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Coupling a SVAT heat and water flow model, a stomatal-photosynthesis model and a crop growth model to simulate energy, water and carbon fluxes in an irrigated maize ecosystem

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ABSTRACT

Irrigation is practiced on approximately 20% of the agricultural land in the world and accounts for approximately 40% of the total crop production. However, with global warming and an increasing population, the agricultural water consumption increases, leaving generally less water for the natural ecosystems. An increase in water efficiency of agro-ecosystems, especially irrigated agro-ecosystems in arid and semi-arid regions, is an urgent task. The use of computer models to simulate interactions and feedbacks between relevant processes during crop growth is becoming more common and almost a prerequisite for proper management of irrigation water. In this paper, we describe the integration of SHAW, a soil-vegetation-atmosphere transfer (SVAT) model, with a stomatal-photosynthesis model and WOFOST, a crop growth model, to simulate the energy, water and carbon budgets during crop growth. The coupled model was tested and applied for a field study on irrigated maize [38°51′ N, 100°25′ E, altitude 1519 m a.s.l.], located in an irrigation oasis of the Heihe river basin in arid Northwest China. The coupled model performs well in simulating the diurnal variation of the leaf water potential, stomatal resistance and transpiration at leaf scale, before and after irrigation. At the canopy scale, the coupled model also reproduces the daily changes in the sensible and latent heat fluxes, carbon dioxide flux, and dynamic soil water content during maize growth and fallow periods. Moreover, there was good agreement between the simulated maize biomass and the field measurements. These results demonstrate that the holistic coupled model not only successfully simulates the actual effect of soil water stress on crop transpiration and photosynthesis, but also can describe the interactions of energy, water, and carbon cycles of the agro-ecosystem and predict crop production under irrigation. This is encouraging for the modelling of crop response to droughts and changed cropping and irrigation regimes aiming at optimized water use. Meanwhile, this study indicates that integrating methods of different physically based models is highly efficient and useful for a better understanding of the interaction between hydrological and ecological processes in the agro-ecosystem.

1. Introduction

The energy available at the land surface is partitioned into latent, sensible, and ground heat fluxes. These fluxes drive most ecosystem processes, such as evapotranspiration, photosynthesis, stomatal processes, and gas exchange at the soil–plant–atmosphere interface (Figuerola and Berlinger, 2006; Brown and Halweil, 1998; Kar, 2005). Meanwhile, energy balance at the soil–plant–atmosphere interface is affected by soil moisture, land cover, and meteorological conditions (Burman and Pochop, 1994; Monteith and Unsworth, 1990). The sensible heat is used for heating the air while the latent heat appears as evapotranspiration in the soil-plant system, which is a crucial component of its water cycle. Further, transpiration of plants is closely related to photosynthesis in ecosystems (Chaves, 1991; Rodriguez-Iturbe et al., 2001; Shepherd et al., 2002; Anwar et al., 2003; Patil and Sheelavantar, 2004) owing to a strong linkage between the carbon and water cycles through leaf stomata-control (Cowan, 1965). The leaf stomatal conductance, which is affected by atmospheric conditions, such as irradiance, temperature, and water vapour

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pressure deficit, as well as soil water status, not only regulates the water use and carbon exchange between plants and atmosphere, but also influences energy partitioning into sensible and latent heat. Therefore, the quantification of the interrelated influences of energy, water, and carbon cycles at the land–atmosphere interface is a complicated problem. However, it is essential to quantitatively model this process in order to better understand the interaction between hydrological and ecological processes (Law et al., 2002; Lee et al., 2004), to determine the availability of water resources (Scanlon et al., 2002), and to sustainably manage limited water resources, especially in irrigated agricultural systems in arid and semi-arid regions (e.g., Gartuza-Payán et al., 1998).

The semi-arid to arid Heihe river basin is the second largest inland river basin in China. Water resources in this area originate from the upper basin in the Qilian Mountains. The middle basin of the Heihe river is a major food production area of northwest China. At an average yearly rainfall of less than 300 mm, the production of staple food grains such as maize and wheat in this region can only be achieved through irrigation. Thus the limited water resources from the Qilian Mountains are mainly used for irrigating agricultural fields in the artificial oasis of the middle basin which covers approximately 12% of the entire basin but contains nearly 90% of its total biomass. However, due to the increased agricultural, industrial and household water demand of the population in the middle basin, the water available for natural ecosystems in the downstream basin of the Heihe river is decreasing, leading to serious ecological and environmental degradation, such as drying up of lakes, die-off of forests, acceleration of land desertification, and aggravation of sand storms in frequency and intensity (Wang and Cheng, 1999; Ji et al., 2006). A more balanced allocation of water resources has become an increasingly important requirement in this region. Yet, how can irrigated agriculture sustain productivity and meet the growing need for food when less water is available for irrigation?

