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Development of a Simple Remote Sensing EvapoTranspiration Model (Sim-ReSET): Algorithm and Model Test

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Abstract

Remote sensing (RS) has been considered as the most promising tool for evapotranspiration (ET) estimations from local, regional to global scales. Many studies have been conducted to estimated ET using RS data, however, most of them are based partially on ground observations. In this study, we developed a new dual-source **Sim**ple **Re**mote **S**ensing **E**vapo**T**ranspiration model (Sim-ReSET) based only on RS data. One merit of this model is that the calculation of aerodynamic resistance can be avoided by means of a reference dry bare soil and an assumption that wind speed at the upper boundary of atmospheric surface layer is homogenous, but the aerodynamic characters are still considered by means of canopy height. The other merit is that all inputs (net radiation, soil heat flux, canopy height, variables related to land surface temperature) can be potentially obtained from remote sensing data, which allows obtaining regular RS-driven ET product. For the purposes of sensitivity analysis and performance evaluation of the Sim-ReSET model without the effect of potential uncertainties and errors from remote sensing data, the Sim-ReSET model was tested only using intensive ground observations at the Yucheng ecological station in the North China Plain from 2006 to 2008. Results show that the model has a good performance for instantaneous ET estimations with a mean absolute difference (MAD) of 34.27 W/m^2 and a root mean square error (RMSE) of 41.84 W/m^2 under neutral or near-neutral atmospheric conditions. On 12 cloudless days, the MAD of daily ET accumulated from instantaneous estimations is 0.26 mm/day, and the RMSE is 0.30 mm/day.

Key words: land surface energy balance, evapotranspiration, Sim-ReSET, remote sensing.

1. Introduction

Evapotranspiration (ET) from land surface to the atmosphere is a very important component of the terrestrial surface water balance (Mu et al., 2007; Rivas and Caselles, 2004); thus, ET information is essential to understand the water cycle, climate dynamics and terrestrial ecological processes (Churkina et al., 1999; Nemani et al, 2002; Potter et al., 1993). ET can be measured using a lysimeter, Bowen ratio system, and eddy covariance system. If intensive ground data are available, ET can also be calculated using sophisticated methods, such as the Penman-Monteith (P-M) method (Monteith, 1981). However, ground observation networks cover only a small portion of the global land surface; thus, regular measurements and calculations on a site scale cannot meet the requirement for ET estimations on a large spatial scale. Satellite remote sensing provides unprecedented global coverages of critical hydrological, vegetation, soil and topographic data that are logistically and economically impossible to obtain from ground observation networks. Remote sensing has been considered the most promising tool for ET estimations on large spatial scales. With the unceasing efforts by many researchers, ET has been estimated on scales from the regional (Ambast et al., 2002; Cleugh et al., 2007; Matsushima, 2007; Seguin et al., 1994) to the global (Mu et al, 2007).

However, these studies still depend on ground measurements or reanalyzed meteorological data. To regularly obtain regional and even global ET, some attempts have been made to improve ET algorithms to reduce the use of ground data (Nishida et al., 2003a, b; Qiu et al., 1998; Qiu et al., 2006; Venturini et al., 2008). These algorithms can be divided into three groups.

The first group is based on the Priestley-Taylor (P-T) equation (Priestley and Taylor, 1972). The P-T equation can be considered a simplified version of the more theoretical Penman equation. It includes only five variables: net radiation, soil heat flux, two variables related to air temperature, and the dimensionless P-T coefficient. Among these variables, the most difficult issue is to determine the P-T coefficient. Over moist surfaces, this coefficient is given approximately 1.26. For dry surfaces, the P-T coefficient, which is determined by surface moisture, wind speed and air temperature, may be much less than 1.26 (Davies and Allen, 1973; Komatsu, 2003). In practice, the P-T coefficient can be obtained using the relationship between remotely sensed vegetation index and surface temperature (VI-Ts diagram) (Jiang and Islam, 2001; Wang et al., 2006). Such a determination of the P-T coefficient may increase uncertainties and errors in ET estimations because the determination of an ideal VI-Ts diagram is largely dependent on the heterogeneity of land surface (Sun et al., 2008). Furthermore, the aerodynamic characters of land surface are not considered in the P-T equation.

The second group is based on the P-M equation. For example, Nishida et al. (2003a, b) developed a dual-source model of ET and evaporation fraction (EF). The main inputs in this model came from remote sensing data. Like other methods based on the P-M equation (Cleugh et al., 2007; Mu et al., 2007), however, some parameters for the calculations of canopy and aerodynamic resistances still depend on ground observations.

The third group is based on the land surface energy balance equation. All variables in such methods can be potentially obtained from remote sensing data except aerodynamic resistance because the calculation of aerodynamic resistance depends on wind speed that cannot be readily retrieved from satellite data (Ambast et al., 2002; French et al., 2005; Gao et al., 1998; Mallick et al., 2007; Matsushima, 2007). Aiming to reduce dependence on the calculation of aerodynamic resistance, a reference site was introduced as a strategy by some studies (Bastiaanssen et al., 1998a, b; Bastiaanssen, 2000; Jia et al., 2003; Kustas et al., 1994; Su, 2002). For example, Loheide and Gorelick (2005) used a scaled value between air temperature and dry surface temperature to estimate ET, where the dry surface temperature was estimated using meteorological data while assuming ET=0. These studies require some auxiliary data and one / two reference objects which are still determined by means of ground observations. In order to avoid the calculation of aerodynamic resistance, Qiu et al. (1998; 2006) developed a simple site-scale model for evapotranspiration using a scaled temperature. In this model, aerodynamic resistance is assumed to be equal to that over a dry bare soil surface, so the aerodynamic characters of land surface can not be considered. Also, no method was proposed to obtain reference temperatures of dry soil surface (no evaporation) and man-made leaf surface (no transpiration) simultaneously from satellite images (Matsushita and Fukushima, 2009).

