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Parameter estimation for a simple two-source evapotranspiration model using Bayesian inference and its application to remotely sensed estimations of latent heat flux at the regional scale

Yi Song[a,*], Long Jin[b], Gaofeng Zhu[c], Mingguo Ma[d]

[a] State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, No. 97# Yanxiang Road, Xi'an, Shaanxi Province 710061, China
[b] Key Laboratory of Highway Construction & Maintenance Technology in Permafrost Regions, Ministry of Transport, CCCC First Highway Consultants Co., LTD., Xi'an 710065, China
[c] Key Laboratory of Western China's Environmental Systems (Ministry of Education), Lanzhou University, Lanzhou 730000, China
[d] School of Geographical Sciences, Southwest University, Chongqing 400715, China

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ABSTRACT

A simple two-source evapotranspiration (ET) model was applied to the Yingke and Daman irrigation districts of the Zhangye Oasis, which is located in the middle reaches of the Heihe River, China. The ET model was composed of two parts, including an evaporation (E) sub-model and a transpiration (T) sub-model. A separated parameter estimation scheme was conducted using Bayesian inference. First, an empirical multiplier was estimated for an E sub-model using observations that were collected after crop harvests. The empirical multiplier was then assigned to the most-likely value in the simple two-source ET model. Second, a global sensitivity analysis was performed to identify the key parameters that were responsible for most of the variability in the λET results within the T sub-model. To avoid equifinality or over-parameterization, Bayesian inference was applied to estimate the key parameters that induced the most variability in the first set. A second set of Bayesian inference was then performed by fixing the most-likely values of these parameters, and the other parameters were defined one-by-one as Bayesian parameters. These parameters were estimated for seven sites. The coefficient of determination for the modeled λET and the observed values exceeded 0.9. Next, a cluster analysis was conducted using the canopy height, leaf area index (LAI) and soil moisture content to classify the fields with the highest similarities and then to distribute the same parameter values to similar fields. Finally, λET was estimated using the most-likely values of the parameters at the regional scale. The root-mean-square error of the remotely sensed estimates was less than 20 W m^{-2}, the mean absolute percent error did not exceed 4%, and the correlation coefficient was greater than 0.97. The validation was conducted for both the modeled λET at the point scale and for the remotely sensed λET at the satellite pixel scale. The results demonstrate that the separated parameter estimation scheme using Bayesian inference yields reasonable parameter values; using cluster analysis, the most-likely values of the parameters can be effectively applied to estimate remotely sensed λET.

1. Introduction

Evapotranspiration (ET) plays an important role in hydrology, meteorology and agriculture and controls the water cycle and energy transport within the biosphere, atmosphere and hydrosphere (Bastiaanssen et al., 2000; Li et al., 2009; Su, 2002). To save water and implement efficient irrigation practices in arid agricultural regions, precise measurements or estimations of ET and its components (evaporation (E) from the soil and transpiration (T) from the vegetation canopy) are required, particularly because the hydrological cycle is strongly affected by crop water consumption (Allen, 2000; Flumignan et al., 2011; Porporato et al., 2004; Sun et al., 2012). Compared with other methods, the Penman–Monteith (P–M) equation (Monteith, 1965) has been proven to be effective in estimating ET at both the point and kilometer scales (Cleugh et al., 2007; Leuning et al., 2008; Mu et al., 2007; Song et al., 2012; Zhang et al., 2008). In addition, many two-source ET models that are based on the P–M equation have been developed using remotely sensed data to estimate ET at the regional or global scale. Mu et al. (2007) developed a global remote sensing ET model based

* Corresponding author.
E-mail address: songyi@ieecas.cn (Y. Song).

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on this equation that considered both the surface energy partitioning process and the environmental constraints on ET. However, the study ignored the effect of soil moisture (especially soil moisture at the rooting depth) on ET. To improve the model, Leuning et al. (2008) developed a two-source ET model that was based on the P–M equation and included biophysical surface resistance; the model calculated the daily average E using remotely sensed leaf area index (LAI) data. To reduce the number of parameters in the model that was developed by Leuning et al. (2008), Song et al. (2012) proposed a simple two-source ET model with an E sub-model that was proposed by Fisher et al. (2008) and a T sub-model that was proposed by Leuning et al. (2008). This simple two-source ET model required fewer parameters and yielded better latent heat flux (λET) estimates at the regional scale. However, the parameter estimation scheme still contains several inefficiencies. Abundant evidence has shown that the Bayesian inference of parameters is a powerful new tool for optimizing model parameters and quantifying the influence of uncertainties (Clark and Gelfand, 2006; Zhu et al., 2013, 2014). Although some significant efforts have been made by Samanta et al. (2007) and Zhu et al. (2013, 2014) to illustrate this method's effectiveness, Bayesian inference has been used much less frequently in the parameterization of ET models than in other environmental sciences (van Oijen et al., 2005).