To answer this question, an eco-hydrological experimental station was established in the middle reach of the Heihe river basin to observe the net exchange of energy, water and carbon dioxide between the ecosystem and the atmosphere over a maize field. Managers and researchers alike need a tool to manage the water use of the crops. The tool can be derived from a system-wide quantitative model, which can reproduce the response of crops to irrigation, as well as the interaction between hydrological and biological processes during crop growth.

Many SVAT models describe energy and moisture transport between the land surface and the adjacent atmosphere. However, they need further improvement in simulating the CO_2 flux, a key factor in determining crop dynamic growth and primary productivity. In the last several years, numerous studies have been conducted regarding the development of an integrated SVAT and terrestrial ecosystem model. For example, a comprehensive terrestrial ecosystem model called Agro-IBIS has been developed to simulate carbon, energy, and water cycling variables both in managed and natural ecosystems (Kucharik, 2003). Arora (2003) coupled land surface and terrestrial ecosystem models to simulate energy and carbon fluxes over winter wheat. De Noblet-Ducoudré et al. (2004) coupled the Soil-Vegetation-Atmosphere-Transfer Scheme, ORCHIDEE, to the agronomy model, STICS, to study the influence of croplands on the European carbon and water budgets. Casanova and Judge (2008) coupled Land Surface Process (LSP) and a widely used crop-growth model (DSSAT) to estimate the energy and moisture fluxes of dynamic vegetation. Maruyama and Kuwagata (2010) coupled 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. Van den Hoof et al. (2011) coupled the Land Environment Simulator (JULES) and a crop-growth model (SUCROS) to evaluate the hydrological cycle and vegetation effects on the energy, water, and carbon fluxes.

For this paper, we focus on cold and arid characteristics of Heihe river basin, SHAW (Flerchinger and Saxton, 1989; Flerchinger and Pierson, 1991), a soil-vegetation-atmosphere transfer (SVAT) model, with WOFOST (Van Keulen and Wolf, 1986; Boogaard et al., 1998), a crop growth model, and with a stomatal photosynthesis model, based on the Farquhar approach (Farquhar et al., 1980), which models are available and open sources, were integrated to simulate energy, water and carbon fluxes of irrigated agro-ecosystems from leaf to canopy scale in cold and arid regions. This study coupled the components of solar radiation and water transfer within a plant canopy in SHAW with a leaf-level stomatal-photosynthesis model. On the one hand, the SHAW model provides a multilayer canopy energy balance, replacing the big-leaf approach and therefore can be extended to simulate CO_2 flux between atmosphere and vegetation after including the component of CO_2 assimilation by photosynthesis. On the other hand, the SHAW model describes the effect of soil freezing and thawing on soil water content, which is suitable for our study field in cold and arid regions. The stomatal-photosynthesis model can describe stomatal opening/closure mechanistically and incorporate interactions between photosynthesis, transpiration, and stomatal conductance. This can be a framework to assess crop response to changes in ambient meteorological and soil moisture conditions. But it requires the incorporation of a detailed plant growth model. The WOFOST model is further coupled to upscale carbon photosynthesis rate for individual leaves to the gross CO_2 assimilation for whole canopy and simulate different organs dynamic development for crop. The objectives for the study are the following. (1) To model the interactions between energy, water and carbon cycles of the agro-ecosystem and the feedback of these cycles to biological and hydrological processes by coupling independent models of all relevant processes. (2) To test and evaluate the performance of the coupled model by comparing the simulated results and measured field data for a maize field, including soil temperature, soil water content, sensible and latent heat fluxes and carbon dioxide flux. (3) To reveal the integrating method of different physically-processed models is high-efficiency and collaborative to solve specific problems in complicated natural systems.

2. Materials and methods

2.1. Study site and measurements

The Yingke comprehensive research station (38°51′ N, 100°25′ E, altitude 1519 m a.s.l.) of the Chinese Academy of Science (CAS) is located in an irrigation oasis in the middle reach of the Heihe river (Fig. 1), the second largest inland river in the arid Northwest of China. This region has a typical temperate continental climate, with a mean annual precipitation from 60 to 280 mm and mean annual potential evapotranspiration ranging from 1000 to 2000 mm. The mean annual wind velocity is 3.2 m s^{-1}, and the prevailing wind direction is northwest. The main crops of this region are maize and wheat. Their water-use efficiencies, defined as the amount of the dry matter production per unit water transpiration, are low, with average values of 0.9 kg m^{-3} and 0.7 kg m^{-3}, for maize and wheat respectively (Deng et al., 2006). Field experiments were conducted to observe the energy, water and carbon cycles of an irrigated maize field.

An automatic meteorological observation system recorded the air temperature, air pressure, humidity and wind speed 3.0 m above the ground (Fig. 2). The short-wave and long-wave radiation (in both upward and downward directions) were measured 4.0 m above the ground (Fig. 2). Data were acquired every 10 min