Results of the comparisons between single-source and dual-source ET models show that the accuracy of dual-source models is much better than that of single-source models, especially in sparsely vegetated areas (Gao and Long, 2008; Timmermans et al., 2007). In this study, therefore, the main objective is to develop a new dual-source **Sim**ple **Re**mote **S**ensing **E**vapo**T**ranspiration model (Sim-ReSET) based on the energy balance of the land surface. In this new model, the calculation of aerodynamic resistance can be effectively avoided, so no ground data are required to calculate aerodynamic resistance. Therefore, all inputs for the model can be potentially obtained from remote sensing data. Then, the Sim-ReSET model is tested only using intensive ground observations at the Yucheng ecological station in the North China Plain from 2006 to 2008.

Insert Table 1

2. Development of the Sim-ReSET model

2.1 Algorithm

If energies stored by the canopy, utilized by plant photosynthesis, and transferred by advection are ignored, the land surface energy balance can be expressed as:

$$H + ET = R_n - G \tag{1}$$

where ET is the latent heat flux or evapotranspiration (W/m^2); R_n is the net radiation (W/m^2); G is the soil heat flux (W/m^2); H is the sensible heat flux (W/m^2), which equals:

$$H = \rho C_p \frac{T_s - T_a}{r_a} \tag{2}$$

where ρ is the air density (kg/m^3); C_p is the heat capacity of air at constant pressure (J/kg/K); r_a is the aerodynamic resistance for heat transfer (s/m); T_s and T_a are the land surface temperature and air temperature (℃), respectively. ET, then, is given as a residual term:

$$ET = R_n - G - \rho C_p \frac{T_s - T_a}{r_a} \tag{3}$$

The ET from dry bare soil surfaces equals 0, so the following formula for dry bare soil can be obtained:

$$r_{ad} = \rho C_p \frac{T_{sd} - T_a}{(R_n - G)_d} \tag{4}$$

where the subscript d denotes dry bare soil.

The Monin – Obukhov similarity (MOS) theory describes the vertical behavior of nondimensionalized mean flow and turbulence properties within the atmospheric surface layer (ASL) as a function of the Monin – Obukhov key parameters (Hills, 1989). Based on the MOS theory, aerodynamic resistance above dry bare soil can also be expressed as:

$$r_{ad} = \frac{1}{k^2 u(z)_d}[\ln(\frac{z}{z_{ohd}}) - \psi_H(\frac{z}{L})_d][\ln(\frac{z}{z_{omd}}) - \psi_M(\frac{z}{L})_d] \tag{5}$$

where k is the von Karman constant, usually given as 0.4; z is the reference height (m); $u(z)$ is the wind speed at the reference height (m/s); z_{oh} and z_{om} are the roughness lengths for heat and momentum transfers (m), respectively; L is the Monin-Obukhov length (m); and $\psi_H(\frac{z}{L})$ and $\psi_M(\frac{z}{L})$ are the surface layer stability correction functions for sensible heat and momentum, respectively. Under strictly neutral conditions, both $\psi_H(\frac{z}{L})$ and $\psi_M(\frac{z}{L})$ equal 0. Under non-neutral conditions, the functions proposed by Hogstrom (1988) are used to calculate $\psi_H(\frac{z}{L})$ and $\psi_M(\frac{z}{L})$.

Under the condition of homogeneous atmospheric forcing, it can be assumed that the wind speed at a certain height (A) above the land surface within a spatial scale on the order of several tens of kilometers is almost homogeneous due to the existence of a well-mixed layer above this height (Brutsaert, 1998). This height is the boundary between the ASL (the lowest 10% or so of the atmospheric boundary layer) and the atmospheric mixed layer (AML). Brutsaert (1998) suggested that this boundary was on the order of 100 m for neutral or unstable conditions above a uniform surface. The MOS is usually valid within the ASL. The vertical profile of wind speed is nearly logarithmic with height in the ASL:

$$u(z) = \frac{u^*}{k}[\ln(\frac{z-d_0}{z_{0m}}) - \psi_M(\frac{z-d_0}{L})] \tag{6}$$

where $u*$ is the friction velocity (m/s), and d_0 is the zero plane displacement height (m). Then, the ratios of wind speed at the reference height to that at the upper boundary of ASL (A) can be obtained over a target surface and a reference dry bare soil surface, respectively:

$$\frac{u(A)}{u(z)}=\frac{\ln(\frac{A-d_0}{z_{0m}})-\psi_M(\frac{A-d_0}{L})}{\ln(\frac{z-d_0}{z_{0m}})-\psi_M(\frac{z-d_0}{L})} \tag{7a}$$

$$\frac{u(A)_d}{u(z)_d}=\frac{\ln(\frac{A}{z_{0md}})-\psi_M(\frac{A}{L})_d}{\ln(\frac{z}{z_{0md}})-\psi_M(\frac{z}{L})_d} \tag{7b}$$

