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A Simple Remote Sensing EvapoTranspiration Model (Sim-ReSET) and its Application

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1. Introduction

Evapotranspiration (ET) refers to the combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration. Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes. Apart from the water availability in the topsoil, the evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface. This fraction decreases over the growing period as the crop develops and the crop canopy shades more and more of the ground area. When the crop is small, water is predominately lost by soil evaporation, but once the crop is well developed and completely covers the soil, transpiration becomes the main process. Weather parameters, crop characteristics, management and environmental aspects are factors affecting ET.

Evapotranspiration is not easy to measure. Specific devices and accurate measurements of various physical parameters or the soil water balance in lysimeters are required to determine evapotranspiration. The most direct method of measuring evapotranspiration is with the eddy covariance technique in which fluctuations of vertical wind speed are correlated with fluctuations in atmospheric water vapor density. This directly estimates the transfer of water vapor (evapotranspiration) from the land (or canopy) surface to the atmosphere. These methods are often expensive, demanding in terms of accuracy of measurement and can only be fully exploited by well-trained research personnel.

Monitoring evapotranspiration (ET) at large scales is important for assessing climate and anthropogenic effects on natural and agricultural ecosystems. Remote sensing is the only way that can efficiently and economically monitoring ET with regional and global coverage. Because the regional and global real-time ET data from satellite remote sensing play a vital role in researches on climate change and water resource management, many studies focus on this topic, which can be classified into three categories according to the contribution of remote sensing data to the ET algorithms. The first category is studies in which ET is estimated only using reanalyzed or simulated data from general circulation models (GCM).

For example, Thomas (2008) estimated monthly ET over China and adjacent areas using the Penman-Monteith (P-M) method and gridded meteorological data (0.25°) from 1951–1990. The second category is studies in which ET estimations depend partially on ground data (Bastiaanssen et al., 1998; Su, 2002; Leuning et al., 2008; Zhang et al., 2009). ET methods in this category, more or less, used ground-based or reanalyzed data. For example, Cleugh et al. (2007) and Mu et al. (2007) obtained regional and global ET rates using ground-based meteorological observations and MODerate Resolution Imaging Spectroradiometer (MODIS) data. The third category is studies in which ET is estimated entirely from satellite remote sensing data. ET can be partitioned from available energy by using an evaporation fraction (EF) that can be defined using the relationship of remotely sensed surface temperature (T_s) and vegetation index (VI) / albedo (Boegh et al., 1999; Fan et al., 2007; Gillies et al., 1997; Venturini et al., 2004; Verstraeten et al., 2005).

The algorithms in the first and second categories are often relatively accurate, but detailed input parameters entirely or partially depend on ground data or simulated data from GCM models. This will limit their application to areas where the necessary input data are unavailable. Even if these input data can be derived from reanalyzed datasets, the spatial resolution is usually poor. Furthermore, we cannot obtain real-time ET rates due to the time delay of acquiring input data. The algorithms in the third category can produce real-time ET rates entirely using latest remote sensing data, such as VI- T_s triangle method (Jiang and Islam, 1999) and S-SEBI method (Roerink et al., 2000), but these methods usually cannot consider the aerodynamic characters of the land surface, such as land surface roughness (Sun et al., 2009).

As remotely sensed data have the advantage of large spatial coverage with high spatial resolution, frequent updates, and consistent quality, the optimal way is to develop a robust algorithm whose input parameters can all be easily derived from remote sensing. We have developed such an algorithm so-called Sim-ReSET based on the energy balance of land surfaces (Sun et al., 2009). In this model, the calculation of aerodynamic resistance can be avoided by using a reference dry bare soil and the assumption that wind speed at the upper boundary of the atmospheric surface layer is laterally homogenous, but the aerodynamic characters of land surface are still considered using canopy height. And all inputs (net radiation, soil heat flux, canopy height, variables related to land surface temperature) can be potentially obtained from satellite remote sensing, which allows mapping routine real-time ET.

