



Modeling crop water use in an irrigated maize cropland using a biophysical process-based model



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SUMMARY

Accurate modeling of crop water use or evapotranspiration (*ET*) is needed to understand the hydrologic cycle and improve water use efficiency. Biophysical process-based multilayer models can capture details of the nonlinear interaction between microclimate and physiology within the canopy and thus accurately simulate *ET*. In this study, we extended a process-based multilayer model, ACASA, which explicitly simulated many of the nonlinear biophysical processes within each of ten crop canopy sublayers and then integrated to represent the complete crop canopy. Based on the original ACASA model, we made the improved modifications including four added modules (C₄ crop photosynthesis, water stress response of stomatal conductance, crop morphological changes, and heterogeneous root water uptake), and two adjusted calculation procedures (soil evaporation resistance and hydraulic characteristic parameters). Key processes were parameterized for the improved ACASA model using observations. The simulated canopy *ET* was validated using eddy covariance measurements over an irrigated maize field in an arid inland region of northwest China. The improved ACASA model predicted maize *ET* for both half-hourly and daily time-scales. The improved model also predicted the reduction in maize *ET* under the condition of soil water deficit. Soil evaporation, an important component of maize *ET*, was also satisfactorily simulated in the improved model. Compared to the original ACASA model, the improved model yielded an improved estimation of maize *ET*. Using the improved model, we found that maize *ET* was nonlinearly affected by changes in leaf area index and photosynthetic capacity through canopy conductance. In general, the improved ACASA model, a biophysical process-based multilayer model, can be used to diagnose and predict crop *ET*, and draw some insights into the nonlinear interactions between crop canopy and ambient environment.

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1. Introduction

Cropland is an important terrestrial ecosystem having an inherent nonlinear interaction between the biosphere and atmosphere (Baldocchi and Xu, 2004; Ramírez et al., 2007; Wang et al., 2006; Yang et al., 2012). Crop water use or evapotranspiration (*ET*) is the largest term in the cropland water balance after precipitation and irrigation (Leuning et al., 2008; Liu et al., 2012) because more than 90% of water used in agriculture is lost by soil evaporation and crop transpiration, referred to as evapotranspiration, *ET* (Rana and Katerji, 2000). Thus, accurate estimation of crop *ET* is required to better understand terrestrial hydrologic cycles and improve our ability to use limited water resources efficiently (Ding et al., 2013a; Zhang et al., 2011a). The *ET* from a crop canopy

is dependent on a number of interacting environmental and biological processes, such as weather condition, crop species, stomatal resistance, irrigation scheduling and field management practices (Allen et al., 1998; Ortega-Farias et al., 2006). However, direct measurement of *ET* is difficult and costly and thus seldom done (Irmak et al., 2008; Katerji and Rana, 2006). Therefore, accurate estimate of *ET* depends on the development, testing and application of mathematical models which can describe and quantify the complex and nonlinear interactions between the environment and biological systems (Baldocchi and Meyers, 1998; Campbell and Norman, 1998).

A wide range of models exist from simple empirical to complex mechanistic models, and from single-layer to multilayer models (Monteith and Unsworth, 2008; Shuttleworth, 2007). The single-layer models, often referred to as big leaf models, determine *ET* as if the crop canopy was treated simply as one big leaf to calculate the energy exchange (Ortega-Farias et al., 2006; Zhang

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et al., 2011a). Many studies have evaluated the limitations of single-layer models, such as Penman–Monteith (PM) equation (Norman and Campbell, 1983; Raupach and Finnigan, 1988). Single-layer models cannot capture details of the nonlinear interaction between microclimate and physiology within the canopy. In contrast, multilayer models divide the crop canopy into several layers and simulate explicitly many of the nonlinear processes, then integrate the fluxes of each layer and its individual microclimate (Lhomme et al., 2013; Paw and Meyers, 1989). Process-based multilayer models are able to describe both the energy exchange of the entire canopy and the partitioning of energy fluxes among various canopy components (e.g., soil, understory, and crown) (Wang et al., 2011). Therefore, it is important to develop process-based multilayer models based on physiological (photosynthesis and stomatal conductance) and micrometeorological (radiative transfer, turbulent transfer and surface energy budget) mechanistic processes. A process-based multilayer model of canopy energy and water vapor exchanges at the canopy level would be useful in many applications (Lambers et al., 2008; Raupach and Finnigan, 1988). For example, multilayer models incorporating variability in environmental and physiological variables within the canopy could help quantify the roles of physiological processes in mediating the exchanges of water, carbon, and heat (Lambers et al., 2008). The models can also be used to investigate how the water and energy budget of a crop canopy respond to changing environment. Furthermore, the multilayer models are valuable tools to quantify the partitioning between soil evaporation and crop transpiration under different cropland management practices, which would be of interest to hydrologists and improve estimation of *ET* (Norman and Campbell, 1983).