With an assumption of homogeneous wind speed at the height of A on the target and reference surfaces, $u(A)_d=u(A)$, then:

$$\begin{aligned}\frac{u(z)}{u(z)_d}&=\frac{\ln(\frac{A}{z_{0md}})-\psi_M(\frac{A}{L})_d}{\ln(\frac{z}{z_{0md}})-\psi_M(\frac{z}{L})_d}\Bigg/\frac{\ln(\frac{A-d_0}{z_{0m}})-\psi_M(\frac{A-d_0}{L})}{\ln(\frac{z-d_0}{z_{0m}})-\psi_M(\frac{z-d_0}{L})}\\&=\frac{[\ln(\frac{A}{z_{0md}})-\psi_M(\frac{A}{L})_d][\ln(\frac{z-d_0}{z_{0m}})-\psi_M(\frac{z-d_0}{L})]}{[\ln(\frac{A-d_0}{z_{0m}})-\psi_M(\frac{A-d_0}{L})][\ln(\frac{z}{z_{0md}})-\psi_M(\frac{z}{L})_d]}\end{aligned} \tag{8}$$

In equation (2), r_a over the target surface is calculated using a formula similar to equation (5):

$$r_a=\frac{1}{k^2u(z)}[\ln(\frac{z-d_0}{z_{oh}})-\psi_H(\frac{z-d_0}{L})][\ln(\frac{z-d_0}{z_{om}})-\psi_M(\frac{z-d_0}{L})] \tag{9}$$

In combination with equations (4-5, 8-9), the relationship between the momentum transfer-related parts at the reference height on the target and reference surfaces can be represented by that at the ASL height on the target and reference surfaces. Then, H at the target surface can be obtained:

$$\begin{aligned} H &= \rho C_p \frac{T_s - T_a}{r_a} \\ &= (R_n - G)_d \frac{T_s - T_a}{T_{sd} - T_a} \frac{[\ln(\frac{z}{z_{ohd}}) - \psi_h(\frac{z}{L})_d][\ln(\frac{A}{z_{0md}}) - \psi_m(\frac{A}{L})_d]}{[\ln(\frac{z-d_0}{z_{oh}}) - \psi_h(\frac{z-d_0}{L})][\ln(\frac{A-d_0}{z_{0m}}) - \psi_m(\frac{A-d_o}{L})]} \end{aligned} \tag{10}$$

The r_a is removed in equation (10) by using a reference dry bare soil and an assumption that wind speed at the upper boundary of ASL is homogenous. However, height-related parameters over a target surface and dry bare soil surface were used to consider the aerodynamic characters of land surface in the model. In this study, A is given as 100 m (Brutsaert, 1998); z is the measuring height of wind speed and air temperature, which is 3 m at our observational site.

The Sim-ReSET model was designed as a dual-source model. A pixel is usually a mixture of vegetation and bare soil, so ET from a pixel can be obtained:

$$ET = f_{veg} ET_{veg} + (1 - f_{veg}) ET_{soil} \tag{11}$$

where f_{veg} is the vegetation cover fraction. The second-order scaled normalized difference vegetation index (NDVI) can be used to calculate f_{veg} (Carlson and Ripley, 1997; Choudhury et al., 1994; Gillies and Carlson, 1995):

$$f_{veg} = (\frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}})^2 \tag{12}$$

where $NDVI_{\max}$ and $NDVI_{\min}$ are the NDVIs for full vegetation (f_{veg} = 1) and bare soil (f_{veg} = 0), respectively. ET_{veg} and ET_{soil} are the ETs for vegetation and soil components within a given pixel, respectively. From equations (1) and (10), ET_{veg} and ET_{soil} can be obtained:

$$ET_{veg}=(R_n-G)_{veg}-(R_n-G)_d\frac{T_{veg}-T_a}{T_{sd}-T_a}\frac{[\ln(\frac{z}{z_{ohd}})-\psi_h(\frac{z}{L})_d][\ln(\frac{A}{z_{0md}})-\psi_m(\frac{A}{L})_d]}{[\ln(\frac{z-d_0}{z_{oh}})-\psi_h(\frac{z-d_0}{L})][\ln(\frac{A-d_0}{z_{0m}})-\psi_m(\frac{A-d_o}{L})]} \quad (13)$$

$$ET_{soil}=(R_n-G)_{soil}-(R_n-G)_d\frac{T_{soil}-T_a}{T_{sd}-T_a}\frac{[\ln(\frac{z}{z_{ohd}})-\psi_h(\frac{z}{L})_d][\ln(\frac{A}{z_{0md}})-\psi_m(\frac{A}{L})_d]}{[\ln(\frac{z}{z_{ohd}})-\psi_h(\frac{z}{L})][\ln(\frac{A}{z_{0md}})-\psi_m(\frac{A}{L})]} \quad (14)$$

If the atmospheric stratification corrections are ignored under neutral or near-neutral conditions, equations (13-14) can be simplified as:

$$ET_{veg}=(R_n-G)_{veg}-(R_n-G)_d\frac{T_{veg}-T_a}{T_{sd}-T_a}\frac{\ln(\frac{z}{z_{ohd}})\ln(\frac{A}{z_{0md}})}{\ln(\frac{z-d_0}{z_{oh}})\ln(\frac{A-d_0}{z_{0m}})} \quad (15)$$

$$ET_{soil}=(R_n-G)_{soil}-(R_n-G)_d\frac{T_{soil}-T_a}{T_{sd}-T_a} \quad (16)$$

where T_{veg} and T_{soil} are the surface temperatures for vegetation and soil components within a pixel, respectively.

