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Impact of drought on canopy carbon and water fluxes

W. Ju et al.

Modeling the impact of drought on canopy carbon and water fluxes through parameter optimization using an ensemble Kalman filter

W. Ju[1], S. Wang[2], G. Yu[2], Y. Zhou[3], and H. Wang[2]

[1]International Institute for Earth System Science, Nanjing University, Nanjing 210093, China
[2]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[3]School of Geographic and Oceanographic Sciences, Nanjing University, Nanjing 210093, China

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Abstract

Soil and atmospheric water deficits have significant influences on CO_2 and energy exchanges between the atmosphere and terrestrial ecosystems. Model parameterization significantly affects the ability of a model to simulate carbon, water, and energy fluxes. In this study, an ensemble Kalman filter (EnKF) and observations of gross primary productivity (GPP) and latent heat (LE) fluxes were used to optimize model parameters significantly affecting the calculation of these fluxes for a subtropical coniferous plantation in southeastern China. The optimized parameters include the maximum carboxylation rate (Vc_{max}), the Ball-Berry coefficient (m) and the coefficient determining the sensitivity of stomatal conductance to atmospheric water vapor deficit D_0). Optimized Vc_{max} and m showed larger seasonal and interannual variations than D_0. Seasonal variations of Vc_{max} and m are more pronounced than the interannual variations. Vc_{max} and m are associated with soil water content (SWC). During dry periods, SWC at the 20 cm depth can explain 61% and 64% of variations of Vc_{max} and m, respectively. EnKF parameter optimization improves the simulations of GPP, LE and sensible heat (SH), mainly during dry periods. After parameter optimization using EnKF, the variations of GPP, LE and SH explained by the model increased by 1% to 4% at half-hourly steps and by 3% to 5% at daily time steps. Efforts are needed to develop algorithms that can properly describe the variations of these parameters under different environmental conditions.

1   Introduction

Carbon (C) and water fluxes between the atmosphere and terrestrial ecosystems are interactively linked at various temporal and spatial scales (Rodrigues-Iturbe, 2000). Two major components of the terrestrial C cycle (C fixation through photosynthesis and C release through heterotrophic respiration) are strongly regulated by soil water content (SWC). Consequently, SWC is a key determinant of net ecosystem productivity (NEP) of a terrestrial ecosystem (Grainer et al., 2003). Photosynthesis peaks when SWC is

Impact of drought on canopy carbon and water fluxes

W. Ju et al.

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

near the field capacity and decreases with the departure of SWC from this optimum. When soil or atmospheric water is insufficient, leaf stomatal conductance reduces and correspondingly CO_2 fixation is limited (Dang et al., 1997; Hogg et al., 2000; Grant et al., 2006a). Extensive studies have demonstrated the influence of SWC on C fixation at leaf (Infante et al., 1999; Lawlor, 1995) and canopy (Reichstein et al., 2002; Rambal et al., 2003) levels. For three Mediterranean evergreen forests, drought caused light-saturated ecosystem gross C fixation and day-time averaged canopy conductance to decline by up to 90% and ecosystem water-use efficiency relative to the gross C fixation to decrease (Reichstein et al., 2002). The heat and drought hitting Europe in 2003 caused a 30% reduction in the continental gross primary productivity (GPP) (Ciais et al., 2005). The sensitivity of GPP to drought depends on vegetation species. In the boreal region of Canada, the decreasing degree of GPP caused by drought during 2001 to 2003 was larger for Aspen than for Jack Pine and Black Spruce (Kljun et al., 2005). The heat and drought in 2003 in Europe caused larger reductions in GPP in temperate deciduous beech and northern Mediterranean forests than in other ecosystems (Ciais et al., 2005; Granier et al., 2007).

Models are useful tools to estimate regional/global terrestrial C budget. However, large discrepancy exists in outputs by models due to differences in model structure, input data, and parameters. The reliability of a model to simulate terrestrial C and energy fluxes depends, to a great extent, on its ability to simulate SWC dynamics and the influence of SWC on C sequestration. Performance of models in simulating the decline of C sequestration caused by soil and atmospheric dryness is quite different (Grant et al., 2006b). Accurate estimation of model parameters is critically important for modeling surface fluxes (Wolf et al., 2006). However, not all model parameters are measurable, especially at canopy level. Properly determining parameter values is always a big challenge for modelers.

The availability of long-term measurements of CO_2, water and energy fluxes using the eddy covariance (EC) technique in different ecosystems provides opportunities to optimize model parameters to which simulated CO_2, water, and energy fluxes are very

sensitive. Various parameter optimization methods have been successfully adopted in combination with EC measurements to optimize model parameters and to analyze the seasonality of parameters. Parameter optimization can be implemented by minimizing a cost function constructed on the basis of one or several criteria quantifying the differ-
5   ences between simulated fluxes and corresponding measurements (Aalto et al., 2004; Owen et al., 2007; Reichstein et al., 2003; Wang et al., 2006; Wolf et al., 2006) or by using the ensemble Kalman filer based approach (Mo et al., 2008). The cost function can be resolved at different temporal intervals to identify the seasonal variations of parameters. Through inverting a mechanistic model every five days, Reichstein et
10   al. (2003) found that both active leaf area and photosynthetic capacity (Vc_{max}) declined during the drought period for three Mediterranean forest ecosystems. With the inclusion of drought-dependent parameter variations, the model's ability to simulate hourly gross CO_2 uptake and transpiration was greatly improved. In a pristine grassland-forb steppe, inverted Vc_{max} and m (the Ball-Berry coefficient) also had large seasonal vari-
15   ations (Wolf et al., 2006). Recently, Mo et al. (2008) studied the trajectories of model parameters for an old aspen stand in Canada at daily time steps using an ensemble Kalman filter-based algorithm with EC measurements of GPP, ecosystem respiration and latent heat (LE) as the observations. Inversed parameter values (clumping index, Vc_{max} and m) show distinct interannual and seasonal variations.
20   Water availability is an important ecological factor affecting C sequestration of terrestrial ecosystems in China (Yu et al., 2006). Long-term CO_2 flux measurements at 8 stations in China show a positive linear relationship between annual NEP and precipitation across biomes with different water availability conditions. In tropical and subtropical regions of China with monsoon climates, seasonal and interannual variability of precip-
25   itation are considerable. In these regions, although annual precipitation is normally plentiful, seasonal droughts occur frequently and influence terrestrial C sequestration. The decease in terrestrial C sequestration under seasonal drought conditions is determined by the accumulation of soil water deficits and a co-occurrence of high temperatures (Sun et al., 2006). On the basis of modeling analysis, Gu et al. (2008) found