Several researchers have been applying biophysical, ecophysiological, and biogeochemical principles to develop process-based multilayer models of water and heat fluxes (Balocchi and Meyers, 1998; Leuning et al., 1995; Pyles et al., 2000; Sellers et al., 1996). Specifically, the Advanced Canopy–Atmosphere–Soil Algorithm (ACASA), which incorporated a diabatic third-order turbulence closure method to model the turbulent fluxes of heat, water vapor and gas exchange within and above the canopy, is one of the most widely recognized process-based multilayer models (Pyles et al., 2000; Staudt et al., 2010). The ACASA model has been tested for many C_3 plants with both dense and sparse canopies, and regarded as a robust model (Marras et al., 2011; Pyles et al., 2000; Staudt et al., 2010). However, the original ACASA model does not include C_4 crop physiological modules which is a substantial limitation since the photosynthetic pathway of C_3 and C_4 plants is completely different (Lambers et al., 2008). The effect of water stress on stomatal conductance was also not accounted for in the ACASA model which is critical in natural ecosystems and managed crops because crops often suffer from water stress due to lower precipitation and scarce water resources in the arid regions (Ding et al., 2013a; Katerji and Rana, 2006). Thus, the application of the ACASA model for modeling *ET* for C_4 crops (e.g., maize), especially in arid areas is severely limited and not is verified.

In this study, we developed an improved ACASA model through adding four processes: C_4 crop photosynthesis, water stress response of stomatal conductance, crop morphological changes (e.g., crop height, leaf area, and root depth), and heterogeneous root water uptake; as well as modifying two calculation procedures: soil evaporation resistance and hydraulic characteristic parameters. Water and heat fluxes over an irrigated maize field with plastic mulch were measured by the eddy covariance technique during the entire growing season in 2009. The ecophysiological factors and soil water content were also measured. The main objectives were to test the improved ACASA model by comparing simulations with measurements and with results of the original

model, and to analyze the sensitivity of the improved model to key parameters.

2. Model development

2.1. Brief description of the original ACASA model

The structure of ACASA is based on defining the relationship between individual elements and their immediate environment at several layers within a canopy, then integrating throughout the canopy to determine the collective effect of all the elements (Marras et al., 2011; Pyles et al., 2000; Staudt et al., 2010). The crop canopy is divided into ten layers. The intercepted radiation at every foliage element is computed by a modified version of the Norman (1979) model, with leaf distribution assumed as spherical. Individual foliage elements at every layer are divided into ten leaf angles, including nine sunlit leaf angles and one shaded leaf angle. The energy balance, photosynthesis, transpiration, stomatal conductance and respiration of sunlit and shaded leaves are computed at every foliage element of each layer. The ACASA model uses a near-exact quartic energy balance formulation that enables it to calculate surface temperatures accurately, even in situations where leaf, stem, or soil surface temperatures differ from ambient temperatures (Paw and Gao, 1988). The model incorporates a diabatic third-order closure method to calculate turbulent transfer within and above the canopy on a theoretical basis (Meyers and Paw, 1986, 1987). Plant physiological responses to immediate micro-environmental conditions are calculated by a combination of the Ball–Berry stomatal conductance (Collatz et al., 1991; Leuning, 1990) with the Farquhar photosynthesis equation following Su et al. (1996) and Pyles et al. (2000). The soil module used to calculate soil surface evaporation, soil moisture, and soil temperature is adapted from mesoscale analysis and prediction system (MAPS) (Marras et al., 2011; Pyles et al., 2000).

2.2. Model modifications

On the basis of the original ACASA model, we added four modules and modified two calculation procedures, and referred to the new extended model as the improved ACASA model. The four added modules included C_4 crop photosynthesis, water stress response of stomatal conductance, crop morphological changes (e.g., crop height, leaf area, and root depth), and heterogeneous root water uptake. The two modified procedures included the method to calculate soil evaporation resistance and use of hydraulic characteristic parameters. The detailed modifications and reasons are given as follows.

2.2.1. Response of leaf stomatal conductance to water stress

Stomatal conductance (the reciprocal of stomatal resistance) in the original ACASA was computed using the Ball–Berry routine (Ball, 1988), which is a function of leaf photosynthesis (A_n), relative humidity (h_s), and the CO_2 concentration at the leaf's surface (C_s). To address the effect of water stress on stomatal conductance, a limiting parameter, $f_w(\theta)$, was introduced in the improved model. The response of $f_w(\theta)$ to soil water content was expressed as an exponential rise to a maximum with respect to relative soil extractable water (*RW*) (Ding et al., 2013a; Zhang et al., 2011b).

$$g_s = f_w(\theta) m \frac{A_n h_s}{C_s} + b \quad (1)$$

$$f_w(\theta) = \min(1.0, m_1(1 - \exp(-m_2 RW))) \quad (2)$$

where g_s is the leaf stomatal conductance to water vapor ($\text{mol m}^{-2} \text{s}^{-1}$); m and b ($\text{mol m}^{-2} \text{s}^{-1}$) are empirical coefficients,

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