Finally, the Sim-ReSET model is achieved based on two requirements: one is a heterogeneous land surface within which reference dry bare soil surfaces are easy to find, and the other is a homogeneous field of wind speed at the ASL height within the heterogeneous land surface. The model consists of four basic equations (11-12, 15-16) while equations (11-14) can be considered as its theoretical version.

Insert Table 2

2.2 Parameterizations

The Sim-ReSET model requires several input variables: net radiation (R_n), soil heat flux (G), surface temperatures (T_{veg} and T_{soil}) of vegetation and soil within pixels, air temperature (T_a), and canopy height (h). All these variables can be potentially obtained from remote sensing data. For examples, Ts, VI and land cover types can be obtained from released MODIS land data products (MOD11, MOD13 and MOD12) (http://modis-land.gsfc.nasa.gov/).

2.2.1 T_a , T_{veg} , T_{soil} and T_{sd}

The T_{sd} and T_a can be generally obtained from the dry (or warm) edge in a triangular VI-Ts diagram (Sandholt et al., 2002), and T_{soil} can be also simply obtained by a linear extrapolation in the triangular VI-Ts diagram while T_{veg} approximates T_a (Nishida et al., 2003a). However, the VI-Ts diagram cannot be well defined if there are no full ranges of land surface moisture and VI, such as in rainy season or in a period with narrow VI range. This will result in more uncertainties in the determinations of T_{soil}, T_{veg}, T_{sd} and T_a. The surface temperature information of components within pixels may provide more possibilities to obtain reasonable T_{soil}, T_{veg}, T_{sd} and T_a. We have proposed a method to obtain T_{veg} and T_{soil} by means of the spatial autocorrelation of the land surface moistures of neighboring pixels, then T_{sd} and T_a respectively approximate the maximum T_{soil} and minimum T_{veg} within a certain sampling window. Our results show that the proposed method can obtain T_{sd} and T_a with respective average accuracies of 1.16 °C and 1.28 °C across the whole year in a semiarid agricultural region (Sun et al., 2008).

2.2.2 Net radiation

Based on the land surface radiation balance, net radiation is the difference between the incoming and outgoing radiations:

$$R_n = R_S^{\downarrow} - R_S^{\uparrow} + R_L^{\downarrow} - R_L^{\uparrow} = (1-\alpha)R_S^{\downarrow} + \sigma(\varepsilon_a T_a^4 - \varepsilon_s T_s^4) \tag{17}$$

where $R_S^{\downarrow}$ and $R_S^{\uparrow}$ are the downward and upward shortwave radiations (W/m^2), $R_L^{\downarrow}$ and $R_L^{\uparrow}$ are the downward and upward long wave radiations (W/m^2), α is the land surface albedo (-), ε_a is the air emissivity (-), ε_s is the land surface emissivity (-), and σ is the Stephan-Boltzmann constant (5.67×10^{-8} W/m^2/K^4). Net radiations for vegetation and bare soil within pixels can be respectively estimated using equation (17) and the specific parameters of land type. In the Sim-ReSET model, a simple scheme proposed by Bisht et al. (2005) was used to estimate instantaneous net radiation for cloud-free days only using remote sensing observations. Their results show that the accuracy of net radiation estimations by their scheme is better than 50 W/m^2.

2.2.3 Soil heat flux, albedo, and emissivity

Soil heat flux can be estimated by multiplying net radiation by a ratio. This ratio is closely related to vegetation cover. Therefore, the vegetation cover fraction weighted equation was used to estimate this ratio in previous studies (*e.g.,* Boegh et al., 2002):

$$\Gamma = G / R_n = f_{veg} \Gamma_{veg} + (1 - f_{veg}) \Gamma_{soil} \tag{18}$$

where Γ is the ratio of soil heat flux to net radiation, and Γ_{veg} and Γ_{soil} are the ratios for vegetation and soil. Since the Sim-ReSET model is a dual-source model, the soil heat fluxes for both soil and vegetation are required. The ratio of G/R_n for vegetation can be given as 0.1 (Boegh et al., 2002); the ratio of G/R_n for soil has a negative relationship with soil water content. Based on our experimental observations and other studies (Boegh et al., 2002; Kustas and Daughtry, 1990), the ratio of G/R_n for soil is close to that for vegetation when soil water content is larger than soil field capacity; and the ratio for soil is close to 0.4 when soil water content is less than soil wilting coefficient. Therefore, the ratio of G/R_n for soil can be scaled between the ratios for dry and wet soils using a scaled temperature. This scaled temperature between air temperature and land surface temperature can be taken as an indicator of the land surface moisture status (Sandholt et al., 2002).

$$\Gamma_{soil} = \frac{T_{soil} - T_a}{T_{soil-dry} - T_a} \Gamma_{soil-dry} + \left(1 - \frac{T_{soil} - T_a}{T_{soil-dry} - T_a}\right) \Gamma_{soil-wet} \tag{19}$$

Both albedo and emissivity are usually directly retrieved from remote sensing data (http://modis-land.gsfc.nasa.gov/). If albedo and emissivity are unavailable for the Sim-ReSET model, albedo and emissivity for vegetation can be considered constants (0.1 and 0.98); albedo and emissivity for soil can also be estimated approximately by means of the scaled temperature in equation (19) where the albedo and emissivity for dry bare soil are 0.25 and 0.89, and those for wet bare soil are 0.1 and 0.98, respectively. These constants of albedo and emissivity related to vegetation canopy, and dry and wet soil surfaces are determined based on our experimental observations and other studies (Gascoin et al., 2009; Rechid et al., 2009; MODIS Emissivity Library, http://g.icess.ucsb.edu/modis/EMIS/html/em.html).

