Agricultural and Forest Meteorology 149 (2009) 1907–1918

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Refinement of rooting depths using satellite-based evapotranspiration seasonality for ecosystem modeling in California

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ARTICLE INFO

Article history:
Received 28 October 2008
Received in revised form 22 June 2009
Accepted 25 June 2009

Keywords:
Terrestrial ecosystem modeling
Water cycle
Carbon cycle
Remote sensing
Regional modeling
Rooting depth

ABSTRACT

Accurate determination of rooting depths in terrestrial biosphere models is important for simulating terrestrial water and carbon cycles. In this study, we developed a method for optimizing rooting depth using satellite-based evapotranspiration (ET) seasonality and an ecosystem model by minimizing the differences between satellite-based and simulated ET. We then analyzed the impacts of rooting depth optimization on the simulated ET and gross primary production (GPP) seasonality in California, USA. First, we conducted a point-based evaluation of the methods against flux observations in California and tested the sensitivities of the simulated ET seasonality to the rooting depth settings. We then extended it spatially by estimating spatial patterns of rooting depth and analyzing the sensitivities of the simulated ET and GPP seasonalities to the rooting depth settings. We found large differences in the optimized and soil survey (STATSGO)-based rooting depths over the northern forest regions. In these regions, the deep rooting depths (>3 m) estimated in the study successfully reproduced the satellite-based ET seasonality, which peaks in summer, whereas the STATSGO-based rooting depth (<1.5 m) failed to sustain a high ET in summer. The rooting depth refinement also has large effects on simulated GPP; the annual GPP in these regions is increased by 50–100% due to sufficient soil water during the summer. In the grassy and shrubby regions of central and southern California, the estimated rooting depths are similar to those of STATSGO, probably due to the shallow rooting depth in these ecosystems. Our analysis suggests that setting a rooting depth is important for terrestrial ecosystem modeling and that satellite-based data could help both to estimate the spatial variability of rooting depths and to improve water and carbon cycle modeling.

1. Introduction

Accurate modeling of the soil water balance and evapotranspiration is essential for analyzing hydrological processes, water management, and carbon cycles in terrestrial environments. Soil water balance, which is determined by various water cycle processes, such as precipitation, snowfall, snowmelt, evaporation, transpiration, infiltration, and runoff, influences precipitation, temperature, and atmospheric circulation through the release of latent heat flux (e.g., Koster et al., 2004; Huang et al., 1996). Photosynthesis and heterotrophic respiration are also affected by soil water availabilities through stomatal conductance closure (e.g., Ball et al., 1987) and water availability for microbes (e.g., Andren and Paustian, 1987), which, in turn, affects the terrestrial carbon budget (e.g., Nemani et al., 2002). The accuracy of soil water simulations also impacts climate forecasting capabilities (e.g., Huang et al., 1996; Yang et al., 2004; Alfaro et al., 2006).

Because evapotranspiration (ET) is a major component of the terrestrial water and energy cycles, its accurate modeling is essential for soil water modeling. The accuracy largely depends on model structure and parameters (Guswa et al., 2002), meteorological data (e.g., White and Nemani, 2004; Rawlins et al., 2006), vegetation phenology (e.g., White and Nemani, 2004; Buermann et al., 2001), and below-ground properties (e.g., soil texture and rooting depth) (Lathrop et al., 1995; Kleidon and Heimann, 1998). Among model-related properties (model structure, ecophysiological parameters and below-ground properties), evaluation of rooting depth is essential because it is the primary determinant of

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doi:10.1016/j.agrformet.2009.06.019

the maximum plant available water in the rooting zone and it affects vegetation productivity through water stress during the dry season. Generally, model-related properties which control evapotranspiration and soil water content include maximum stomatal conductance, limiting functions of stomatal conductance to environment variables, soil texture, and rooting depth. Maximum conductance determines magnitude of seasonal ET variations and its peak, limiting functions of stomatal conductance regulate ET due to severe environmental condition, soil texture determines volumetric water content, and only rooting depth substantially determines amount of plant available water in the vertical soil layer.

Although rooting depth can be determined via soil surveys, several studies have pointed out that soil survey-based values underestimate the true depth because direct observation of rooting depth is not available for many regions, and only a small portion of direct observations (<10%) reached to maximum rooting depth (Schenk and Jackson, 2002). A small number of deep roots could have a significant role in water uptake in dry seasons. Indeed, default rooting depth settings in many ecosystem models are shallow (usually <2 m; e.g. 1.5 m for LPJ model; Sitch et al., 2003, 1.0 m for CASA model; Potter et al., 1993), and some studies have highlighted the existence of deep rooting systems in seasonally water-limited ecosystems (e.g., Nepstad et al., 1994; Canadell et al., 1996; Schenk and Jackson, 2002, 2005) and the importance of their inclusion in models for the accurate simulation of the carbon and water cycles (Kleidon and Heimann, 1998; Tanaka et al., 2004; Ichii et al., 2007; Baker et al., 2008). Several studies have inferred rooting depth by finding the depth that achieves maximum net primary productivity (NPP) (Kleidon and Heimann, 1998) or that maximizes the correlation of modeled GPP and the satellite-based vegetation index seasonality (Ichii et al., 2007). However, none of these studies used actual observations (e.g., observed ET) to determine rooting depth.

