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Coupling land surface and crop growth models to estimate the effects of changes in the growing season on energy balance and water use of rice paddies

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ABSTRACT

A crop growth model was coupled to a simple land surface model to estimate the effect of changes in the growing season for rice (*Oryza sativa* L.) on the energy balance and water use of rice paddy fields. The crop growth model consisted of calculations of phenological development (P_s), growth of leaf area index (LAI) and canopy height (h). The land surface model consisted of calculations of energy balance, radiation transport and stomatal movements using the output of the crop growth model (P_s, LAI, h). Using a coupled model, the energy fluxes and water/canopy temperatures of rice paddies can be calculated from climatic data only. The model was evaluated using whole season observations at three experimental sites with different growing seasons in a humid temperate climate. The seasonal variations in calculated energy fluxes showed good agreement with observed values with a root mean square error of 10–20 $W m^2$.

To understand how the change in growing season affects energy balance and water use of rice paddies, variations in water/canopy temperatures and evapotranspiration were estimated using the model for five different transplanting times based on climatic data for the Miyazaki Plain in Japan. A common trend in energy balance was obtained for all growing seasons (i.e., water temperature was higher than air temperature, whereas canopy temperature was lower than air temperature after transplanting, and these differences decreases with rice growth) under normal climatic conditions. Mean values of the ratios of total transpiration to total evapotranspiration (T/ET) during the rice growth period based on climatic data from 20 years (1981–2000) were 0.40, 0.48, 0.48, 0.46 and 0.36 for transplanting at March 1, April 1, May 1, June 1 and July 1, respectively. This suggests that the water use efficiency based on total evapotranspiration would be higher for transplanting during mid-season. Using the proposed model, the water use by rice paddies can be estimated for given climatic conditions and growing seasons, which makes it possible to modify the growing season and water management for climate change.

1. Introduction

Evapotranspiration from the land surface is an important factor that affects regional water balance and ecosystems. The energy and water balance on the land surface has been studied extensively, and many models have been developed to express these land surface processes (Dickinson et al., 1986; Sellers et al., 1986; Meyers and Paw U, 1987). With the predicted global warming, the effects of climate change on land surface processes have become a major concern. There have been many studies that estimate the effects of climate change or land-use change on the energy and water balance (e.g., Martin et al., 1999; Kim et al., 2005) using the advanced land surface models including the photosynthesis process (e.g., Pyles et al., 2000) and considering time-series changes in vegetation using satellite data (Sellers et al., 1996a,b).

On farmland, the energy balance and temperatures at the surface affect both crop growth and water use. These are important for both agricultural production and irrigation practices. Rice (*Oryza sativa* L.) is an important crop worldwide, and paddy fields are a dominant land use form. Water use for irrigation accounts for almost 70% of global water withdrawals (Kundzewicz et al., 2007), and water use for rice paddies is a major portion of that water consumption, especially in Asian countries. Therefore, the energy balance on rice paddy fields has been studied extensively to understand the physical processes (Uchijima, 1961; Inoue et al., 1984; Oue, 2001), to evaluate heat fluxes at the surface (Iwakiri, 1965; Harazono et al., 1998; Tsai et al., 2007), to determine the radiation and water use efficiency (Campbell et al., 2001a,b; Yoshimoto et al., 2005), and to estimate field water requirements (Tyagi et al., 2000; Shah and Edling, 2000).

Several land surface models have been applied to rice paddies to estimate the energy balance. Kondo and Watanabe (1992) applied three different models to rice paddies; calculating the energy balance assuming the surface as single entity (the single

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source model); calculating the energy balance at the ground and canopy separately (the double source model); and calculating the energy balance by dividing the canopy into multiple layers (the multi-layer model). Kimura and Kondo (1998) simplified the single source model to calculate the energy balance from climatic data and the leaf area index (LAI). The variation in LAI for rice canopies can be estimated from the air temperature using a crop growth model (Horie, 1987). Therefore, it should be possible to estimate the energy balance throughout the rice-growing season using only climatic data by coupling the crop growth model to a land surface model. In addition, this model could be useful for estimating effects of climate change (or shifts in the planting time of rice) on water management and planning a suitable crop calendar. However, changes in the rice-growing season affect not only physical growth (such as variation in LAI), but also plant phenology (such as timing of flowering and characteristics of stomata). Therefore, it was also necessary to consider the effects of these phenological changes on land surface processes.

In this study, we aimed to develop a simple model to calculate the energy balance of rice paddies from climatic data, which can be applied to a wide range of growing seasons considering the effects of phenological change. The crop growth model was coupled to a land surface model based on an empirical relationship between stomatal conductance and rice phenology. The relationship between leaf geometry and phenology was also used to express the change in radiation transport in the canopy. The model was evaluated using season-long observations from transplanting to maturity at three experimental sites with different growing seasons in a humid temperate climate. Furthermore, seasonal variations in water temperature and evapotranspiration were estimated using the model for different rice transplanting times to understand how the change in growing season affects water use for rice paddies.