$$\alpha_{soil} = \frac{T_{soil} - T_a}{T_{soil-dry} - T_a}\alpha_{soil-dry} + (1 - \frac{T_{soil} - T_a}{T_{soil-dry} - T_a})\alpha_{soil-wet} \tag{20}$$

$$\varepsilon_{soil} = \frac{T_{soil} - T_a}{T_{soil-dry} - T_a}\varepsilon_{soil-dry} + (1 - \frac{T_{soil} - T_a}{T_{soil-dry} - T_a})\varepsilon_{soil-wet} \tag{21}$$

2.2.4 Roughness length, zero plane displacement height, and canopy height

In the Sim-ReSET model, the roughness lengths for bare soil surface, z_{0md} and z_{ohd}, are approximately 0.005 m and 0.0005 m, respectively (Braud et al., 1993). For crops and grass, z_{0m} and d_0 can be estimated as z_{0m} = 0.123h and d_0 = 0.67h, where h is the canopy height (Monteith, 1981). For forests, it is assumed that z_{0m} = 0.1h and d_0 = 0.7h (Verseghy et al., 1993). Following Brutsaert (1979) and Garrat and Hicks (1973), z_{0h} is assumed as:

$$z_{oh} = \begin{cases} z_{om}/2.0 & (forest) \\ z_{om}/7.0 & (crops) \\ z_{om}/12.0 & (grass) \end{cases} \tag{22}$$

For vegetation, the values of z_{0m}, z_{0h} and d_0 are dependent on the vegetation canopy height (h). For a simple manner in the Sim-ReSET model, a look-up table (LUT) was adopted to determine canopy height according to the land cover types released by the International Geosphere-Biosphere Programme (IGBP). Generally, the heights of forest and shrub don't change significantly with seasons, but grass and crop are annual plants; thus, their canopy heights vary with time during their whole lifecycles. It is noted that crop heights have linear relationships with leaf area indexes (LAIs) before their heights reach the maximum (Figure 1). Following this relationship, the heights of crop and grass can be approximately estimated:

$$h = h_{\max} LAI \tag{23}$$

where h_{max} is the maximum height of crop or grass. When the Sim-ReSET model is applied to map ET using satellite remote sensing data, LAI can be estimated using spectral vegetation indices (Turner et al., 1999), and vegetation types can be determined from a land cover map.

Insert Figure 1

3. Testing the performance of the Sim-ReSET model only using ground observations

3.1 Purpose of the model test

The MODIS land data products such as land surface temperature, emissivity and reflectance have been routinely generated (http://modis-land.gsfc.nasa.gov/). Compared with the ground "truth" observations, these satellite data are unsuitable for the model test because of some uncertainties and errors due to their retrieving algorithms and the atmospheric effect on remote sensing observations. For the purposes of sensitivity analysis and performance evaluation of the Sim-ReSET model without the effect of potential uncertainties and errors from remote sensing data, intensive ground observational data were used to test the Sim-ReSET model. Another purpose of the model test is to understand the effect of ignoring the atmospheric stratification corrections on the Sim-ReSET model. Measurements were carried out at two sites in a cropland in the Yucheng ecological station. Site A is for observations on bare soil. Site B, which is about 500 m east to Site A, is for micrometeorological and flux observations on natural cropland (Figure 2). The Sim-ReSET model-based ET from the cropland near the flux tower can be calculated by only using intensive ground observations from two sites while Site A and Site B are set as a reference site and a target site, respectively. This calculated ET, then, is evaluated using ET (latent heat flux) directly from the flux measurements of the eddy covariance system.

Insert Figure 2

3.2 Test area

The Yucheng ecological station (36°50’N, 116°35’E, and 26 m above sea level) is located in the North China Plain (NCP), China. The main land use around the station is irrigated cropland. The yearly mean air temperature is 13.1℃; annual precipitation is 610 mm, of which about 70% falls between June and August. The soil is mainly sandy loam, and the cropping system is mainly annual cotton or a rotation of winter wheat and summer maize. Cotton is usually seeded in the last ten days of April and harvested in the first ten days of November. Winter wheat is seeded in the first ten days of October and harvested in the first ten days of June of the following year, while the summer maize growing period is between June and October, immediately following the winter wheat harvest.

3.3 Field experiment for the model test

As a reference site, a dry bare soil surface is required in the Sim-ReSET model. In this study, intensive observations on the bare soil surface were carried out in the Yucheng station. A 20 m × 20 m bare soil surface (Site A) was plotted for the experiment. An observational pole was set at the center of Site A. An ultrathin PVC sheet with a thickness of 0.15 mm was spread around the pole at 10 cm soil depth in order to stop the upgoing soil water. We assumed that the effect of such an ultrathin PVC sheet at 10 cm soil depth on the soil heat flux measurement was insignificant, so this effect was not considered in this study. Measurements of net radiation by a CNR-1 net radiometer (Kipp and Zonen Inc., Delft, The Netherlands), soil heat flux by a PHF-01 soil heat flux plate at 2 cm soil depth (REBS Inc., Seattle, USA), surface temperature by a 303N infrared thermometer (Minolta, Tokyo, Japan), and soil water content of the surface layer (0-10 cm) by a CS-616 soil moisture sensor

(Campbell Scientific Inc., North Logan, UT, USA) were made from March 2006 to June 2008. All data were recorded in a half-hour interval. By the way, the heat storage of soil above the heat flux plate at 2 cm depth was not considered in this study because soil water content and soil temperature data were unavailable for correcting measurements of soil heat flux. When the soil water content of the soil surface layer is close to the wilting coefficient of 10%, this surface can be considered as a dry bare soil surface because soil water content near or less than 10% means that very little or no water can be evaporated from soil (Figure 3). Observational datasets were then selected for the model test during the periods when the bare soil surface was dry at Site A (Table 3).