that drought caused NEP of a subtropical coniferous plantation in southern China to decrease by 63% and 47%, respectively. C fixation is more sensitive to drought than ecosystem respiration. Soil drought has a much larger influence on NEP than atmospheric drought. Therefore, it is of importance for reliable estimation of terrestrial C balance in China to study the impact on C sequestration by soil and atmospheric water deficits. Although some observational and modeling research have been conducted to study the response of C sequestration by forests to drought in subtropical region of China (Sun et al., 2006; Gu et al., 2008), drought driven changes of model parameters have not been studied yet.

The objectives of this study are: (1) to study the interannual and seasonal variations of model parameters significantly affecting the calculations of canopy C and water exchanges; (2) to analyze the linkage between variations of parameters and SWC; (3) to investigate the improvement in simulated canopy C and water fluxes by the inclusion of drought-dependent parameters. To achieve these objectives, the BEPS (Boreal Ecosystem Productivity Simulator) model (Ju et al., 2006) was optimized using eddy covariance measurements of GPP and LE fluxes taken over a subtropical coniferous plantation at QianYanZhou ecological station, located in southeastern China.

2 Materials and methods

2.1 Site description

The QianYanZhou ecological station (115°01′13″ E, 26°44′48″ N) is located at the southwest portion of Jiangxi province (Fig. 1). This site belongs to the typical red earth hilly region in the mid-subtropical monsoon landscape zone of southeastern China. The mean annual temperature is 17.9°C and annual precipitation is 1542.4 mm during 1985–2002, respectively. The vegetation is mainly evergreen coniferous trees planted after 1985, including *Pinus massoniana*, *Pinus elliottii engelm*, and *Cunninghama Lanceolata*. An above-canopy flux system mounted in a 39.6 m tower has been

Impact of drought on canopy carbon and water fluxes

W. Ju et al.

◄◄ ►►

◄ ►

Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

in operation to record half-hourly exchanges of CO_2, H_2O and energy fluxes between the ecosystem and atmosphere and meteorological conditions since September 2002 (Liu et al., 2006). This site is a typical plantation ecosystem in Jiangxi province, in which vegetation restoration (mainly reforestation and afforestation) has been widely
5　and successfully practiced in the past three decades. Therefore, parameters optimized at this site can be used for investigating the effect of vegetation restoration on C sequestration in this region.

2.2　Data used

Half-hourly measurements of air temperature, incoming solar radiation, relative humid-
10　ity, wind speed and precipitation during 2003 and 2004 were used for driving the BEPS model. The time course of leaf area index (LAI) was determined according to measurements of LAI taken using the TRAC instrument in the growing season (Huang et al., 2007) and the measured solar radiation flux over the canopy and on the ground surface. Measurements of LE and CO_2 fluxes using the EC method (Liu et al., 2006) are
15　used for parameter optimization. In order to reduce the influence of observation noises on parameter optimization, the flux data were checked in two steps. The methodology of Song et al. (2006) was first used to exclude abnormal records of half-hourly NEP and LE data. Then, if the summation of LE and sensible heat (SH) fluxes are below 70% or above 125% of the measured above-canopy net energy flux, the LE data was
20　marked as abnormal values. GPP was derived from measured NEP, air temperature and SWC (Wen et al., 2006). The averages of measured GPP and LE for the period between 09:00 and 17:00 were calculated for parameter optimization.

2.3　Model description

The BEPS model used in this study includes a module for photosynthesis calculation
25　(Chen et al., 1999), a soil biogeochemical module for soil C, N and heterotrophic respiration simulations following CENTURY (Parton et al., 1993), and a land surface scheme

for the computations of energy balance, SH and LE fluxes, SWC and soil temperatures (Ju et al., 2006). GPP is calculated by scaling leaf-level Farquhar's biochemical model (Farquhar et al., 1980) up to canopy-level implemented through a sunlit and shaded leaves separation algorithm (Chen et al., 1999). Fluxes of C, water, and energy are separately simulated for sunlit and shaded leaves. Details about the model are described in Ju et al. (2006). We only highlight processes directly related to parameter optimization here.

GPP is calculated as:

$$GPP = A_{net, sunlit}LAI_{sunlit} + A_{net, shaded}LAI_{shaded} \qquad (1)$$

where $A_{net, sunlit}$ and $A_{net, shaded}$ are net photosynthesis rates of sunlit and shaded leaves (mol m^{-2} s^{-1}), respectively, calculated using the leaf-level Farquhar model (Farquhar et al., 1980; Chen et al., 1999); LAI$_{sunlit}$ and LAI$_{shaded}$ are the leaf area index of sunlit and shaded leaves, respectively.

The bulk stomatal conductance of the sunlit and shaded leaves for water vapor ($G_{s,i}$, mol m^{-2} s^{-1}) is calculated using a modified version of the Ball-Woodrow-Berry (Ball et al., 1987) empirical model following Wang and Leuning (1998):

$$G_{s,i} = G_{o,i} + \frac{mA_{net,i}}{C_{s,i}(1 + D_{s,i}/D_0)} \qquad (2)$$

where $G_{o,i}$ is the residual conductance (mol m^{-2} s^{-1}); m is the Ball-Berry coefficient; $C_{s,i}$ is the CO$_2$ concentration at the leaf surface (mol mol^{-1}); $D_{s,i}$ is the water vapor saturate deficit at the leaf surface (kPa); and D_0 is an empirical parameter determining the sensitivity of stomatal conductance to water vapor saturate deficit (kPa).