2. Model descriptions

2.1. Land surface model

The model development aimed to estimate the energy balance at the land surface and some important factors for water use by rice paddies, such as water temperature, evaporation and transpiration, as simply as possible and to enable consideration of the effects of changes in rice phenology. A double source model (Kondo and Watanabe, 1992) was used to determine the heat balance at the land surface, as it is simple and robust (low sensitivity) in model structure and is stable when calculating the energy balance. The double source model can consider the effects of changes in canopy structure and plant physiology using bulk-parameters, such as leaf geometric factor and bulk stomatal conductance. It has been applied to rice paddies in many previous studies and accurately estimates the heat fluxes (Kondo and Watanabe, 1992; Yamazaki et al., 1992) and relationships between above bulk-parameters and rice phenology have been studied (Maruyama et al., 2007; Maruyama and Kuwagata, 2008). The model can calculate the heat fluxes on the ground and vegetation separately as a SW-type model (Shuttleworth and Wallace, 1985). The heat exchanges between the ground-atmosphere and plant-atmosphere in the double source model are expressed using the following equations:

$$\begin{aligned} Rn_g &= H_g + \lambda E_g + G \\ Rn_c &= H_c + \lambda E_c \end{aligned} \tag{1}$$

where Rn_g is the net radiation on the ground surface (W m^{-2}); H_g is the sensible heat flux between the ground and atmosphere (W m^{-2}); λE_g is the latent heat flux between the ground and atmosphere (W m^{-2}); G is heat flux into the ground including the heat flux into the water layer; Rn_c is the net radiation absorbed by the vegetation canopy; H_c is the sensible heat flux between the canopy and atmosphere (W m^{-2}); and λE_c is the latent heat flux between the canopy and atmosphere (W m^{-2}). Values of Rn_g and Rn_c are positive for downward flux, and conversely, values of H_g, H_c, λE_g and λE_c are positive for upward flux.

Both measures of net radiation, Rn_g and Rn_c, are expressed using downward short-wave radiation above the canopy R_S (W m^{-2}) and downward long-wave radiation above the canopy R_L (W m^{-2}) based on following radiation balance equations:

$$\begin{aligned} Rn_g &= (1-r_g)\tau_S R_S + \tau_L R_L + (1-\tau_L)\sigma T_c^4 - \sigma T_g^4 \\ Rn_c &= (1-r)R_S - (1-r_g)\tau_S R_S + (1-\tau_L)(R_L + \sigma T_g^4) - 2(1-\tau_L)\sigma T_c^4 \end{aligned} \tag{2}$$

where r_g is the albedo of the ground (or water surface in the case of rice paddies); r is the albedo on the canopy, τ_S and τ_L are the transmissivities of the canopy for short-wave and long-wave radiation, respectively; and σT_g^4 and σT_c^4 are the long-wave radiation emitted from the ground and foliage, respectively. The emissivity of long-wave radiation for the ground and the canopy was assumed to be 1.0 (black body). σ is the Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}); T_g is the ground/water surface temperature (K); and T_c is the mean canopy temperature (K). The sum of second and third term on right hand side in the equation for Rn_g corresponds to the downward long-wave radiation to the ground, while the third term in the equation for Rn_c corresponds to the incident long-wave radiation into the canopy from the sky and the ground (e.g., Kustas and Norman, 1999). The sum of first and second terms on right hand side of the equation for Rn_c corresponds to the short-wave radiation absorbed by the canopy (e.g., Monteith and Unsworth, 1990).

Heat fluxes between ground-atmosphere and canopy-atmosphere can be expressed using the ground/water surface temperature T_g (K), mean canopy temperature T_c (K), air temperature T_a (K), specific humidity of the air q_a (kg kg^{-1}), and wind speed U (m s^{-1}) based on the following heat transfer equations:

$$\begin{aligned} H_g &= c_P \rho C_{H_g} U (T_g - T_a) \\ \lambda E_g &= \lambda \rho C_{E_g} U (q_{sat}(T_g) - q_a) \\ H_c &= c_P \rho C_{H_c} U (T_c - T_a) \\ \lambda E_c &= \lambda \rho C_{E_c} U (q_{sat}(T_c) - q_a) \end{aligned} \tag{3}$$

where c_P is the specific heat capacity of the air under constant pressure (J kg^{-1} K^{-1}); ρ is density of the air (kg m^{-3}); λ is the latent heat of vaporization of liquid water (J kg^{-1}); and $q_{sat}(T_g)$ and $q_{sat}(T_c)$ are the saturation specific humidities (kg kg^{-1}) at temperatures of T_g and T_c, respectively. These values can be calculated based on basic thermodynamic formulae using values of T_g, T_c, T_a and q_a. The coefficients C_{H_g} and C_{E_g} are bulk transfer coefficients for sensible and latent heat exchange between the ground and atmosphere, respectively. Similarly, C_{H_c} and C_{E_c} are the bulk transfer coefficients for sensible and latent heat exchange between the canopy and atmosphere, respectively.

Heat flux into the ground is expressed using the ground surface temperature T_g based on the Force–Restore model (Bhumralkar, 1975):

$$G = \left(\frac{C_g \lambda_g \omega}{2}\right)^{1/2} \left[\frac{1}{\omega}\frac{dT_g}{dt} + (T_g - T_{g0})\right] \tag{4}$$

where T_{g0} is the daily mean ground surface temperature; ω is the angular frequency (s^{-1}); and C_g and λ are the volumetric heat capacity (J m^{-3} K^{-1}) and heat conductivity (J m^{-1} K^{-1} s^{-1}) of the paddy soil, respectively. Here, the heat capacity and conductivity of water was used for C_g and λ values since the most of G in rice paddies is heat flux into the water body. The value of T_{g0} was