2. Model description

The Sim-ReSET model is dual-source model (Sun et al., 2009). ET from a pixel can be approximately considered as a combination of ETs from vegetation and bare soil within the pixel.

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

where f_{veg} is the vegetation cover fraction. The ET_{veg} and ET_{soil} are ETs of vegetation and soil components within the pixel, respectively. They are obtained under neutral or near-neutral conditions:

$$ET_{veg} = (R_{nveg} - G_{veg}) - (R_{nd} - G_d) \frac{T_{veg} - T_a}{T_{sd} - T_a} \frac{\ln(\frac{z}{z_{0hd}}) \ln(\frac{A}{z_{0md}})}{\ln(\frac{z - d_0}{z_{0h}}) \ln(\frac{A - d_0}{z_{0m}})} \quad (2)$$

$$ET_{\text{soil}} = (R_{\text{nsoil}} - G_{\text{soil}}) - (R_{\text{nd}} - G_{\text{d}}) \frac{T_{\text{soil}} - T_{\text{a}}}{T_{\text{sd}} - T_{\text{a}}} \quad (3)$$

where the subscripts of d, veg, and soil denote reference dry bare soil, vegetation, and soil, respectively. R_n and G are the net radiation and soil heat flux (W/m^2). T_{veg} and T_{soil} are the surface temperatures for vegetation and soil components within the pixel ($^{\circ}\text{C}$), respectively. T_{sd} and T_{a} are the surface temperature of reference dry bare soil and air temperature ($^{\circ}\text{C}$), respectively. The d_0 , z_{0h} and z_{0m} are the zero plane displacement height and roughness lengths for heat and momentum transfers (m), respectively. The z and A are the reference height and height of the upper boundary of the atmospheric surface layer (m), respectively. In the model, z is defined as 2 m plus the height of the vegetation canopy, and A is given as 100 m (Brutsaert, 1998).

Three categories of model inputs are required for the implementation of the Sim-ReSET model: solar radiation-related fluxes, temperature-related parameters, and height-related parameters (Sun et al., 2009). At first, we adopted the simple scheme proposed by Bisht et al. (2005) to estimate instantaneous net radiation for cloud-free days only using remote sensing observations. The soil heat flux is calculated from R_n multiplied by the ratio of G/R_n . The roughness lengths are determined from prior literatures and from a look-up table (LUT) by means of canopy heights. The canopy heights of forest and shrub are determined according to the IGBP land cover types (Sun et al., 2009). Generally, the heights of forests and shrubs do not change significantly throughout the four seasons. However, grasses and crops change seasonally, so their canopy heights vary with time throughout their whole life cycles. Since the heights of grasses and crops have linear relationships with their leaf area indexes (LAIs) before their heights reach the maximums, the heights of crops and grasses can be approximately estimated by means of spectral vegetation indices or f_{veg} (Turner et al., 1999).

Finally, T_{sd} and T_{a} can be generally obtained from the dry (or warm) edge in a triangular VI- T_s diagram (e.g., Sandholt et al., 2002), and T_{soil} can also be simply obtained by a linear extrapolation in the triangular VI- T_s diagram under an assumption that T_{veg} approximates T_{a} (Nishida et al., 2003). However, the VI- T_s diagram cannot be well defined when the ranges of land surface moisture and VI are incomplete, such as in the rainy season or within a period or an area with a narrow VI range (Sun et al., 2008). This will result in more uncertainties in the determinations of T_{soil} , T_{veg} , T_{sd} , and T_{a} . Here, we proposed a strategy to decrease these uncertainties. If the spatial range of a sampling area for defining a VI- T_s diagram is large enough under the homogeneous condition of atmospheric forcing, the condition of $T_{\text{sd}} - T_{\text{a}} \leq 2^{\circ}\text{C}$ represents two cases: either thoroughly wet ($f_{\text{veg}} \geq 0.2$, e.g., humid areas, wetland, or areas after strong rainfall) or thoroughly dry ($f_{\text{veg}} < 0.2$, e.g., desert) within the sampling area; then, ET is considered approximately 0 for a dry case and $R_n - G$ for a wet case. If $T_{\text{sd}} - T_{\text{a}} > 2^{\circ}\text{C}$, then ET is calculated by the model.