LE is simulated as:

$$LE = (T_r + E_i + E_g)\lambda \qquad (3)$$

where T_r is the transpiration rate from canopy (kg m^{-2} s^{-1}); E_i and E_g are evaporation rates of intercepted water from canopy and ground surface (kg m^{-2} s^{-1}), respectively;

Impact of drought on canopy carbon and water fluxes

W. Ju et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀ | ▶

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

and λ is the latent heat of water vaporization. Sublimation is not considered at this subtropical forest site.

2.4 Parameter optimization

Model parameter optimization was implemented using a dual state-parameter estimation method based on the ensemble Kalman filter (Moradkani et al., 2005; Mo et al., 2008). The parameter ensembles are updated as:

$$\boldsymbol{\theta}_{t+1}^{i+} = \boldsymbol{\theta}_{t+1}^{i-} + \mathbf{K}_{t+1}^{\theta}(\boldsymbol{y}_{t+1}^{i} - \hat{\boldsymbol{y}}_{t+1}^{i}) \tag{4}$$

where $\boldsymbol{\theta}_{t+1}^{i+}$ is the updated parameter ensemble member at time step $t+1$; $\boldsymbol{\theta}_{t+1}^{i-}$ is the parameter sample generated with an assumption that model parameters follow a random walk in the space prescribed (Moradkhani et al., 2005); $\mathbf{K}_{t+1}^{\theta}$ is the Kalman gain matrix for correcting the parameter trajectories; and $\boldsymbol{y}_{t+1}^{i}$ and $\hat{\boldsymbol{y}}_{t+1}^{i}$ are the ensemble members of observations and predictions, respectively

Parameter sample $\boldsymbol{\theta}_{t+1}^{i-}$ is made as:

$$\boldsymbol{\theta}_{t+1}^{i-} = \boldsymbol{\theta}_{t}^{i+} + \boldsymbol{\tau}_{t}^{i}, \qquad \boldsymbol{\tau}_{t}^{i} \sim N(0, \boldsymbol{\Sigma}_{t}^{\theta}) \tag{5}$$

In above Eq. (5), the Kalman gain matrix $\mathbf{K}_{t+1}^{\theta}$ is calculated as:

$$\mathbf{K}_{t+1}^{\theta} = \boldsymbol{\Sigma}_{t+1}^{\theta y}[\boldsymbol{\Sigma}_{t+1}^{yy} + \boldsymbol{\Sigma}_{t+1}^{y}]^{-1} \tag{6}$$

where $\boldsymbol{\Sigma}_{t+1}^{\theta y}$ is the cross covariance between parameter ensemble and prediction ensemble; $\boldsymbol{\Sigma}_{t+1}^{yy}$ is the error covariance matrix of the prediction $\hat{\boldsymbol{y}}_{t+1}^{i}$; and $\boldsymbol{\Sigma}_{t+1}^{y}$ is the error covariance of observation.

2.5 Parameters optimized and ensemble generation

Through sensitivity analysis, three parameters including V_{cmax}, m, and D_0 are selected for optimization. These parameters have significant impacts on simulated GPP and

Impact of drought on canopy carbon and water fluxes

W. Ju et al.

◄◄ | ►►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

LE. Although the electron transport rate J_{max} is also an important parameter for calculating GPP and LE, it was calculated according to V_{cmax} in the BEPS model (Chen et al., 1999). Therefore, J_{max} was not optimized in this study. The ranges and standard deviations of these parameters are listed in Table 1. The ensemble members of predicted GPP and LE are generated by disturbing these parameters using Eq. (5) with an assumption that data used to force the model are perfect.

Estimation of observational errors is important for EnKF data assimilation since the observational errors determine the degree to which the simulated results are to be corrected (Mo et al., 2008). In this study, the uncertainties of GPP and LE are set as 15% of their daily averages and assumed to be independent of each other. The ensemble size is set to 200 to ensure the correct estimate of cross covariance between parameter and prediction ensembles and that of the prediction error covariance. Parameter optimization is conducted in days when both GPP and LE measurements are available. The parameters are updated by adding up corrections calculated using Eq. (4). Then the new parameters are used to simulate fluxes in the following days until next parameter optimization is conducted.

3 Results

3.1 Interannual and seasonal variations of the parameters

The seasonal variations of three optimized parameters were analyzed with 10-day averages since there are certain daily fluctuations of retrieved parameters. Figure 2 shows the seasonal variations of Vc_{max} in years 2003 and 2004. This parameter was in the range from 14.4 to 29.3 μmol m^{-2} s^{-1} in 2003 and from 13.3 to 28.6 μmol m^{-2} s^{-1} in 2004, respectively. The averages of Vc_{max} were 19.2 and 20.1 μmol m^{-2} s^{-1} in 2003 and 2004, respectively. In 2003, this parameter gradually increased to a peak value of 29.3 μmol m^{-2} s^{-1} in the middle of June and then quickly decreased due to the impact of sever summer drought. It started to recover with the increase of precipitation in the

middle of August and approached the second peak of 23.9 μmol m^{-2} s^{-1} in the middle of September. Then this parameter declined again and showed a relatively small variation after the middle of October. The seasonality of Vc_{max} in 2004 was very similar to that in 2003. The summer decrease of Vc_{max} was smaller in 2004 than in 2003. Starting from late September, this parameter was larger in 2004 than in 2003.

