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Mapping daily evapotranspiration based on spatiotemporal fusion of ASTER and MODIS images over irrigated agricultural areas in the Heihe River Basin, Northwest China

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A B S T R A C T

Continuous monitoring of daily evapotranspiration (ET) is crucial for allocating and managing water resources in irrigated agricultural areas in arid regions. In this study, continuous daily ET at a 90-m spatial resolution was estimated using the Surface Energy Balance System (SEBS) by fusing Moderate Resolution Imaging Spectroradiometer (MODIS) images with high temporal resolution and Advanced Space-borne Thermal Emission Reflectance Radiometer (ASTER) images with high spatial resolution. The spatiotemporal characteristics of these sensors were obtained using the Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM). The performance of this approach was validated over a heterogeneous oasis-desert region covered by cropland, residential, woodland, water, Gobi desert, sandy desert, desert steppe, and wetland areas using in situ observations from automatic meteorological systems (AMS) and eddy covariance (EC) systems in the middle reaches of the Heihe River Basin in Northwest China. The error introduced during the data fusion process based on STARFM is within an acceptable range for predicted LST at a 90-m spatial resolution. The surface energy fluxes estimated using SEBS based on predicted remotely sensed data that combined the spatiotemporal characteristics of MODIS and ASTER agree well with the surface energy fluxes observed using EC systems for all land cover types, especially for vegetated area with MAP values range from 9% to 15%, which are less than the uncertainty (18%) of the observed λE in this study area. Time series of daily ET modelled from SEBS were compared to that modelled from PT-JPL (one of Satellite-based Priestley-Taylor ET model) and observations from EC systems. SEBS performed generally better than PT-JPL for vegetated area, especially irrigated cropland with bias, RMSE, and MAP values of 0.29 mm/d, 0.75 mm/d, 13% at maize site, −0.33 mm/d, 0.81 mm/d, and 14% at vegetable sites.

1. Introduction

Evapotranspiration (ET), the sum of land surface evaporation and plant transpiration, is a major component of the water cycle and energy exchange of the soil-vegetation-atmosphere system that affects the redistribution of terrestrial surface radiation and precipitation (Rivas and Caselles, 2003). The simulation of ET is beneficial for water resources and agricultural management, flood and drought monitoring, weather forecasting, and climate change research (Courault et al., 2005; Huang et al., 2015). In semi-arid and arid regions, water resources are scarce, and agricultural irrigation water is mainly from channels and pumping wells (Li et al., 2016). Therefore, it is very important to monitor spatiotemporal variations in water use in irrigated fields with high spatial resolution data and facilitate water resources management and irrigation scheduling.

Accurate quantification of ET can be achieved using in situ measurements, such as those collected with weighing lysimeters, Bowen ratio systems, eddy covariance systems, and large aperture scintillometers. However, in situ observations are costly and only obtain the turbulent fluxes over small and homogeneous regions. With the

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development of remote sensing technology, accurate estimates of ET can be achieved using remote sensing data related to land surface variations over large regions at satellite overpass times (Schmugge et al., 2002). Over the past few decades, several remotely sense-based approaches have been proposed to estimate land surface fluxes and ET (Kalma et al., 2008), and these methods can be divided into four main categories: (1) empirical and semi-empirical methods (Jackson et al., 1997; Wang et al., 2007), (2) surface energy balance models (SEB) (Bastiaanssen et al., 1998; Roerink et al., 2000; Su, 2002; Allen et al., 2007; Norman et al., 1995; Anderson et al., 1997; Norman et al., 2003), (3) the tradition ET estimation approaches (e.g. Penman-Monteith (PM) approach and Priestley-Taylor (PT) approach) combined with remote sensing (Cleugh et al., 2007; Leuning et al., 2008; Fisher et al., 2008; Yao et al., 2013, 2015), (4) data assimilation combined with land surface models and observations (Caparrini et al., 2004; Huang et al., 2016). The surface energy balance models (SEB) has been commonly used in estimates of ET at regional scales. These estimates involve the calculation of the latent heat flux (λE) as a residual of the surface energy balance and the sensible heat flux (H) using a land surface temperature and vegetation index. Some of these methods consider the land surface as a single system when estimating ET, such as the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998), Simplified Surface Energy Balance Index (S-SEBI) (Roerink et al., 2000), Surface Energy Balance System (SEBS) (Su, 2002), and Satellite-based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC) (Allen et al., 2007). However, some methods compute evaporation from the land surface and transpiration from plants separately, such as the Two-Source Energy Balance Model (TSEB) (Norman et al., 1995), Atmosphere-Land Exchange Inverse (ALEXI) (Anderson et al., 1997), and ALEXI flux disaggregation approach (DisALEXI) (Norman et al., 2003). SEB methods are based on measurement of a physical property of the surface (i.e. land surface temperature, LST) that provides valuable information about the sub-surface moisture status required for estimating ET (Anderson et al., 2011; Glenn et al., 2010). By contrast, most of empirical, PM-based and PT-based approaches depend on vegetation index (VI) that indirectly related to ET by estimating of the density of green vegetation over the landscape (Glenn et al., 2010; Kalma et al., 2008). Over the last decade, VI methods have been developed and applied over a wide range of spatial scales from local to global and a wide range of temporal scales from daily to annual (Cleugh et al., 2007; Fisher et al., 2008; Glenn et al., 2010; Leuning et al., 2008; Wang et al., 2007; Yao et al., 2013, 2015, 2017). Cleugh et al. (2007) developed an ET model for estimating daily and monthly ET over Australia based on PM equation using LAI as the main remotely sensed variable for estimating surface conductance. To overcome surface conductance parameterization problems, the PT equation was developed, which can be considered as a simplified version of PM equation by replacing the surface and aerodynamic resistance terms with an empirical multiplier alpha (Fisher et al., 2008; Yao et al., 2013). Fisher et al. (2008) proposed a bio-meteorological approach called PT-JPL for reducing PT-based estimates of monthly potential ET to actual ET using eco-physiology constraints.