Insert Figure 3 and Table 3

A flux tower (the eddy covariance system) and an automated meteorological station exist at Site B. Both of them have been working from March 2002. The measurements from the flux tower and automated meteorological station include half-hour air temperature, humidity, wind speed, components of radiation balance, soil heat flux, soil water content, and fluxes of heat, vapor and CO_2 (Wang et al., 2005). Meanwhile, canopy height and LAI by an LAI2000 plant canopy analyzer (LI-COR Inc., Lincoln, NE, USA) are also measured at Site B. The instruments at Site A, and the flux tower and automated meteorological station at Site B were strictly calibrated before installation and maintained once a year after installation (Wang et al., 2005). In this study, air temperature, surface temperature, wind speed, net radiation, soil heat flux, latent heat flux, canopy height and LAI were collected for the model test according to the time schedule in Table 3. The observed latent heat flux from the flux tower has been widely used to validate ET estimations (Cleugh et al., 2007; Mu et al, 2007; Nishida et al., 2003a; Sun et al., 2007). In this study, the flux observations with a closure rate of large than 0.7 were used to validate the model, where the closure rate was defined as $(H+ET)/(R_n-G)$.

3.4 Results of the model test

3.4.1 Sensitivity analysis

The sensitivities of key variables in the Sim-ReSET model were tested using ground data. The strategy of sensitivity analysis is to compare ET estimations without any changed variable to those with only one variable changed by ±10%. Results are shown in Table 4. ET estimations are insensitive to the heights of the atmospheric surface layer (A) and canopy (h). The 10% changes of A and h result in about 0.45% and 3.7% changes of ET, respectively.

ET estimations are very sensitive to variables related to temperature. A small change of temperature will result in a large change of ET estimations. A ±10% change in T_s results in -34.17% and 82.48% changes of ET, respectively. A ±10% change of T_a results in 86.10% and -34.81% changes of ET, respectively. A ±10% change of T_{sd} results in 32.97% and -34.00% changes of ET, respectively. In the Sim-ReSET model, T_a and T_{sd} are obtained from T_s while T_s is retrieved from remote sensing, so probable errors of T_s from sensor deviation, atmospheric effect, and the retrieval algorithm are brought to T_a and T_{sd}. However, these probable errors can be disregarded because T_a, T_{sd} and T_s are used in a difference-ratio form, $(T_s - T_a)/(T_{sd} - T_a)$. For example, a +10% error of T_s from sensor deviation, atmospheric effect, and the retrieval algorithm will also result in a +10% error in T_a and T_{sd}, so $(1.1T_s - 1.1T_a)/(1.1T_{sd} - 1.1T_a) = (T_s - T_a)/(T_{sd} - T_a)$. Actually, a 10% change of the term of $(T_s - T_a)/(T_{sd} - T_a)$ only results in less than about 15% change of ET in the Sim-ReSET model. Hence, potential error sources related to temperature mainly come from the determinations of T_a and T_{sd}.

Available energy (R_n-G) is the energy source of evapotranspiration, so the ET accuracy relates directly to the accuracies of R_n and G. The 10% changes in R_{nd} and R_n result in 20.81% and 25.43% changes of ET, respectively. The 10% changes in G_d and G and result in 8.13% and 5.18% changes of ET, respectively.

To avoid the effects of potential errors in input variable estimations on the model test, we used field observations as model inputs to test the Sim-ReSET model.

Insert Table 4

3.4.2 Comparison of ETs from the Sim-ReSET model using flux data from the eddy covariance system

The cropland ETs around the automated meteorological station were obtained from the

Sim-ReSET model and its theoretical version using intensive ground observations. By viewing the daily variation curve of solar radiation, we only found two periods of six consecutive cloudless days in the autumn of 2006 (cotton field) and in the spring of 2008 (bare soil), respectively. Figures 4a and 4b show the diurnal variations of ETs during these periods. On cloudless days, the Sim-ReSET model can obtain diurnal ET variations similar to the direct observations from the eddy covariance system over both vegetation and bare soil. From DOY 77 to 82 in 2008, soil water content measured by TDR at the 5 cm depth was almost stable (20-22%) at Site B, but wind speed at the reference height varied significantly. It can be included that the difference of wind speed results in obvious difference of ET across six days in Figure 4b. Instantaneous ETs on two periods of six consecutive cloudless days were accumulated into daily ETs (Figure 5). We compared daily ET based on the flux data with daily ETs respectively based on the Sim-ReSET model and its theoretical version, and found that their respective mean absolute differences (MADs) for cotton field are 0.24 mm/day and 0.11 mm/day, and their respective root mean square errors (RMSEs) are 0.30 mm/day and 0.13 mm/day. For bare soil, their respective MADs are 0.26 mm/day and 0.17 mm/day, and their respective RMSEs are 0.30 mm/day and 0.19 mm/day.