Considering the 1°C accuracy of MODIS T_s retrievals (Wan et al., 2004), we took 2°C as a threshold. For completely dry areas, f_{veg} is usually close to 0; for thoroughly wet areas, there is usually extensive vegetation coverage. Hence, we approximately took 0.2 of f_{veg} as a threshold to distinguish wet and dry conditions.

3. Data collection and observation

The MODIS satellite data were used as inputs to drive the Sim-ReSET model, and ground data were used to validate the outputs. Three MODIS/Terra land products were collected

(Tiles: h22-h29, v03-v07; Projection: sinusoidal; Period: Mar. 5 2000 - Mar. 6 2010): 8-day global 1 km land surface temperature / emissivity, yearly global 1 km land cover type (Figure 1), and 16-day global 1 km vegetation indices. These land products were used to generate ET maps from 2000 to 2010 based on our model (Figure 2).

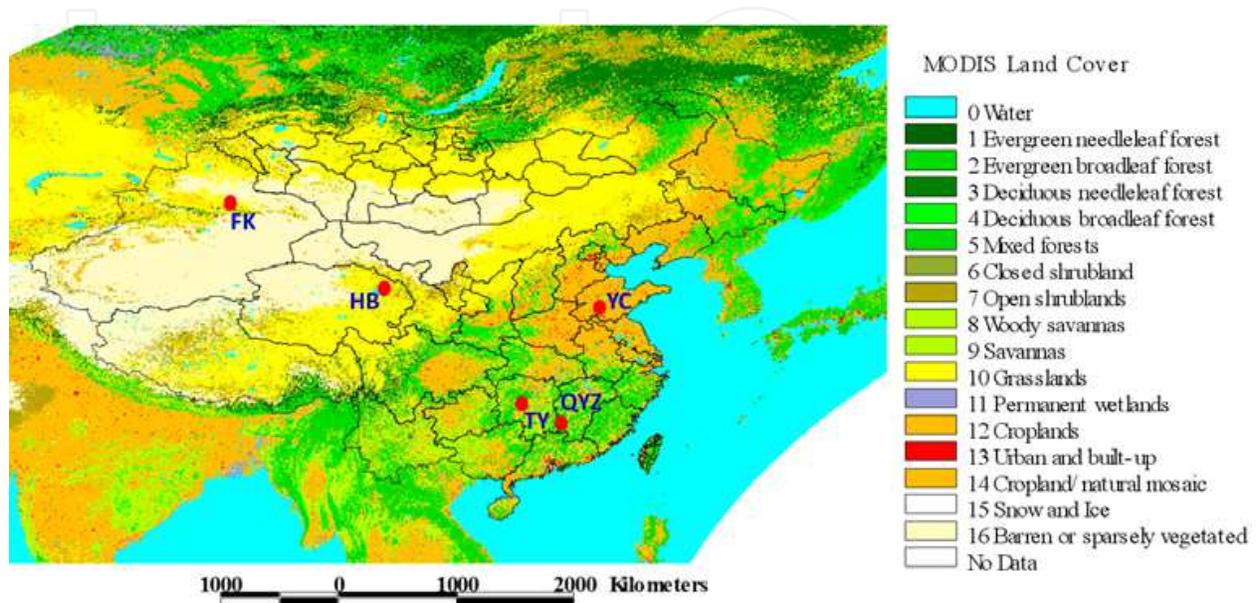


Fig. 1. Asian land-cover map and locations of ecological stations for ET validations in China (HB: Haibei, YC: Yucheng, TY: Taoyuan, QYZ: Qianyanzhou, FK: Fukang).

