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An evapotranspiration product for arid regions based on the three-temperature model and thermal remote sensing

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SUMMARY

An accurate estimation of evapotranspiration (ET) is crucial to better understand the water budget and improve related studies. Satellite remote sensing provides an unprecedented opportunity to map the spatiotemporal distribution of ET. However, ET values from barren or sparsely vegetated areas in arid regions are often assumed to be zero in typical ET products because of their low values. In addition, separating ET into soil evaporation (E_s) and vegetation transpiration (E_c) is difficult. To address these challenges, we developed an ET product (MOD3T) based on a three-temperature model and thermal remote sensing, specifically Moderate Resolution Imaging Spectroradiometer (MODIS) data. MOD3T has a spatial resolution of 1 km and a temporal resolution of 8 days. All input parameters except air temperature were obtained from MODIS datasets. Validation in two adjacent arid river basins in northwestern China showed that the mean absolute errors (mean absolute percent errors) between the MOD3T and flux tower ET were 0.71 mm d^{-1} (18.5%) and 0.16 mm d^{-1} (24.9%) for a densely vegetated area and sparsely vegetated sandy desert, respectively. The error between the MOD3T and water balance ET was 24 mm y^{-1} (8.1%). The E_c/ET or E_s/ET of MOD3T was comparable to the observed stable oxygen and hydrogen isotopes. Unlike the MODIS ET (MOD16), MOD3T could not provide continuous ET values (as 70% of the MOD16 area lacked data) but exhibited relatively low uncertainty, particularly in cold seasons. Therefore, MOD3T can provide ET, E_s and E_c estimates for arid regions within acceptable ranges.

1. Introduction

Evapotranspiration (ET), which includes evaporation from soil and water surfaces and transpiration from vegetation, is a major hydrological variable that links water, energy and carbon cycles (Law et al., 2002; Kothavala et al., 2005; Anderson et al., 2008; Wang, 2008; Yang et al., 2014). Therefore, accurate ET estimates are required to understand local to global water and energy cycles and improve hydrological applications (Nemani et al., 2002; Dirmeyer et al., 2006; Trenberth et al., 2007; Cheng et al., 2011), water resource management (Bastiaanssen et al., 2005; Oki and Kanae, 2006; Yang et al., 2012), drought monitoring and assessment (Heim, 2002; Yao et al., 2011), irrigation scheduling (Allen et al., 1998; Dodds et al., 2005) and climatological studies (Pielke et al., 1998; Teuling et al., 2009). However, ET is one of the most problematic components of the water cycle to accurately quantify (Mu et al., 2007; Long et al., 2014) because of the heterogeneity of land surfaces and the large number of controlling factors that are involved, such as plant biophysics, soil properties, atmospheric conditions and topography (Shuttleworth and Wallace, 1985; Bastiaanssen et al., 1998; Glenn et al., 2007).

Numerous methods (e.g., weighing lysimetry, the Bowen ratio system and the eddy covariance technique) have been proposed to measure or estimate ET based on ground measurements; however, these methods are usually applicable to homogeneous areas that are smaller than 1 km^2 (Scott et al., 2000; Baldocchi, 2003; Allen et al., 2011). Ground-based methodologies are inadequate for regional- and global-scale requirements (Wang and Dickinson, 2012). Because satellite remote sensing provides temporally and spatially continuous information over land surfaces that is useful for estimating surface biophysical variables, this approach has been increasingly used to map the spatial distribution of ET at regional (e.g., Moran et al., 1989; Norman et al.,

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1995; Bastiaanssen et al., 1998; Li et al., 2005; Allen et al., 2007; Cleugh et al., 2007; Yang and Shang, 2013) to global scales (e.g., Mu et al., 2007, 2011; Jung et al., 2010; Zhang et al., 2010; Vinukollu et al., 2011).

Moderate Resolution Imaging Spectroradiometer (MODIS) ET (MOD16) (Mu et al., 2007, 2011) and global land ET (Jung et al., 2010; Zhang et al., 2009, 2010) have been produced at the global scale based on the Penman–Monteith equation. These ET products provide important information on global terrestrial water and energy cycles and environmental changes (e.g., Loarie et al., 2011; Mu et al., 2013; Schlesinger and Jasechko, 2014). Although substantial progress has been made in ET studies (Li et al., 2009a; Allen et al., 2011; Wang et al., 2013), accurately estimating ET based on remote sensing is a challenge, particularly in arid regions with large barren or sparsely vegetated areas. For example, the ET in barren/desert regions is often excluded from model calculations and is set to zero in the two global ET products. The annual ET in arid regions could exceed 200 mm (Tian et al., 2013, 2014), and neglecting soil moisture restrictions on transpiration would cause an underestimation of the MOD16 and global land ET (Mu et al., 2011; Yang et al., 2015). Mu et al. (2007) suggested that further research is required to improve this algorithm in barren areas. Furthermore, barren/desert regions account for 24% of the Earth's land surface; the ET in these regions is important for regional and global water budgets (Falkenmark and Rockstrom, 2004; Bastiaanssen et al., 2005; Li et al., 2009a).