The parameter of Vc_{max} represents the foliage photosynthetic capacity at a reference temperature (25°C in this study) and is believed to be linearly related with leaf nitrogen content (Chen et al., 1999). It is also affected by photosynthetic enzyme capacity, acclimation to seasonal change of environmental conditions and aging. Vc_{max} is also affected by soil water stress, leaf massarea ratio, and leaf age (Wilson et al., 2000; Mo et al., 2008). Many studies have demonstrated the seasonal variations of Vc_{max} (Reichstein et al., 2003; Wolf et al., 2006; Wang et al., 2006; Mo et al., 2008). However, the reported seasonal patterns of Vc_{max} varied considerably in different ecosystems. The seasonal changes of Vc_{max} identified in this study are similar to those in three Mediterranean forests reported by Reichstein et al. (2003). In both cases, Vc_{max} show increasing trends in the spring and early summer and noticeable decline during a summer drought period.

Parameter m ranged from 7.5 to 13.4 in 2003 and from 7.0 to 12.9 in 2004, respectively (Fig. 3). It averaged 10.3 and 10.7 in these two years. In 2003, it showed an increasing trend prior to the end of March and a decreasing trend after April. It dropped during the summer drought and recovered when the soil was getting wet after the middle of August. This parameter reached the second peak of 11.7 in the middle of September. Then, it continuously decreased as the soil was getting dry again. The seasonal pattern of m in 2004 is different from that in 2003. In 2004, this parameter gradually increased during the period from the middle of March to early September and then slowly decreased. It did not decrease during the summer of 2004.

The seasonal and interannual variations of parameter m have been confirmed in many studies (Sala and Tenhunen, 1996; Lai et al., 2000; Wolf et al., 2006; Mo et al., 2008). There is still no consistent conclusion on the seasonal pattern of this parameter

and its association with SWC due to different strategies used to invert m. Sala and Tenhunen (1996) used single values of LAI and Vc_{max} for the entire growing season to invert m and found that this parameter changed dramatically. Lai et al. (2000) found that m was associated with SWC. Wolf et al. (2006) demonstrated that the seasonal variability of m could reach to about 60% and the association between m and SWC was not strong. Mo et al. (2008) indicated that m was smaller in dry years than in wet years for an aspen forest in the southern study area of BOREAS, Canada. The variations of m in this study are similar to the results reported by Mo et al. (2008). Both of studies found that m is smaller in dry years than in wet years.

The annual averages of D_0 were almost identical in 2003 and 2004, equal to 1.47 kPa. This value is close to those used in many modeling studies (Wang and Leuning, 1998; Arrain et al., 2003; Ju et al., 2006). This parameter showed similar seasonal patterns in 2003 and 2004. The seasonal variations of this parameter were relatively small, ranging from 1.35 to 1.64 kPa in 2003 and from 1.33 to 1.62 kPa in 2004, respectively. During the summer drought period in 2003, it decreased slightly and had smaller values than those in the same period of 2004. D_0 was slightly below the average during the periods from April to early August in 2003 and from the middle of February to late May in 2004.

3.2 The relationship between the parameters and soil water content

As expected, parameters Vc_{max} and m showed a certain degree of association with SWC (Fig. 5). These two parameters started to decline when SWC decreased. They are more tightly linked with SWC in deep layers than with SWC in the surface layer. Vc_{max} kept increasing when SWC at 5 cm depth started to decrease and SWC at depths of 20 cm and 40 cm remained above the field capacity. This confirms the hypothesis that forest is able to uptake deep water to maintain normal photosynthesis and transpiration rates during the initial stage of drought. With the continuation of drought, deep soil water is consumed and the stomatal conductance decreases (Ju et al., 2006). Consequently, the photosynthetic capacity (parameterized as Vc_{max} in

Impact of drought on canopy carbon and water fluxes

W. Ju et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

the model) showed a considerable reduction (Reichstein et al., 2003). Vc_{max} showed a stronger response to decrease in SWC in middle summer of 2003 than in middle summer of 2004 due to co-occurrence of drought and high temperature in 2003 (Sun et al., 2006). Vc_{max} and SWC at depths of 20 cm and 40 cm almost started to decrease simultaneously. However, the recovering rate of Vc_{max} was slower than that of SWC, indicating drought has a lagged effect on the photosynthetic capacity. Parameter m decreased during the summer drought period in 2003. This decrease of m did not occur during the summer of 2004 although Vc_{max} showed a moderate decrease because SWC of deep layers were relatively high.

When SWC at 20 cm depth was below the field capacity, both m and Vc_{max} linearly increased with SWC. If SWC is above the field capacity, its change had no detectable influence on m and Vc_{max} (Fig. 6). This is similar to the findings of the impact of SWC on m by Lai et al. (2000) and Wolf et al. (2006) and on Vc_{max} by Reichstein et al. (2003). SWC alone can explain 61% and 64% of the variations in Vc_{max} and m when SWC was below the field capacity. Vc_{max} and m showed very large variations when SWC was above the field capacity, indicating that SWC was the key determinant of Vc_{max} and m when SWC was low, causing stress on forest growth, but other factors may also have significant influences on them when SWC was high.

3.3 Performance of the optimized BEPS model in flux simulation

Since fluxes of GPP, LE and SH were predicted with the corrected parameters on the previous day, the efficiency of model parameter optimization in improving flux estimation was evaluated by comparing measured and simulated fluxes. Figure 7 shows the comparisons for half-hourly GPP, LE and SH. The simulated fluxes used here are the averages of 200 ensemble predictions. With the optimized parameters, the BEPS model can interpret 83%, 81% and 83% of variations of measured half-hourly LE, SH and GPP in 2003, respectively. In 2004, the optimized model can capture 83%, 79% and 83% of variation in measurements of LE, SH and GPP. The model tends to overestimate smaller values of LE and GPP and underestimate their large values. In contrast,

Impact of drought on canopy carbon and water fluxes

W. Ju et al.

the small and large values of SH were underestimated and overestimated by the model, respectively.