In order to validate remote sensing data products, a ground observation network was established in 2002 (Wang et al., 2004; Watanabe et al., 2005). Long-term micrometeorological, vegetation and soil measurements, and flux measurements of water vapor, energy, and CO₂ from a variety of ecosystems across China—grassland (HB: Haibei), irrigated cropland (YC: Yucheng), paddy cropland (TY: Taoyuan), forest (QYZ: Qianyanzhou), and desert (FK: Fukang) were implemented and integrated into a consistent, quality-assured, and documented dataset. These five stations represent different typical climates (from subtropical humid climate to temperate arid climate), terrains (from plain to plateau), and land covers. This dataset has been playing a vital role in validations of satellite remote sensing products and in related terrestrial studies (e.g., Sun et al., 2007; Wang et al., 2005).

Compared against other ET methods, the Penman-Monteith (P-M) method has a better performance for ET estimations, and thus it is usually used as the standard for evaluating other methods (Jensen et al., 1990; Irmak et al., 2003). We also compared the eddy covariance observations with the estimation by the P-M method, and found that they were consistent. Due to many gaps of eddy covariance (EC) measurements at the Fukang, Taoyuan, and Yucheng stations and no EC data at the Haibei and Qianyanzhou stations, in this study, the P-M method together with intensive ground data was used to estimate ET at the five stations, and then these ETs at the Terra satellite's overpass time were selected to validate the ET estimations obtained from the MODIS-driven Sim-ReSET model.

