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Assimilating multi-source data into land surface model to simultaneously improve estimations of soil moisture, soil temperature, and surface turbulent fluxes in irrigated fields

Chunlin Huang[a,e,*], Weijing Chen[b], Yan Li[a,c], Huanfeng Shen[b], Xin Li[a,d]

[a] Key Laboratory of Remote Sensing of Gansu Province, Heihe Remote Sensing Experimental Research Station, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, Gansu, China
[b] School of Resource and Environmental Science, Wuhan University, Wuhan, Hubei, China
[c] University of Chinese Academy of Sciences, Beijing, China
[d] CAS Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing, China
[e] Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing, China

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ABSTRACT

The optimal estimation of soil moisture, soil temperature, and surface turbulent fluxes in irrigation fields is restricted by a lack of accurate irrigation information. To resolve the input uncertainty from imprecise irrigation quantity, an improved data assimilation scheme that is EnKS (Ensemble Kalman Smoother) implemented with inflation and localization (referred to as ESIL) is proposed to estimate soil moisture, soil temperature, and surface turbulent fluxes for irrigated fields by assimilating multi-source observations. The Daman station, which is located at an irrigated maize farmland in the middle reaches of the Heihe River Basin (HRB), is selected in this study to investigate the performance of the proposed assimilation scheme. The measured land surface temperature (LST) and surface soil moisture (SSM) in the first soil layer are taken as observations to conduct a series of data assimilation experiments to analyze the influence of a lack of irrigation information and combinations of multi-source observations on estimations of soil moisture, soil temperature, and surface turbulent fluxes. This study demonstrates the feasibility of ESIL in improving the estimation of hydrothermal conditions under unknown irrigation. The coefficient correlation (***R***) with the ESIL method increases from 0.342 and 0.703 to 0.877 and 0.830 for the soil moisture and soil temperature in the first layer, respectively. Meanwhile, the surface turbulent fluxes are significantly improved and the ***RMSE*** decreases from 173 W/m^2 and 186 W/m^2 to 97 W/m^2 and 111 W/m^2 for the sensible and latent heat fluxes, respectively.

1. Introduction

Accurate estimations of the soil moisture, soil temperature, and surface turbulent fluxes are crucial to agriculture and water management in irrigated fields. Land surface variables and fluxes can be acquired by modeling or observations. Modeling provides the evolution of continuous states in the time-space domain *via* parameterizing the inherent physical processes in the geo-sphere. However, the uncertainties that exist in forcing data, model parameters and model structure adversely affect the model output. Observations provide relatively accurate information, but the space gaps in *in-situ* measurements or the time gaps in remote sensing data cannot fulfill the requirements of practical application. Data assimilation takes full advantage of imperfect models and limited observations by merging the information embodied in observations into a dynamic model to correct the forecast trajectory. Numerous studies have assimilated both the surface soil moisture from ground-based networks or from microwave sensors and passive microwave brightness temperature data to improve soil moisture estimation and assimilate land surface temperatures from ground-based networks or satellite sensors to obtain more precise soil temperature profiles (Kumar and Kaleita, 2003; Gao et al., 2007; Huang et al., 2008a, b; Jia et al., 2009; Chen et al., 2011; Chen et al., 2015; Chu et al., 2015).

In the framework of a dynamic model, the soil moisture and soil temperature mutually influence to constitute the water and energy balance in solums. The soil temperature is a function of the soil moisture. Subsurface moisture influences the heat conductivity

* Corresponding author.
E-mail address: huangcl@lzb.ac.cn (C. Huang).

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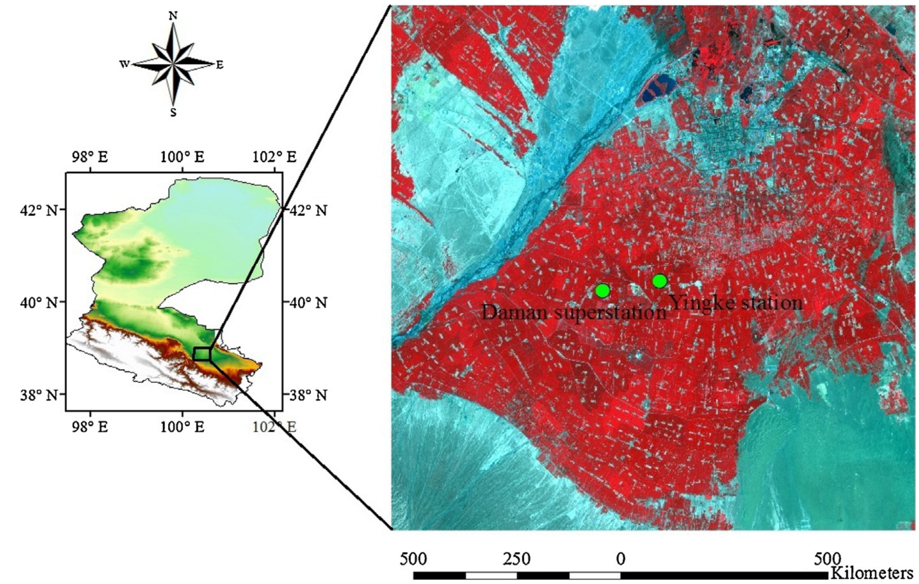

