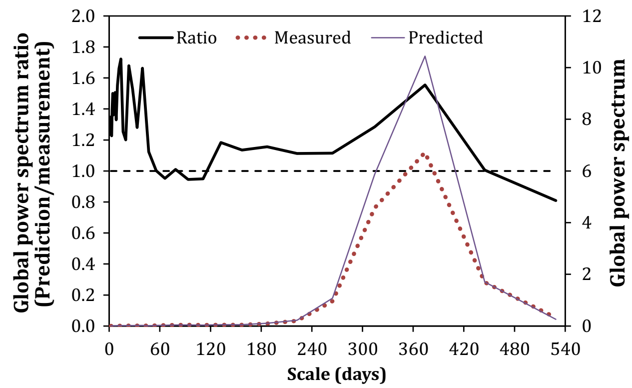

Fig. 7. Global wavelet spectra for measured and predicted daily ET and their ratios from 2005 to 2009.

Results showed that predictions and measurements were out of phase in several locations (Fig. 6A) and with very low coherence at monthly to seasonal scales (Fig. 6B), especially during the dry year of 2007. It is known that soil moisture dynamics is one of the key factors affecting monthly and seasonal variations of ET and it is challenging to simulate ET dynamics under drought conditions (Vargas et al., 2013). This discrepancy between predictions and measurements can be either attributed to errors in soil moisture predictions or ET simulation under soil moisture limited conditions. In DRAINMOD-FOREST, the soil water content in the unsaturated zone is estimated by assuming a drained-to-equilibrium condition, which is dynamically linked to changes in soil water table depth (Skaggs et al., 2012). In addition to the potential bias in predicting soil moisture dynamics that are inherent with the hydrostatic assumption, errors in predicting water table depth also contribute to the ET prediction and measurements discrepancies. For instance, DRAINMOD-FOREST continuously over-predicted water table depth by approximately 14.8 cm from March to October in 2006, which may be the principal reason for the low coherence between predictions and measurements at the seasonal scale in 2006 (Fig. 6B).

Modeled-to-measured data comparisons also depicted low coherency on monthly to seasonal scales during the dry year 2007, but not during the second consecutive dry year in 2008 (Fig. 6B). Meanwhile, the model over predicted the power spectra of ET during 2007 but under predicted that during 2008 (Fig. 5). These findings revealed that the model did not properly and fully capture drought effects on ET dynamics. The predicted effects of drought on ET were delayed by one growing season, which explained the relatively high coherency during 2008. Accordingly, the low model-data coherency in 2009 was possibly caused by the exaggerated carryover effects of drought from 2008. Improper quantification of drought effects on ET is not unique to DRAINMOD-FOREST and is common for other models as well (Ichii et al., 2009; Soylu et al., 2011; Wang et al., 2011; Vargas et al., 2013; Zhou et al., 2013). In DRAINMOD-FOREST, the misrepresentation of plant responses to drought is likely due to the fact that the model does not explicitly consider the effect of soil water deficit on root elongation and stomatal conductance. It is known that root growth of loblolly pine could shift downward under drought conditions (Torreano and Morris, 1998; Joslin et al., 2000). In addition, other research on the study site showed that the severe drought in 2007 significantly decreased stomatal conductance (Domec et al., 2009), which is not explicitly considered in DRAINMOD-FOREST. Incorporating a more mechanistic algorithm to directly consider drought impacts on root growth (Bengough et al., 2011), stomatal conductance (Domec et al., 2009), and better simulate root water uptake (Manoli et al., 2014) could improve model performance during periods of drought.

Previously discussed potential sources of error more or less also contributed to the discrepancies between ET predictions and field measurements on a daily basis. However, we cannot exclude other factors that may also contribute to model-data deviations at a daily scale. For example, the deviation between daily predictions and field measurements could also be partially attributed to the lag time effects between soil water depletion and stand water losses (Domec et al., 2012b). Meanwhile, the assumed instantaneous stomatal responses to fluctuations in environmental variables may not be appropriate for rapidly changing conditions on short temporal scales (Ward et al., 2008). In addition, DRAINMOD-FOREST does not consider the phenomenon of hydraulic redistribution, which is a process passively transferring water from deeper wet soil layers to an upper drier soil layers by roots (Domec et al., 2010). On-site experimental studies have shown that hydraulic redistribution could be a key mechanism for regulating ET and could account for 15–25% of total water losses during dry seasons (Domec et al., 2010, 2012a,b). Lastly, we cannot exclude contributions from potential errors in eddy covariance measurements to model-data deviation. ET measurement bias/errors due to the lack of energy closure is very common to eddy covariance studies (Wilson et al., 2002), and on-site measurements in this study are not an exception (Sun et al., 2010). Nevertheless, we believe the discrepancies between model predictions and field measurements in the time–frequency domain were mainly due to either model parameterization errors or structural deficiencies of the model. Future refining and improving model parameterization and structure requires consideration of potential ET measurement errors (Williams et al., 2009; Dietze et al., 2011; Wang et al., 2011).

4. Conclusions

This study demonstrated that DRAINMOD-FOREST accurately predicted annual and monthly ET after calibration and validation based on measured drainage rates and water table depth. Wavelet transform and coherence analysis demonstrated that the model reasonably captured the high power spectra of ET at an annual scale with significantly high model-data coherence. These results suggested that calibrated DRAINMOD-FOREST could collectively capture factors/mechanisms controlling ET dynamics in drained pine plantations. These findings support the assumption that the model accuracy for estimating ET would be acceptable after successful calibration and validation for commonly measured hydrological variables. However, the global power spectrum revealed that the model over predicted the power spectrum of ET at an annual scale, suggesting the model may have under predicted canopy conductance during non-growing seasons. In addition, this study also suggested that DRAINMOD-FOREST did not properly capture the seasonal dynamics of ET under drought conditions. These results have helped us identify several opportunities to further refine parameters and structures of DRAINMOD-FOREST to improve agreement between predictions and measurements in the time–frequency domain. Implementing these recommendations requires intensive model calibration using high frequency ET measurements with the inclusion of potential observation errors.

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