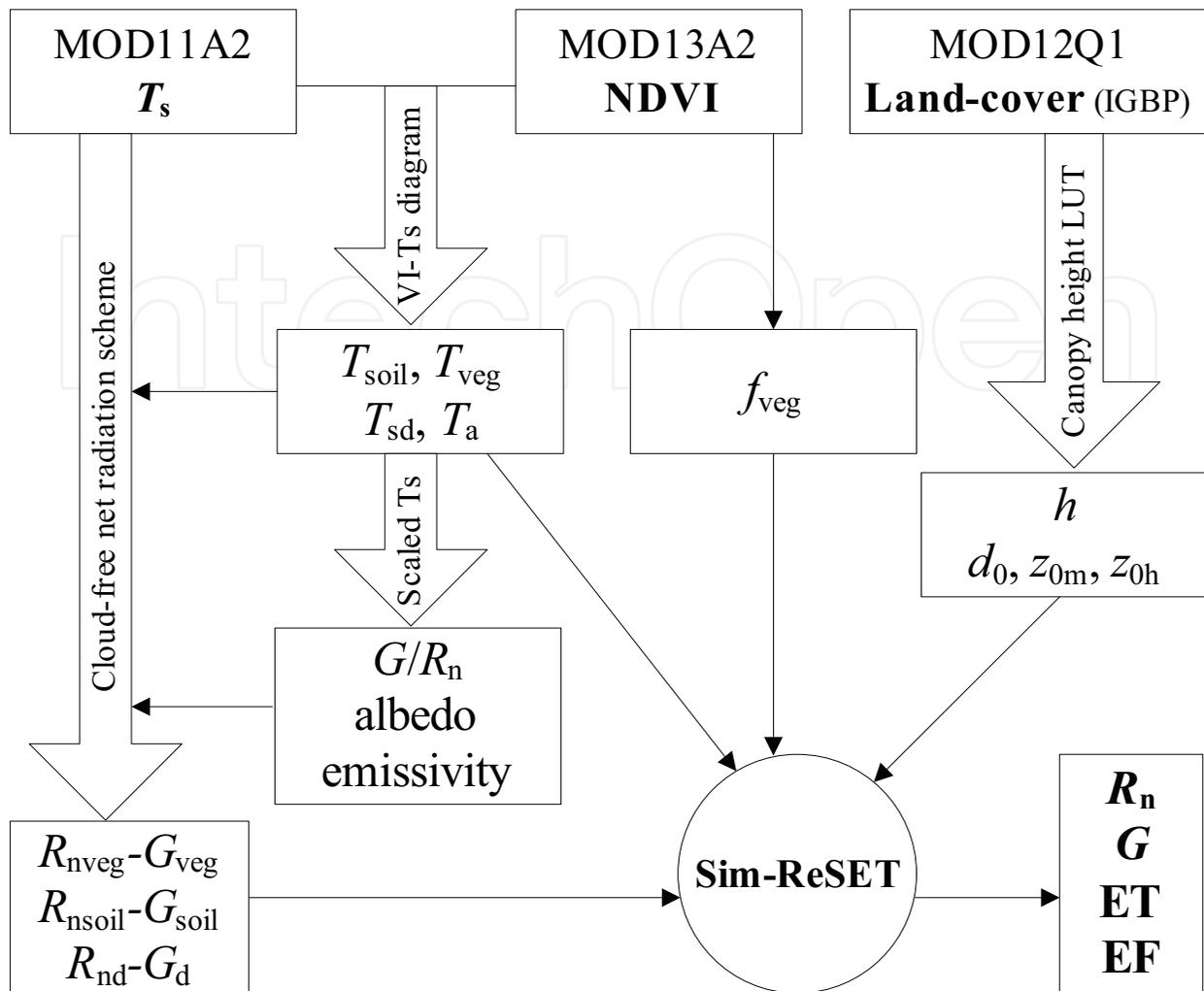


Fig. 2. Flowchart of ET estimations based on the Sim-ReSET model and MODIS land surface products.

4. Model estimation and validation

The 16-day 1 km Asian terrestrial R_n , G , ET , and EF maps from 05 Mar. 2000 to 06 Mar. 2010 were generated. Here we give an example of ET maps to represent the seasonal and spatial distribution of ET over Asia (Figure 3). The figure clearly shows that ET is relatively large in near-sea humid regions, such as Japan, the Korean Peninsula, the east and south of China, South Asia, and Southeastern Asia. In summer, ET over the high-latitude regions is also large because of the strong vapor exchange from a boreal forest ecosystem. ET is relatively low in arid and semi-arid areas, such as northwestern China, Mongolia, and Central Asia. These spatial and temporal distributions of Asian ET maps closely correspond to climates on the continental scale.

The ET and EF profiles extracted from 16-day Asian ET and EF time series maps were significantly different at the five stations (Figure 4). The ET and EF at the Haibei (grassland) and Fukang (desert) stations increase sharply in spring because ice and snow melt; however, the surface soil water supplied from ice, snow, and limited precipitation is soon completely evaporated, and then the ET and EF decrease sharply. Concentrated irrigation for crops and