These results are significant improvements over the results using a manually optimized parameter set (D_0=1.58, m=11, Vc_{max}=35) (Table 2). The biggest improvement was achieved for GPP, followed by LE and SH. The RMSE (root mean square error) values of GPP with EnKF parameter optimization decreased to 0.173 and 0.187 mg CO_2 m^{-2} s^{-1} in 2003 and 2004, respectively, from 0.209 and 0.212 mg CO_2 m^{-2} s^{-1} based on the manually tuned optimum parameter set. Correspondingly, the EnKF parameter optimization makes the RMSE of LE decrease from 42.2 to 36.3 W m^{-2} in 2003 and from 46.9 to 40.4 W m^{-2} in 2004.

At daily steps, the optimized model can explain 90% and 91% of daily GPP variations in 2003 and 2004, respectively (Fig. 8). These percentages for the simulations using the manually optimized parameter set are 86% and 89%. The improvement for daily GPP simulation was mainly in the periods of the summer and autumn droughts of 2003 and 2004. The improvement in simulated GPP after EnKF parameter optimization was smaller in 2004 than in 2003.

The simulation of LE was more improved by the EnKF parameter optimization than GPP (Figs. 8 and 9). 93% and 90% of variations of day time LE were captured by the BEPS model optimized using EnKF in 2003 and 2004, respectively while corresponding values were 89% and 85% for simulations using the manually optimized parameter set in 2003 and 2004. The improvements for LE simulations was also mainly during the drought periods in 2003 and 2004.

The improvement for simulations of GPP and LE fluxes achieved by the EnKF parameter optimization was larger at daily time steps than at half-hourly steps since the adjustments of parameters was carried out using daily values of observations. The model was still unable to capture some peaks of GPP and LE in the midday even if parameters were updated using EnKF and daily observations.

4 Discussions

Parameters in the ecosystem models are temporally and spatially interlinked in non-linear forms. Parameter values derived from measurements taken at leaf or canopy scales may lead to incorrect predictions at other scales (Mo et al., 2008). Eddy co-variance measurements represent the information at 100–1000 m footprint distance, similar to the spatial resolution of many hydrological and ecological models. There-fore, parameter values optimized using eddy covariance measurement will improve the simulations at regional scales.

Many studies have demonstrated the applicability of eddy covariance measurements to optimizing model parameters (Reichstein et al., 2003; Wolf et al., 2006; Wang et al., 2006; Santaren et al., 2007; Mo et al., 2008). EnKF sequential data assimilation is an effective technique for model parameter optimization, which is able to track the sea-sonal variations of the parameters affecting the photophynthetic capacity and stomotal conductance (Vc_{max} and m). The estimation of observation errors is critical to the EnKF parameter optimization algorithm. If larger observation errors are used in the calcula-tion of Kalman gain matrix, the trajectories of model parameters will be corrected to a smaller degree. In this study, the errors of GPP and LE are set as 15% of their daily averages, which are in the range of reported uncertainties of GPP and LE measure-ments (Santaren et al., 2007; Mo et al., 2008). The construction of the second eddy covariance tower in July 2008 at this site will make it possible to estimate uncertainties of GPP and LE measurements more reasonably. In this study, the observation error is assumed to be Gaussian distributed and independent between GPP and LE. Re-ports indicated that flux measurement errors are more close to a double exponential distribution (Hollinger and Richardson, 2005). The effects of this assumption about the distribution of observation errors on optimized parameters need further investigation.

Compared with the global optimization algorithms, which use eddy covariance mea-surements in long time periods to invert parameters, the EnKF optimization method updates the model parameters using measurements in one day. Although this strat-

egy is able to trace day to day variations of parameters, it makes the optimization results sensitive to the quality of observation. One or several abnormal observational values in one day might cause the parameters to vary unrealistically. Therefore, careful quality control of observation data is of importance prior to the implementation of
5 the EnKF parameter optimization scheme. Since the daily averages of observed and simulated GPP and LE are used to correct the parameters, the simulation accuracy is more improved at daily time steps than at half-hourly time steps. This is because in the calculations of daily values, the underestimation/overestimation of large GPP or LE values will be possibly compensated by overestimation/underestimation of small GPP
10 or LE values.

Similar to findings in other studies, considerable seasonal and interannual variations of Vc_{max} and m are derived through assimilating eddy covariance. There are many possible mechanisms causing the changes of these parameters. Development of algorithms to represent the variations of these parameters is of importance for improving
15 the simulations of carbon and water fluxes at various scales. It was found that SWC is a good predictor for Vc_{max} and m during dry periods for this coniferous plantation ecosystem in subtropical zone of southeastern China. During wet periods, Vc_{max} and m showed large variations around the averages (Fig. 6). The simultaneous observations of nitrogen content, Vc_{max}, m, photosynthesis rate are required to understand the
20 mechanisms underlying the variations of V_{cmax} and m and for developing methodologies to describe the variations of V_{cmax} and m.

5 Conclusions

From this study, following conclusions can be drawn:

1. The EnkF data assimilation is an effective technique for model parameter opti-
25   mization, which is able to track the seasonal and interannual variations of the parameters. The optimized parameter values are sensitive to the estimation of observation errors and quality of observation data.

Impact of drought on canopy carbon and water fluxes

W. Ju et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

2. Optimized Vc_{max} and m showed considerable seasonal and interannual variations. The seasonal variations of parameters are larger than their interannual variations. SWC is a good predictor of Vc_{max} and m during dry periods with SWC of 20 cm depth below the field capacity. SWC of 20 cm depth alone can capture 61% and 64% variations of Vc_{max} and m in 2003 and 2004, respectively. During wet periods, other factors can cause these parameters to vary largely.

3. The EnKF parameter optimization is useful for improving the simulation of GPP, LE and SH, mainly during dry periods. The improvement of flux simulation accuracy after parameter optimization is larger at daily steps than at half-hourly steps. After parameter optimization using EnKF, the variations of GPP, LE and SH explained by the model increased by 1% to 4% at half-hourly steps and increased by 3% to 5% at daily time steps.