In addition, the Penman–Monteith equation and some methods that are based on the energy balance equation require surface and aerodynamic resistances to estimate water vapor transfer in the soil–vegetation–atmosphere system. However, these resistances are difficult to quantify (Priestley and Taylor, 1972; Qiu, 1996; Qiu et al., 1996, 1998), especially in arid regions that are characterized by aerodynamic and land surface properties with high spatial heterogeneity, because the resistances are significantly affected by aerodynamic and land surface properties. In fact, the parameterization of resistance is one of the greatest limitations when remotely estimating ET (Li et al., 2009a; Matsushita and Fukushima, 2009; Vinukollu et al., 2011). The improper parameterization of resistance might lead to error propagation. Our previous results showed that the observations were better fit by the ET that was estimated without aerodynamic resistance than the ET that was estimated with aerodynamic resistance (Xiong and Qiu, 2014). In addition, the available ET products, including the two mainstream ET datasets, are seldom partitioned into the two ET components of soil evaporation (E_s) and vegetation transpiration (E_c) (Schlesinger and Jasechko, 2014).

The objective of this study is to estimate and develop an ET product that includes both soil evaporation and vegetation transpiration for arid regions based on a three-temperature model (3T model) to address two limitations in ET estimation: the assumption that the ET values from barren or sparsely vegetated areas in arid regions are zero in typical ET products, and the difficulty in separating ET into soil evaporation (E_s) and vegetation transpiration (E_c).

2. Development of an ET product for arid regions

2.1. Theoretical basis of the 3T model

The 3T model can be expressed as follows (Qiu, 1996):

$$LE_s = R_{n,s} - G_s - (R_{n,sr} - G_{sr})\frac{T_s - T_a}{T_{sr} - T_a} \quad \text{soil} \tag{1}$$

$$LE_c = R_{n,c} - R_{n,cr}\frac{T_c - T_a}{T_{cr} - T_a} \quad \text{vegetation} \tag{2}$$

For a mixture of soil and vegetation,

$$L(\mathrm{ET}) = LE_s + LE_c \tag{3}$$

where ET is the evapotranspiration; E_s and E_c are the soil and vegetation components of ET within a given pixel, respectively, in mm; L is the latent heat of vaporization; the subscripts "*s*," "*c*," "*a*," "*sr*" and "*cr*" represent the soil, canopy, air, reference soil and reference canopy, respectively; R_n is the net radiation in W m^{-2}; G is the soil heat flux in W m^{-2}; and T is the temperature in K.

Although the 3T model was based on the energy balance, a reference surface (a surface without evaporation or transpiration) was introduced to eliminate sensible heat flux and aerodynamic resistance (Qiu, 1996; Qiu et al., 1996, 1998). This variable constitutes the greatest difference between the 3T model and other ET estimation methods that include resistance deduced from the energy balance, such as the surface energy balance algorithm for land (SEBAL) (Bastiaanssen et al., 1998), surface energy balance system (SEBS) (Su, 2002; Jia et al., 2003), Penman–Monteith equation (Cleugh et al., 2007) and two-source energy balance model (TSEB) (Norman et al., 1995).

We previously proposed two parameterization methods for remote sensing applications of the 3T model: a 3T–R model (Xiong and Qiu, 2011) and a 3T–S model (Xiong and Qiu, 2014). The differences between the 3T–R and 3T–S models are a function of the method that is used to obtain the reference temperatures (T_{sr} and T_{cr}). In the 3T–R model, T_{sr} and T_{cr} are obtained by inverting the energy balance method, which leads to an aerodynamic resistance requirement:

$$T_{sr} = \frac{R_{n,s} - G_s}{\rho C_p} r_a + T_a \tag{4}$$

$$T_{cr} = \frac{R_{n,c}}{\rho C_p} r_a + T_a \tag{5}$$

where T_{sr} and T_{cr} represent the reference soil temperature and reference canopy temperature, respectively; r_a is the aerodynamic resistance (the diffusion resistance of the air layer to water vapor movement) in s m^{-1}; ρ is the air density in kg m^{-3}; and C_p is the specific heat of air at a constant pressure in MJ kg^{-1} °C^{-1}. The remaining parameters are the same as those in Eqs. (1) and (2).

In the 3T–S model, T_{sr} and T_{cr} are assumed to be the regional maximum values for soil surface temperature and vegetation temperature, respectively, which are collected from a region with approximately equivalent solar radiation and terrain:

$$T_{sr} = T_{s,max} = \max(T_{s1}, T_{s2}, \ldots, T_{si}) \tag{6}$$

$$T_{cr} = T_{c,max} = \max(T_{c1}, T_{c2}, \ldots, T_{ci}) \tag{7}$$

where T_{si} and T_{ci} represent the soil and vegetation components of land surface temperature (LST) within pixel i (i = 1,2,3,. . ..), respectively. For commonly used LSTs that are estimated from single-view-angle satellite data, T_s and T_c can only be decomposed through certain assumptions; for example, this study assumes that LST is a vegetation-weighted summation of T_s and T_c (see Section 2.2 for details).

Thus, the simplification of obtaining the reference temperatures (T_{sr} and T_{cr}) with only remotely sensed land surface temperature makes the 3T–S model more viable. Although observations from only two Bowen flux towers over several days were used, our previous validation results indicated that the 3T–R and 3T–S models can capture ET at 30 m resolution in semiarid grasslands in northern China (Xiong and Qiu, 2011, 2014).