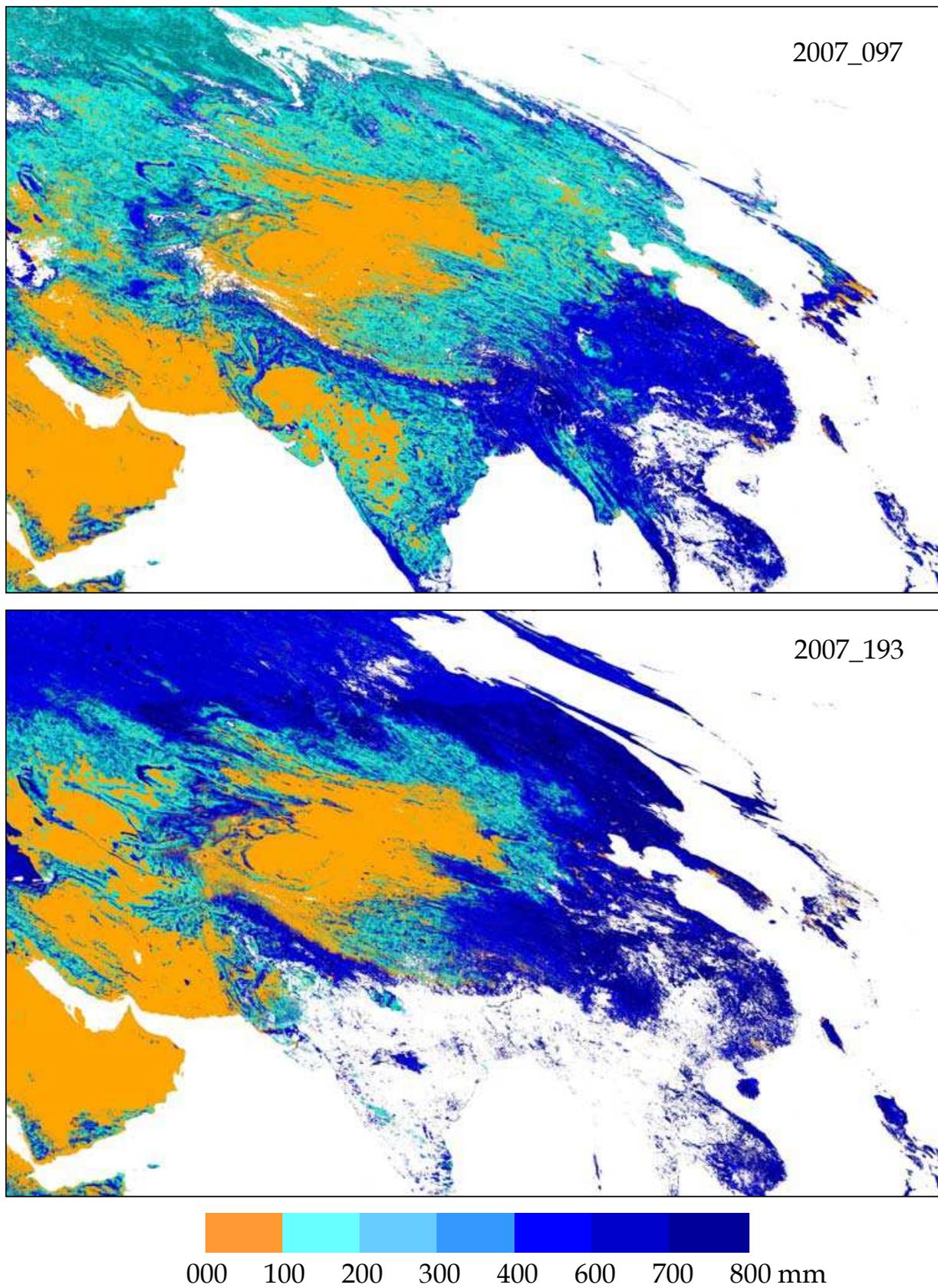


Fig. 3. An example of Asian ET maps (Apr. 7 and Jul. 12, 2007), in which white colour shows the areas no data due to clouds