Insert Figures 4-5

Figure 6 also shows that both instantaneous ETs obtained from the Sim-ReSET model and its theoretical version are close to that measured on the flux tower. Both R^2 are more than 0.5.

Their respective MADs are 34.27 W/m^2 and 33.56 W/m^2, and their respective RMSEs are 41.84 W/m^2 and 40.21 W/m^2. In comparing Figures 6a and 6b, it is obvious that ET from the theoretical version of the Sim-ReSET model, which considers the atmospheric stratification corrections, is a little more accurate than that from the Sim-ReSET model. From Figure 6a to 6b, the slope of regression line is decreased from 0.96 to 0.85, and the intercept is increased from 1.79 to 6.55.

Since the Sim-ReSET model is sensitive to temperature-related parameters, ET data points in Figure 6 were separated into two groups by using a daily average air temperature of 20 ℃, cold season (daily average air temperature < 20 ℃) and warm season (daily average air temperature ≥ 20 ℃). We tested the data points in Figure 6a, and found that the model has a better performance in the warm season. The slope of regression line is decreased from 1.33 in warm season to 0.42 in cold season, the intercept is increased from -55.26 to 58.28, and the R^2 is decreased from 0.69 to 0.18.

Insert Figures 6

4. Discussions

4.1 Effect of atmospheric stratification correction on the Sim-ReSET model

Jiang et al. (2004) summarized the potential accuracies of ET estimations when errors from input variables were reduced to the minimum, and the results showed that the accuracy of ET estimations was typically from 20 W/m^2 to 70 W/m^2. The accuracies of both the Sim-ReSET model and its theoretical version are within this range in our model test. It is noted that the ET obtained from the theoretical version of the Sim-ReSET model, which considers atmospheric stratification corrections, is a little more accurate than that from the Sim-ReSET model, but the difference between them is not significant. Bukhlova et al. (2008) carried out an experiment in a medium-latitude region in 2005-2007 for intensive observations of the state of the atmosphere using an acoustic radar (sodar) and ultrasonic meteorological complex. Their results show that neutral stratification dominates from 10 am to 8 pm local time in all seasons except summer in which unstable stratification dominates in the afternoon. Actually, neutral or weak-unstable stratifications still dominate in the morning in summer. In this study, datasets for the model test did not include data observed in summer. This is the reason why the results of Figures 6a and 6b are close. Hence, it means that the stratification corrections can be ignored in the Sim-ReSET model under neutral or weak-unstable conditions in the daytime (spring, autumn, winter, and morning in summer). Under the unstable condition in the daytime (afternoon in summer), the Sim-ReSET model may need stratification corrections. An operational iteration process can be proposed to calculate surface layer stability correction functions (Sun et al., 2007). Because rain is frequent in summer, it is difficult to keep the 20 m × 20 m plot of bare soil surface dry, and observational data of reference dry bare soil cannot be easily obtained at Site A in summer. Hence, the effect of unstable stratification correction on ET estimations from the Sim-ReSET model was not evaluated in this paper. This work is expected to be carried out in the future.

If remote sensing data recorded in the morning, such as Terra-MODIS, is used to estimate ET, the correction of atmospheric stratifications may be not required in the Sim-ReSET model.

4.2 Potential errors due to the determinations of T_a and T_{sd}

The Sim-ReSET model is sensitive to T_a and T_{sd}. T_a is close to the surface temperature of a well-watered thick vegetation canopy, so T_a can be obtained by using a VI-Ts diagram (Prihodko and Goward, 1997). However, it is not easy to find a well-watered vegetation canopy on pixel scales using remote sensing data with low or moderate resolutions in arid or semiarid areas. In a remote sensing image, a dry soil surface corresponds to a pixel with a high surface temperature and low vegetation cover. If the reference pixels of dry bare soil cannot be found correctly in a remote sensing image, it will result in large errors of ET estimations from the Sim-ReSET model. In this study, a test was done to evaluate the effect of an incorrect determination of reference dry bare soil using the observational data of several days after DOY 82 in 2008. ET was estimated using the Sim-ReSET model when the soil water content of the surface layer was in the range of 14–17% at Site A. Consideration of this moderately wet soil as a reference dry bare soil results in large errors in ET estimations from the Sim-ReSET model (Figure 7). The slope of regression line is reduced to 0.80, and the intercept is increased to 23.63, respectively. The regression line in Figure 7 is farther from the 1:1 line than that in Figure 6, and R^2 is only 0.4. However, the MAD (RMSE) in Figure 7 is lower than that in Figure 6 because the absolute values of ET from bare soil are relatively low. This test shows that a potential error will be caused from the incorrect determination of a dry bare soil surface when the Sim-ReSET model is used to map ET together with remote sensing data. Also, the results of sensitivity analysis in Table 4 show that potential error in ET estimations will come from the incorrect determinations of T_a and T_{sd}.