Another difficulty with soil water and evapotranspiration modeling is the lack of sufficient observations to provide the information necessary to constrain the model parameters (e.g., Zhu and Liang, 2005). However, recent advances in satellite observations provide an opportunity to monitor spatio-temporal patterns in terrestrial water cycles, enabling spatial patterns of ET to be obtained with sufficient accuracy (e.g., Nishida et al., 2003; Yang et al., 2006; Zhang and Wegehenkel, 2006). These seasonal variations have the potential to be used to constrain the model.

The purpose of this study is to refine the rooting depth data in the terrestrial biosphere model using satellite-based ET seasonality to improve the modeling capability for simulating both water and carbon cycle seasonalities in California. We used the Terrestrial Observation and Prediction System (TOPS) (Nemani et al., 2003) as an ecosystem model and we used a support vector machine (SVM)-based ET estimation (Yang et al., 2006) as a satellite-based ET. First, TOPS was used to estimate rooting depths, and we tested the sensitivities of the simulated ET seasonality to the rooting depth settings at flux sites in California. The analysis was then extended spatially, and we analyzed the sensitivities of the simulated ET and GPP seasonalities to the rooting depth setting.

2. Data and method

2.1. Study area

We focused our analysis on California, USA (Fig. 1). California is mostly characterized by a Mediterranean climate with a dry season in summer (e.g., April–September and March–October in the northern and southern regions, respectively) and a wet season in winter (e.g., December–February) (Fig. 2). Land cover patterns

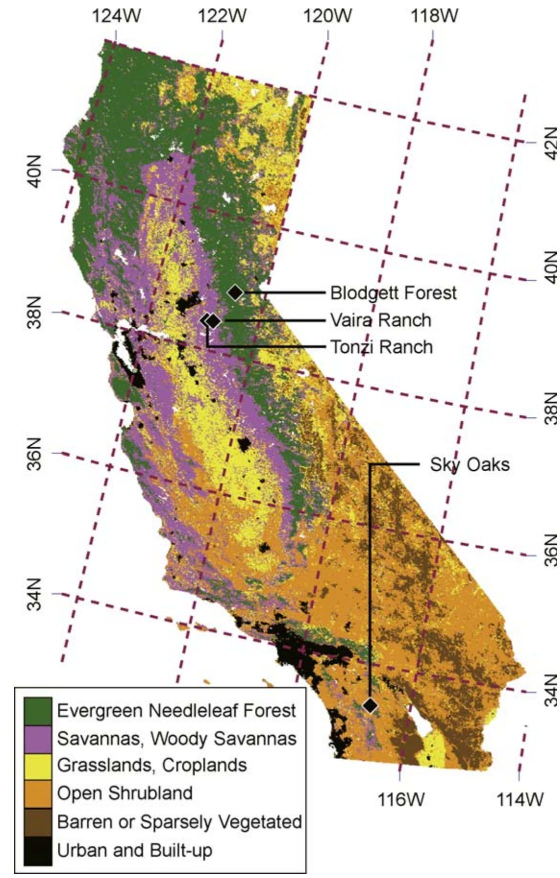

Fig. 1. Land cover of the study area with flux observation sites in California based on MODIS land cover data (MOD12Q1; Friedl et al., 2002) in the year 2001. Diamonds (◆) show the locations of flux observation stations used in the study.

follow the precipitation patterns, with evergreen needle-leaf forests over northern California in the high-precipitation regions, cropland and Savanna in the central valley, and open shrubland that has little precipitation in the southern regions. The middle to southern coastal regions are characterized by higher precipitation than the inland areas.

2.2. Models

2.2.1. Satellite data-based ET

We used a machine learning technique for regressions to obtain spatio-temporal ET variations as described by Yang et al. (2006). The method is based on the regression-type support vector machine (SVM), which transforms a non-linear regression into a linear regression by mapping the original low-dimensional input space to a higher dimensional feature space using kernel functions (e.g., Vapnik, 1998; Cristianini and Shawe-Taylor, 2000), with inputs of satellite-based incoming surface solar radiation (Rad), land surface temperature (LST), enhanced vegetation index (EVI), and land cover (Yang et al., 2006). The method was assessed at more than 20 Ameriflux sites over the continental United States, and the method was extended spatially using satellite data. The method was determined to be effective for predicting spatio-temporal ET patterns with acceptable accuracy (e.g., R^2 = 0.75 and root mean square error (RMSE) = 0.62 mmH_2O day^{-1}; Yang et al., 2006).

The SVM analysis consists of three main steps for model tuning and testing. First, the SVM model parameters (C: cost of errors, ε: width of an insensitive error band, and σ: kernel parameter) were obtained from a training set. Second, with the obtained parameters