Our study area is located in the Zhangye Oasis of the Heihe River Basin, which is the second largest Inland River Basin in the arid region of Northwest China (Cheng et al., 2014). In 2012, the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) project began operating as part of the Heihe Plan. HiWATER is a comprehensive eco-hydrological experiment that was executed under the framework of the Heihe Plan; it is based on the diverse needs of interdisciplinary research and the existing observational infrastructure in the basin (Li et al., 2013). An observation matrix that consisted of 17 stations was built in the study area in late April 2012. Each station was equipped with an eddy covariance (EC) system and an automatic meteorological station (AMS). The intensive observation period of the fieldwork began in late May 2012 and produced a large number of hydrological and meteorological measurements and field observations for ET estimations. The primary objectives of our study were (1) to improve the parameter estimation scheme for the P-M-based simple two-source ET model (Song et al., 2012) using Bayesian inference; (2) to analyze the primary effects of the external environment on the most-likely values of the parameters in this ET model; (3) to produce better λET estimates using remotely sensed images at the regional scale; and (4) to assess the applicability of the most-likely values of the parameters to farmlands in arid regions.

2. Study area and materials

2.1. Study area

Our study area, which is a 4 km × 4 km field, is located in the Yingke and Daman irrigation districts of the Zhangye Oasis along the middle reaches of Heihe River, Gansu Province, China (see Fig. 1). The total annual precipitation and average annual temperature are 126.5 mm and 16.3 °C (1970–2000), respectively. The land use is heterogeneous but is dominated by agriculture, including seed corn, corn planted with spring wheat, vegetables, and orchards. Our study focused on seed corn, which is typically sown in late April and harvested in the middle third of September. To maintain the soil moisture, the corn seedlings were covered with plastic film.

2.2. Meteorological data and field observations

The meteorological data and field observations from the HiWATER middle reaches experiment had the greatest integrity from June to August 2012. Canopy structure parameters, including the canopy height and LAI at each EC/AMS observation site, were collected every five days. The days without records were filled using estimated values. The LAI was measured using an LI-CORLAI-2200 canopy analyzer. Of the 17 EC/AMS observation sites in the HiWATER experiment observation matrix, only 7 sites (EC/AMS 01, 02, 05, 08, 12, 15 and 17) had the complete input data that were required by the two-source ET model. The measurements that were collected at these 7 EC/AMS stations from mid-June to August 2012 were used to estimate the parameters in the canopy T sub-model using Bayesian inference. Assuming that the parameters in the soil E sub-model were the same before and after the harvest, we used the observations that were made after the harvest to estimate the parameters in the soil E sub-model. After the HiWATER experiment in the middle reaches, only EC tower 15 was maintained for long-term observations. Thus, only measurements from EC 15 that were collected from October to November of 2012 and 2013 were used to the estimate the parameters in the soil E sub-model. The meteorological measurements that were used in this study include the wind speed, air temperature, humidity, air pressure, 4 radiation components (total solar radiation, reflective shortwave radiation, land surface longwave radiation, and atmospheric longwave radiation), soil temperature, soil moisture profile and λET. The sensor type and height (or depth) of each instrument are shown in Table 1.

The raw high-frequency (10 Hz) data that were collected at the EC towers were processed using the EdiRe software, which was developed by Edinburgh University, UK. The process included de-spiking (Vickers and Mahrt, 1997), tilt correction (Wilczak et al., 2001), sonic virtual temperature corrections (Schotanus et al., 1983), time-lag calculations, frequency response corrections (Moore, 1986) and Webb, Pearman and Leuning (WPL) correlations (Webb et al., 1980). Half-hour-averaged λET values were calculated from the processed EC measurements (Liu et al., 2011). The energy balance closure reached 85% during the intensive HiWATER observation period (Xu et al., 2013). However, a bias that was caused by the underestimation of vertical winds was not corrected in our study. Thus, the measurements of λET were probably underestimated by 5% (Horst et al., 2015). Records with a friction velocity of less than 0.1 ($m\,s^{-1}$) were not used in the energy balance closure analysis, parameter estimation or ET validation.

2.3. Satellite images

Two Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) L1B images with a spatial resolution of 30 m, which were acquired on 10 July and 11 August 2012, were selected to estimate λE. Measurements from all 17 EC towers in the observation matrix were available for validation. The images were pre-processed through radiative, atmospheric and geometric corrections using the Environment for Visualizing Images (ENVI). An atmospheric correction was performed using the ENVI Fast Line-of-sight Atmospheric Analysis of Hypercubes (FLAASH).

3. Methodology

3.1. Description of the revised two-source ET model

The total λET is the sum of the λT ($W\,m^{-2}$) from the vegetation canopy (Leuning et al., 2008) and the λE ($W\,m^{-2}$) from the soil