Only on 30% of global land cover is LAI more than 1, and these land covers mainly locate in humid regions (Olson et al., 1983). ET is close to potential ET in these humid regions. On 70% global land cover with less than 1 of LAI are there more possibilities to find reference dry bare soil from remote sensing. If T_a and T_{sd} are not easily found from remote sensing images on pixel scales, available subpixel information can help to obtain T_a and T_{sd}, and this subpixel information can be obtained using a pixel decomposing technology (Sun et al., 2008). Within a given sampling window, the minimum surface temperature of vegetation within pixels can be considered as T_a, and the maximum surface temperature of soil within pixels can be considered as T_{sd}. This approach has been proved to obtain T_a and T_{sd} successfully while they are not easily found on pixels scales (Sun et al., 2008). However, this method is still helpless if dry bare soil and vegetation without water stress cannot be found even on subpixel scales. When this extreme case occurs, we should consider two extreme geographic conditions. In a completely arid area, dry bare soil can be easily found, but vegetation cannot be easily found even on subpixel scales. As for this case, however, ET within this area is approximate to 0, so we will not need T_a and T_{sd}. In a completely humid area, inversely, vegetation without water stress can be easily found, but dry bare soil cannot be easily found even on subpixel scales. As for this case, ET is approximate to (R_n-G).

Insert Figure 7

4.3 Scaling remote sensing-based instantaneous ET to daily ET

Although actual daily ET is more meaningful for most hydrological applications, only instantaneous ET can be obtained from satellite remote sensing when satellites observer the land surface. Similar to the sinusoidal variation of solar radiation in the daytime on cloudless days, daily ET in mm/day can be estimated from an instantaneous ET in W/m^2 at the satellite overpass time (Chen et al., 2005):

$$ET_d = \frac{3600ET}{\lambda}\frac{2N_E}{\pi\sin(\pi t / N_E)} \qquad (24)$$

where ET_d is the daily ET (mm/day); λ is the latent heat of vaporization, 2.45×10^6 J/Kg; t is the time range from the evaporation start to satellite overpass (h). N_E is the duration of evaporation in the daytime (h), which can be calculated by subtracting two hours from the daily sunshine hours. If information of cloudless days is available, instantaneous ET from our proposed Sim-ReSET model can also be scaled to daily ET using equation (24). By viewing cloud mask from satellite images, however, we can judge cloudy or cloudless sky conditions only at the overpass time of satellites, so actual daily ET cannot be obtained directly from remote sensing now.

The EF can be estimated from ET, which indicates the moisture status of land surface (García et al., 2008):

$$EF = \frac{ET}{R_n - G} \tag{25}$$

The value of EF ranges from 0 to 1, which is determined by the vegetation surface moisture and soil water that are the water sources for evapotranspiration. Directly due to the stabilities of surface moisture and soil water in a short period on order of one or several days, EF is remarkably stable in the daytime (Crago, 1996). This property of EF provides us a method to extrapolate ET from an instantaneous value to a daily value when daily net radiation is available (Brutsaert and Sugita, 1992; Mallick et al., 2007; Sugita and Brutsaert, 1991).

In this study, our purpose is to develop a model to estimate ET only using remote sensing data, so the output from the model is only instantaneous ET, not daily ET. If the information of cloudless days or daily net radiation is available, instantaneous ET from the Sim-ReSET model can also be easily scaled to daily ET.

5. Conclusion

A new simple dual-source model (Sim-ReSET) was developed to estimate ET. In this model, the calculation of aerodynamic resistance is avoided by means of a reference dry bare soil and an assumption that wind speed at the ASL height is homogenous, but the aerodynamic characters are still considered by means of canopy height. Furthermore, all inputs for the model can be potentially obtained from remote sensing data, which allows obtaining regular RS-driven ET product. The sensitivity analysis and performance evaluation of the Sim-ReSET model were carried out using intensive ground observations at the Yucheng ecological station in the North China Plain from 2006 to 2008. The results of sensitivity analysis show that the Sim-ReSET model is sensitive to variables related to temperature, but insensitive to the heights of the atmospheric surface layer and canopy. The accuracies of net radiation and soil heat flux linearly determine the accuracy of ET. Under neutral or near-neutral conditions, the Sim-ReSET model has a good performance in obtaining ET with a MAD of 34.27 W/m^2 and a RMSE of 41.84 W/m^2. On 12 cloudless days, the MAD of daily ET accumulated from instantaneous estimations is 0.24 mm/day, and the RMSE is 0.30 mm/day. Now we are applying this model to generate Asian 16-day ET product from 2000 to 2009 using available MODIS land data products. The Sim-ReSET model and its data products are expected to be further validated at various ecological zones.

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Figure captions:

Figure 1. Linear relationships between crop heights and LAIs in the Yucheng ecological station in 2005-2007.

Figure 2. Two observational sites within the Yucheng ecological station. A reference bare soil surface is at Site A; and there are a flux tower and an automatic meteorological station at Site B. The line with an arrow is used to show the location of Site A relative to Site B.

Figure 3. Soil water content of surface layer at Site A. The wilting coefficient of 10% was measured in the laboratory. Soil water content near or less than 10% means that very little or no water can be evaporated from soil.

Figure 4. Diurnal variations of ETs from the flux tower, the Sim-ReSET model and its theoretical version. **a** is the diurnal variation of six consecutive days over cotton field in the autumn of 2006; **b** is the diurnal variation of six consecutive days over bare soil in the spring of 2008.

Figure 5. Daily ETs from the flux tower, the Sim-ReSET model and its theoretical version. **a** is the daily ETs of six consecutive days over cotton field in the autumn of 2006; **b** is the daily ETs of six consecutive days over bare soil in the spring of 2008.

Figure 6. Comparisons of ET (on fine days listed in Table 3) from the flux tower with ETs from the theoretical Sim-ReSET model (a) and the Sim-ReSET model (b).

Figure 7. Comparison of ETs from the flux tower and Sim-ReSET model while the soil water content of soil surface layer was 14–17% at Site A.