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Impact of drought on canopy carbon and water fluxes

W. Ju et al.

Title Page

Abstract	Introduction
Conclusions	References
Tables	Figures

|◄ | ►|
◄ | ►
Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Impact of drought on canopy carbon and water fluxes

W. Ju et al.

Table 1. The standard deviations and ranges of three parameters optimized.

Symbol	Unit	Standard deviation	Range
V_{cmax}	$\mu\mathrm{mol\,m^{-2}\,s^{-1}}$	4	10–60
m	Dimensionless	0.8	4–14
D_0	kPa	0.15	1.2–2.2

Table 2. Statistics from the regression ($Y=aX+b$) of simulated (as Y) on observed (as X) half-hourly fluxes of GPP (mg CO_2 m^{-2} s^{-1}), LE (W m^{-2}) and SH (W m^{-2}).

ITEM	Year	Parameters optimized using EnKF				Parameters manually optimized			
		a	b	R^2	RMSE	a	b	R^2	RMSE
LE	2003	0.834	9.538	0.837	36.3	0.985	13.013	0.822	42.2
	2004	0.825	10.941	0.831	40.4	0.984	13.841	0.810	46.9
SH	2003	1.129	−18.892	0.823	41.3	1.126	−22.171	0.814	42.9
	2004	1.129	−21.841	0.789	36.4	1.118	−25.997	0.755	39.4
