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Modelling the effects of plastic mulch on water, heat and CO_2 fluxes over cropland in an arid region

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SUMMARY

Plastic mulches are often used to improve agricultural production by suppressing soil evaporation in the vast arid and semi-arid regions. As a special surface cover, plastic mulch evidently affects the surface albedo and prevents vapour exchange between the land surface and the atmosphere, but these physical processes were not contained in the present land surface models. Therefore, simulations remarkably deviate from observations when land surface models are applied to areas with underlying plastic mulch covering. Investigating the effects of various plastic mulches assists in better understanding the atmosphere-land interaction. In this study, a detailed plastic mulch layer model, which considers the effect of plastic mulch on the radiation and heat transfer is constructed and incorporated into a land surface model Two-Big-Leaf-SHAW (TBLSHAW) to simulate the water (H_2O), heat and CO_2 (carbon dioxide) fluxes in an agro-ecosystem covered by plastic mulch. Data collected by Gulang Heterogeneous Underlying Surface Layer Experiment (GHUSLE) at a plastic mulch-covered cropland site in an arid region were employed to verify the model; simultaneously, the TBLSHAW model was run with the same atmospheric forcing as a comparison to investigate the effect of the plastic mulch. Results suggest that the model can appropriately simulate the water, heat and CO_2 fluxes over an arid cropland. The model efficiency is high, and the mean bias error and root mean bias error between the simulated and the observed values are minor. Compared to TBLSHAW simulations, the plastic mulch with special optical properties obviously influenced the surface albedo and radiation balance. By limiting the underside soil evaporation, plastic mulch changes the energy and water transfer between the atmosphere and the land surface. The soil temperature and soil moisture are improved by the transparent plastic mulch, and the plastic mulch not only suppresses the CO_2 generated by soil respiration but also affects CO_2 budget as a result of the net assimilation controlled by the soil water and heat conditions.

1. Introduction

Since the concept of a geoscience system was proposed in the 1970s, weather/climate studies have no longer been limited to the atmosphere per se and have focused on interactions between the atmo-, hydro- and biosphere (Hare, 1971; Karl and Trenberth, 2003). Land ecosystems, as an important component of the earth and atmosphere interaction system, have aroused increasing interest from researchers. Vapour and CO_2 exchange between an ecosystem and the atmosphere greatly depends on plant transpiration and photosynthesis (Collatz et al., 2000; Davi et al., 2006; Gerten et al., 2004; Kuchment et al., 2006; Subin et al., 2011). Climate change, in turn, acts on the atmosphere-land exchange of energy and mass (Chen et al., 2003; Goldstein et al., 2000), thereby further feeding back to surface ecology and hydrological processes (Barron et al., 2012; Boyer et al., 2010) and controlling vegetation growth (Nakano et al., 2008; Theurillat and Guisan, 2001). Research on the interaction between the atmosphere and land is used to analyse the mechanisms for energy and species exchange by observing the water, heat and CO_2 fluxes in various land ecosystems to formulate and improve the parameterisation schemes of land surface models to even more truly describe the physical and biochemical processes of the atmosphere-land interactions (Dai et al., 2004; Dickinson et al., 2002; Sellers et al., 1996; Yang et al., 1998), thereby enhancing the accuracy of numerical weather forecasting and climate prediction (Delire et al., 2002; Zeng et al., 2002).

As an important part of the ecosystem, the agro-ecosystem, especially land use and land cover changes, affects climate (Bounoua et al., 2002; Findell et al., 2007; Grossman-Clarke et al., 2010). Irrigation, tillage, and the application of new technology have greatly changed land surface characteristics (Haddeland et al., 2006; Li et al., 2009) and are often associated with changes in vegetation and soil parameters that influence the regional and even global climate through atmospheric circulation (Adegoke

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et al., 2003; Lobell et al., 2008). The development of plastic mulch technology for suppressing soil evaporation has led to the widespread use of plastic mulches in vast arid and semi-arid regions for the purpose of increasing crop production during the last 30 years. For example, in northwest China, plastic mulches are used in most parts of these regions to reduce evaporation and promote water use efficiency (Li et al., 2008; Liu et al., 2009), where scarcity of water severely restricts agricultural development, since the yearly rainfall ranges from approximately 40 to 200 mm, whereas the potential evaporation ranges from 1500 to 3000 mm (Xie et al., 2005). Furthermore, field experiments have indicated that plastic mulch can modify soil temperature and moisture (Dahiya et al., 2007; Ramakrishna et al., 2006; Wang et al., 2011), which control the near-surface biological processes, including seedling germination, plant growth, and insect population dynamics (Anikwe et al., 2007; Díaz-Pérez et al., 2007). Thus, plastic mulch is used in arid and semiarid regions. The widespread application of plastic mulch has obviously altered the surface microclimate and parameters such as soil moisture and temperature, surface albedo, roughness and aerodynamic resistance (Ham and Kluitenberg, 1994; Tarara and Ham, 1999; Wang et al., 2011). Numerous researchers have indicated that land surface models and atmospheric general circulation models (GCMs) are particularly sensitive to these parameters (Gedney and Cox, 2003; Gettelman et al., 2011; Kirk-Davidoff and Keith, 2008; Liang and Guo, 2003). Consequently, the large area of plastic mulch covering can influence the regional weather forecasting and climate prediction by changing land surface parameters.