All of these models perform well over homogeneous surfaces at approximately 1–5 km spatial resolutions based on remotely sensed data, which are available multiple times per day from several geostationary satellites and polar-orbiting satellites (Kustas et al., 2003). However, this spatial resolution is too coarse for monitoring the impacts of land cover change and the land cover distribution on ET or for estimating ET from different crop covers at the field scale (Kustas et al., 2003, 2004). In addition, the coarse-resolution data could introduce errors into estimated ET values due to the presence of pixels that include multiple land cover types, especially in arid and semi-arid regions where irrigated fields are surrounded by dry landscapes (Kustas et al., 2004; Ha and Howell, 2013a). Land surface and ET at a pixel resolution on the order of 100 m have been calculated using high-resolution satellite data, such as data from the Land Remote Sensing Satellite (Landsat) and the Advanced Space-borne Thermal Emission Reflectance Radiometer (ASTER), at the regional scale (Ma et al., 2011; Senay et al., 2016; Singh et al., 2012; Song et al., 2016; Yang et al., 2015; Liu et al., 2016). However, it is difficult to obtain temporally continuous daily ET and seasonal ET using remotely sensed data with a high spatial resolution because of the low frequency of repeated coverage and cloud contamination.

Multi-resolution data fusion methods have been used to overcome spatial and temporal scaling issues associated with remote sensing data and to obtain land surface temperature and reflectance at high spatiotemporal resolutions (Ha et al., 2013a, 2013b). In recent years, data fusion methods have been further applied for high-resolution spatiotemporal ET mapping, which can be classified into two categories: (1) fusing land surface temperature datasets with high spatiotemporal resolutions and reflectance images as ET model inputs (Kustas et al., 2003; Norman et al., 2003) and (2) fusing multi-scale ET products derived from high spatial resolution and high temporal resolution remote sensing data (Anderson et al., 2011; Jia et al., 2012). Kustas et al. (2003) proposed a method called the disaggregation procedure for radiometric surface temperature (DisTrad), which can be used to estimate land surface temperatures at the subpixel scale and energy fluxes based on the vegetation index-radiometric temperature relationship. ALEXI and disALEXI are multi-scale approaches to energy balance modelling that can estimate surface fluxes and ET at multiple scales using remotely sensed data from multiple satellite platforms (Anderson et al., 1997; Norman et al., 2003; and Yang et al., 2016). Anderson et al. (2011) described a scheme for fusing hourly/daily ET derived from multiple satellite platforms at a spatial resolution ranging from 10 km to 30 m using ALEXI, disALEXI, TSEB, DisTrad, and the Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM). STARFM is a data fusion method that can produce high spatiotemporal land surface reflectance (Gao et al., 2006), and it has been widely utilized in corn and soybean fields (Cammalleri et al., 2013), rainfed and irrigated agricultural areas (Cammalleri et al., 2014), forests (Yang et al., 2017), and vineyards (Semmens et al., 2016).

In this study, instantaneous land surface fluxes and daily ET at a 90-m spatial resolution was estimated from SEBS using the land surface temperature and land surface reflectance of visible/near-infrared (VNIR) combined with the spatiotemporal characteristics of MODIS and ASTER obtained using STARFM. This scheme was utilized and verified over a heterogeneous oasis-desert region covered by cropland, residential areas, woodland, water, the Gobi desert, sandy desert, desert steppe, and wetlands. Moreover, the daily ET modelled from SEBS was compared with that modelled from PT-JPL based on fusion VNIR data from STARFM. Furthermore, the introduction of error during the data fusion process was validated in multiple land cover types using in situ observations from automatic meteorological systems (AMS) and eddy covariance (EC) systems installed in the study area.

2. Study area and data

2.1. Study area

The Heihe River Basin is the second largest inland river basin in the arid region of northwest China. The basin features glaciers, frozen soil, alpine meadows, forests, irrigated crops, riparian ecosystems, and deserts from upstream to downstream. The study area is located in a desert-oasis zone in the middle reaches of the Heihe River Basin, as shown in Fig. 1. The land cover is complex in the area. The central part of the area is a typical irrigated crop ecosystem covered by maize, vegetables, wheat, and orchard and surrounded by residential areas, wetlands, water bodies, the Gobi desert, desert steppe, and sandy desert. In this area, the annual precipitation is approximately 100–250 mm; however, the annual potential evaporation can be as high as 1200–1800 mm. In 2012, a comprehensive eco-hydrological experiment called the Heihe Water Allied Telemetry Experimental Research project included the