GPP	2003	0.860	0.024	0.826	0.173	1.043	0.035	0.797	0.209
	2004	0.826	0.024	0.828	0.187	0.984	0.035	0.809	0.212
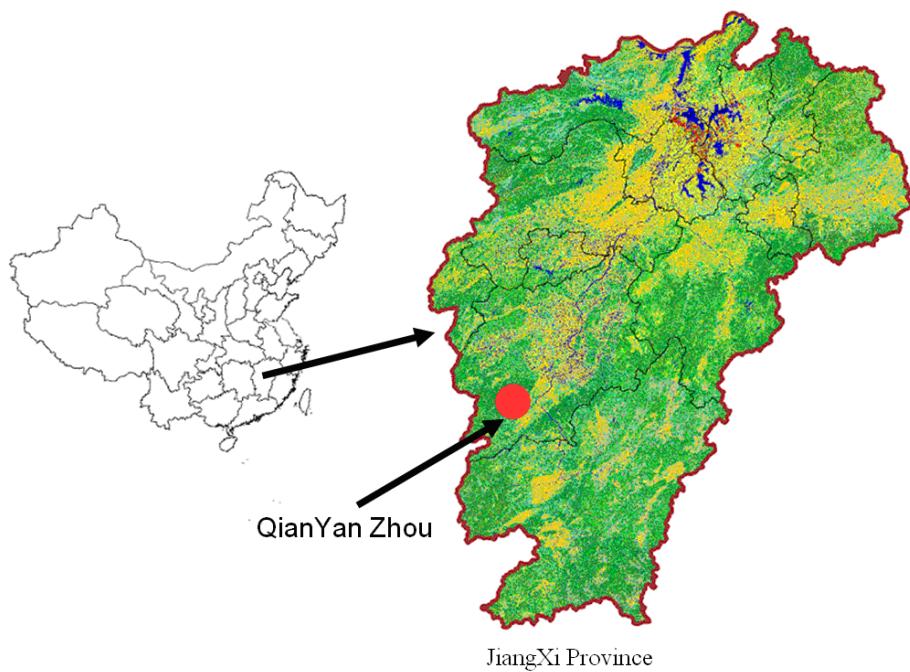
Fig. 1. The location of the study area. Green colored areas are forests. The red solid circle represent the QianYanZhou Ecological station.
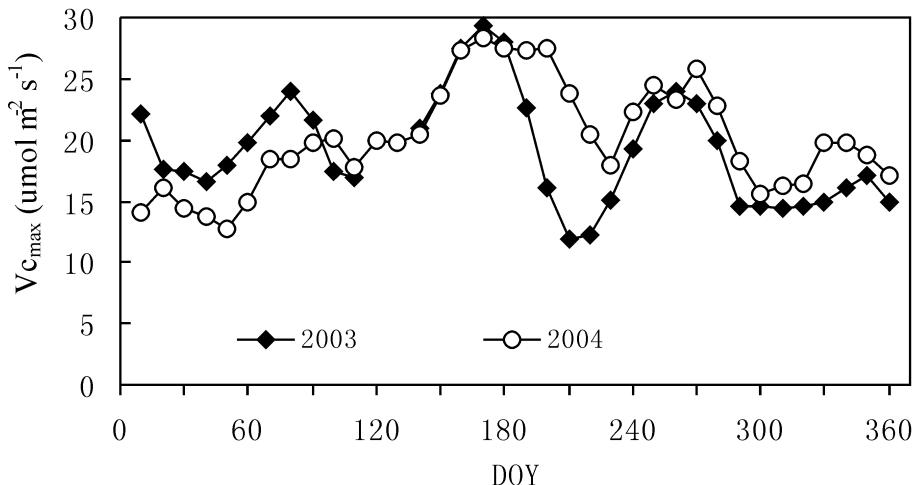
Fig. 2. Seasonal variations of optimized Vc_{max} in 2003 and 2004.
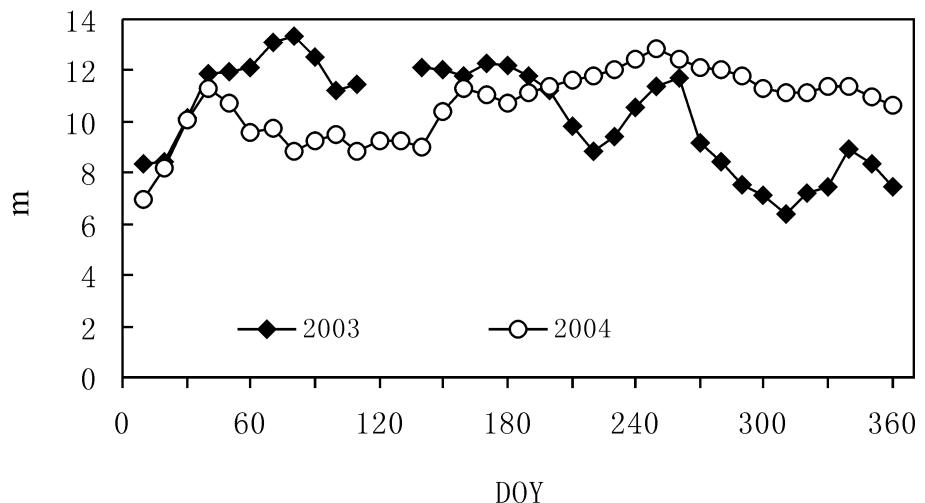
Fig. 3. Seasonal variations of optimized *m* in 2003 and 2004.
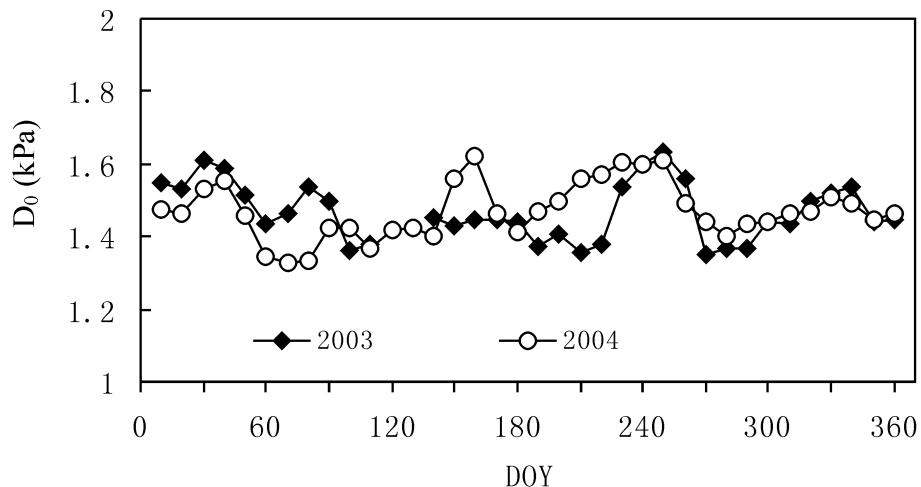
Fig. 4. Seasonal variations of optimized D_0 in 2003 and 2004.
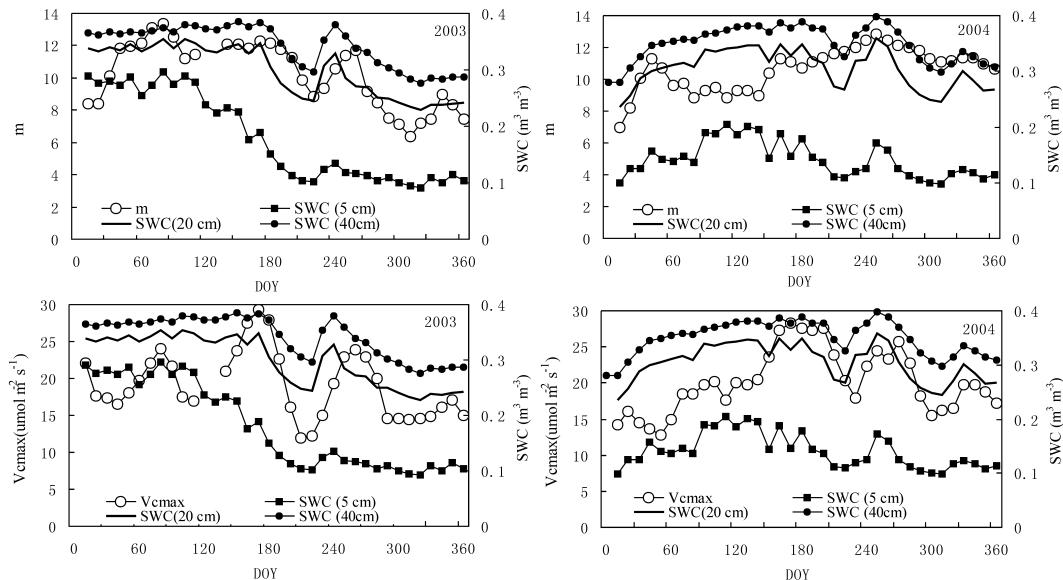
Fig. 5. Seasonal variations of optimized parameters of Vc_{max} and m and measured soil water content at depths of 5 cm, 20 cm and 40 cm. The left panel is for year 2003 and the right one is for year 2004.
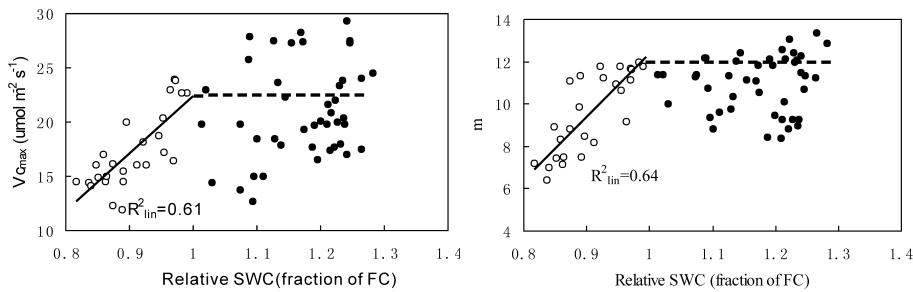
Fig. 6. Association of optimized Vc_{max} and m with measured relative soil water content (fraction of field capacity) at 20 cm depth in 2003 and 2004. Values shown are 10-day averages. Curves are linear functions with upper threshold, fitted to unfilled symbols. Also indicated are the R^2 values of fitted linear functions.