In recent years, with the support of a series of comprehensive surface layer experiments, numerous numerical models have been developed, particularly land surface process models, such as the Common Land Model (CoLM; Dai et al., 2003), the Simple Biosphere Model 2 (SiB2; Sellers et al., 1996), and the Canadian Land Surface Scheme (C_CLASS; Wang et al., 2002). These models contain a detailed plant canopy model, especially in regards to photosynthesis and stomatal conductance, which link the terrestrial biosphere to the atmosphere. A number of simulations of ecosystem water, heat and CO_2 fluxes have been conducted by these models, and numerous meaningful conclusions have been reached (Arora, 2003; Bartlett et al., 2002; Colello et al., 1998). Numerical models have become an effective tool to study the ecosystem. Attention has been given to plastic mulches by meteorologists as a special surface cover. The effects of plastic mulches have been explored by numerous researchers both through field observations and numerical models (Bonachela et al., 2012; Ham and Kluitenberg, 1994; Tarara and Ham, 1999; Wu et al., 2007), and the impacts of plastic mulch have been demonstrated from different perspectives by these studies. However, several limitations and difficulties still exist in former studies. (1) Plastic mulch cover significantly changes surface albedo and suppresses the vapour and CO_2 exchange between the soil and the atmosphere, but these physical processes are not accounted for in the existing land surface models. Therefore, simulations have remarkably deviated from observations when land surface models have been applied to underlying plastic mulch-covered areas. (2) Although plastic mulch is widely used in arid regions, limited comprehensive surface layer experiments have been conducted on plastic mulch-covered cropland. This scarcity of observation data has made it difficult to determine the key land surface parameters and develop suitable parameterisation schemes. (3) Few studies have been conducted on the influence of physical processes, such as the radiation budget, heat and water transport, and CO_2 exchange, which are often coupled together. A change in any one process can lead to changes in the others, which has typically been difficult to measure with direct methods. Accordingly, it is necessary to develop a land surface model containing a plastic mulch layer to simultaneously describe the complex physical and biochemical processes more accurately for the purpose of better understanding the energy and species exchange.

To address the aforementioned issues, the objective of this study was to develop a ground albedo parameterisation scheme based on the observations at a plastic mulch-covered cropland site during GHUSLE and to design a plastic mulch layer submodel and incorporate the submodel into a land surface model TBLSHAW to construct a new model TBLSHAW_MULCH to simultaneously simulate water, heat and CO_2 flux in a soil-mulch-plant-atmosphere continuum system. The TBLSHAW_MULCH model was evaluated by comparing the simulated fluxes and soil temperature and moisture with observations and by a contrast simulation demonstrated by the TBLSHAW model with the same forcing data to investigate the impacts of the plastic mulch. The study improves model development and enhances our understanding of the interaction between cropland ecosystems and the atmosphere. Furthermore, the model can be incorporated into GCMs to assess the influence of plastic mulches on regional weather and climate.

2. Model descriptions

The physical system of a cropland ecosystem covered by plastic mulch can be described as a model that consists of a vertical, one-dimensional profile extending from the vegetation canopy, plastic mulch, and soil surface to a specified depth within the soil. The plastic mulch layer is a special aspect in this physical system, and the key question is how to addresses the interaction among plastic mulch, atmosphere, soil and vegetation. In accordance with the principles of energy, water and CO_2 balance between the land and the atmosphere, a submodel for the plastic mulch layer was developed to addresses the mulch temperature and heat fluxes in the present study. The submodel was incorporated into the TBLSHAW model to simulate the vapour, heat and CO_2 fluxes throughout the system, including soil profiles of temperature and moisture, for exploring the land surface characteristics with plastic mulch coverage.

2.1. Brief description of the TBLSHAW model

The TBLSHAW land surface model, which was developed from the Simultaneous Heat and Water Model (SHAW; Flerchinger and Saxton, 2000) and CoLM (Dai et al., 2003) models, was constructed for land–atmosphere interactions in semi-arid climates. The TBLSHAW applies the SHAW dynamic framework and adopts the two-big-leaf parameterisation scheme from CoLM. The primary features of the TBLSHAW model are that the water-heat coupling equation has been simplified after the analysis of soil water-heat transfer features in semi-arid climates and that several parameterisation schemes that are applicable to semi-arid climates have been derived from long-term semi-arid surface layer and soil observations. The physical system of the TBLSHAW model consists of one-layer vegetation, multi-layer soil (50 soil layers at most) and a turbulent boundary layer. The key processes are presented as follows.

2.1.1. Governing equation of the vegetation layer leaf temperature

The energy equilibrium is closely related to leaf temperature, which is determined by a two-big-leaf parameterisation scheme in such a manner that the radiation transmission and turbulent exchange are computed for both the sunny and the shaded sides of a leaf, as given by Dai et al. (2004).

$$C_c \frac{\partial [T_l]_j}{\partial t} = [R_{n,c}]_j - [H_c]_j - L_v [E_c]_j = 0, \tag{1}$$

where the subscript j indicates a leaf side, with the sunny (shaded) side denoted by $j = 1$ ($j = 2$) and $[T_l]_j$ is the leaf temperature (K), C_c is