Fig. 1. Location of the study area in an SRTM 1-km DEM map and the locations of the field observation stations in an ASTER false color composite map with bands 3, 2, and 1.

at the interfaces of layers and the heat storage in different layers. In addition, the soil temperature determines the phase of the soil water content, including the transformation between frozen and unfrozen. Furthermore, the surface temperature affects the partitioning of incoming radiant energy into the ground (sensible heat flux and latent heat flux) and thus changes the delivery of the soil moisture, soil temperature, and surface turbulent fluxes. Yang et al. (2007) validated the feasibility of correcting the surface temperature and surface energy budget by assimilating soil moisture. Lakshmi (2000) demonstrated that surface temperature assimilation can reduce the effect of errors in precipitation and/or shortwave radiation data on simulated soil moisture. Given the internal positive interactions in the modification of soil moisture and soil temperature, simultaneously assimilating temperature and moisture observations is important to produce more exact soil moisture, soil temperature and surface turbulent fluxes.

A vital factor in retrieving accurate soil moisture and temperature profiles in arid and semi-arid agricultural areas is irrigation. Irrigation, which is a human intrusion into soil systems, alters the hydrothermal conditions of soil and changes the water transfer mechanisms between soil layers. Abundant irrigation rapidly increases the soil moisture and dramatic decreases the soil temperature, even in deeper layers. Moreover, irrigation applications in agricultural practices normally occur under dry conditions, in which the soil moisture is highly sensitive to irrigation applications. However, the irrigation schedules (when and how much to irrigate) that have been recorded in government departments are usually not sufficiently inclusive to be prescribed as model inputs. Several scientists have emphasized the impact of irrigation on hydrologic processes and relevant variables (Ozdogan and Salvucci, 2004; Ines et al., 2006; Moiwo and Tao, 2015; Lawston et al., 2015). Wang and Cai (2007) attempted to investigate the information of irrigation schedules for specific crops by using predefined empirical criteria to determine irrigation actions and an optimization algorithm to invert the irrigation quantification.

The objective of this article is to investigate how to assimilate the SSM in the first layer and/or the LST to improve the profiles of soil moisture and soil temperature and surface turbulent fluxes for different situations of known and unknown irrigation. We establish a data assimilation framework that is based on the CoLM (Common Land Model) and consider the SSM in the first layer and/or the LST that was measured at Daman station as observations. First, we distinguish the influence of assimilating different observations on the state variables and fluxes to ascertain the capability of combinations of multi-source information (SSM and LST) in improving the forecast accuracy of model outputs. Second, the aforementioned experiments are repeated under two postulations—known irrigation and unknown irrigation. The former is implemented through substituting the soil moisture and temperature profiles with the *in-situ* measurements at the irrigation moments, which are defined by the mutational volume of the soil water in the deeper layer, while the latter is implemented without any modifications to soil moisture and temperature profiles. We compare the discrepancies of the experimental results from these circumstances to determine the competence of assimilating observation information in improving soil moisture, soil temperature, and surface turbulent fluxes under unknown irrigation circumstances. Finally, considering the application of satellite data in the future work, we retest the combinations of multi-source information (SSM and LST) with various observation intervals or standard deviations. In addition, an ESIL that was modified to retrieve parameters is compared to the original ESIL to investigate the necessity of parameter estimation.

This article is structurally organized as follows. The land data assimilation scheme is briefly described in Section 2, including the hydrothermal process of the CoLM, experimental design and assimilation algorithms. The study area and data are also introduced in Section 2. Sections 3 and 4 present the results and discussion regarding the experiments. We finish this paper with some conclusions in Section 5.

2. Land data assimilation scheme

2.1. Model operator

The Common Land Model (CoLM) (Dai et al., 2003) is the improved version of the Community Land Model (version 2.0) with one vegetation layer, 10 unevenly spaced vertical soil layers, and up to 5 snow layers (depending on the total snow depth). Every surface grid cell can be subdivided into any number of tiles, and each tile contains a single land cover type. We employ the CoLM as a dynamic model (model operator) to maintain prognostic state variables, such as the soil moisture and soil temperature.

The vertical soil moisture transport is governed by infiltration, runoff, gradient diffusion, gravity, and soil water extraction through