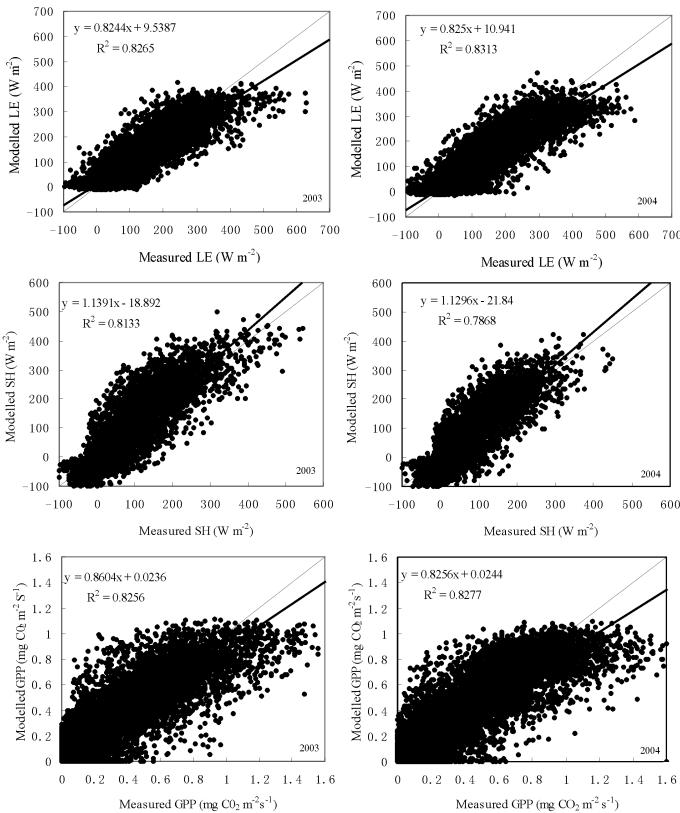
Fig. 7. Comparison between observed and simulated half-hourly fluxes of GPP, LE, and SH. The grey line is the 1:1 line and dark solid one is the regression line.
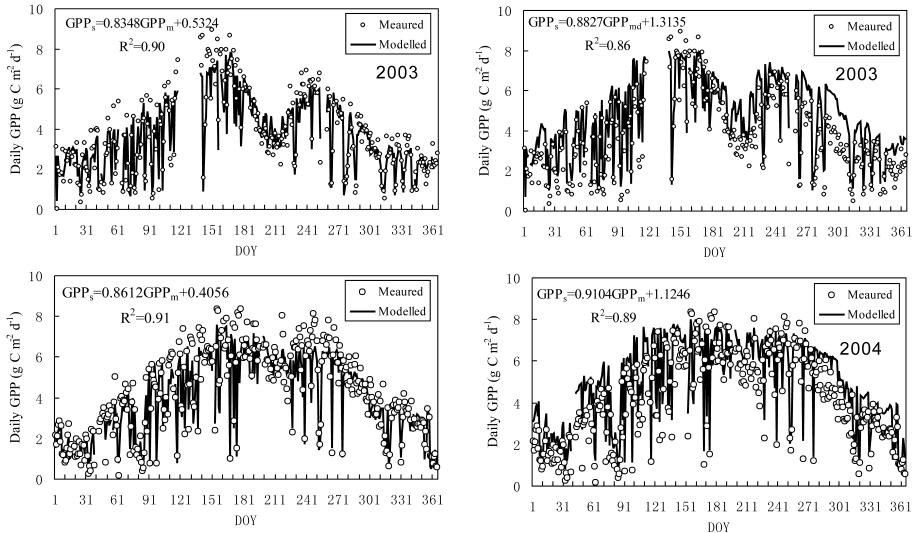
Fig. 8. The averages of simulated daily GPP and corresponding observations during 2003 and 2004. The left panel is for the simulation with parameters optimized by EnKF and the right one is for the simulation with parameters manually optimized. GPP_s and GPP_m are simulated and measured daily GPP, respectively.
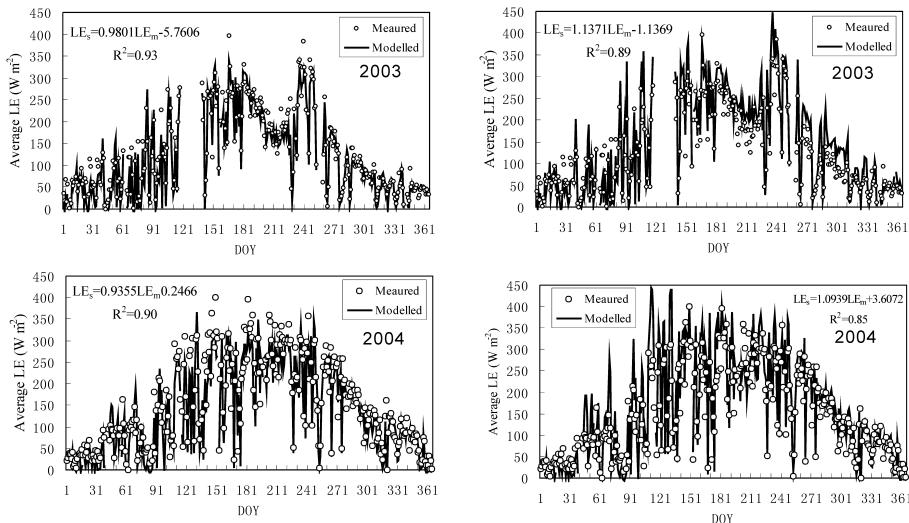
Fig. 9. The averages of simulated daytime LE and corresponding observations during 2003 and 2004. The left panel is for the simulation with parameters optimized by EnKF and the right one is for the simulation with parameters manually optimized. LE_s and LE_m are simulated and measured latent heat fluxes, respectively.