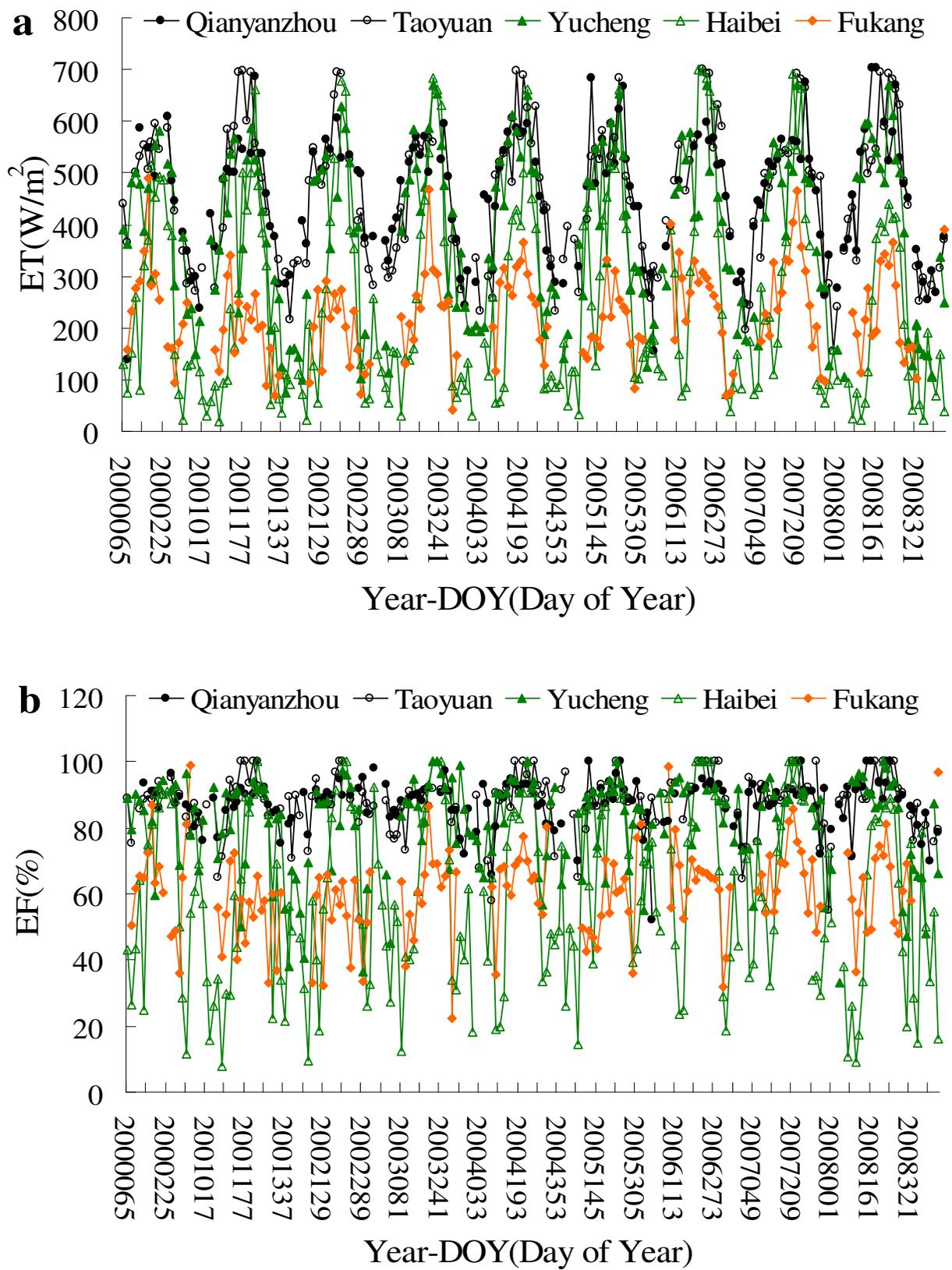


Fig. 4. Time series of MODIS-based ET (a) and EF (b) from 2000 to 2009 at 5 ecological stations

precipitation during growing seasons result in large ET and EF at the Yucheng (irrigated field) station. Due to plentiful precipitation, the EFs at the Qianyanzhou (forest) and Taoyuan (paddy field) stations are relatively large through the whole year, and the ET is close to the available energy.

The MODIS-based ETs were compared with the ETs calculated using the P-M method at the five experimental stations. Figure 5 shows that the MODIS-based ETs are in agreement with the ETs by the P-M method at the five stations. The slope, intercept, and R^2 are 0.84, 85.65, and 0.88, respectively. The MODIS-based ETs show smaller biases at the Qianyanzhou, Taoyuan, and Haibei stations, but larger biases at the Yucheng and Fukang stations. Error analysis shows that the mean absolute differences (MADs) of ET are 41.04, 50.38 and 52.36 W/m^2 at the Qianyanzhou, Taoyuan, and Haibei stations, respectively, and the MADs of ET are 68.60 and 66.95 W/m^2 at the Yucheng and Fukang stations, respectively. Because of the low evaporation and transpiration in the cold season, the ET biases are not significant in the cold season. Therefore, larger ET biases at the Yucheng and Fukang stations mainly occur in the warm season.

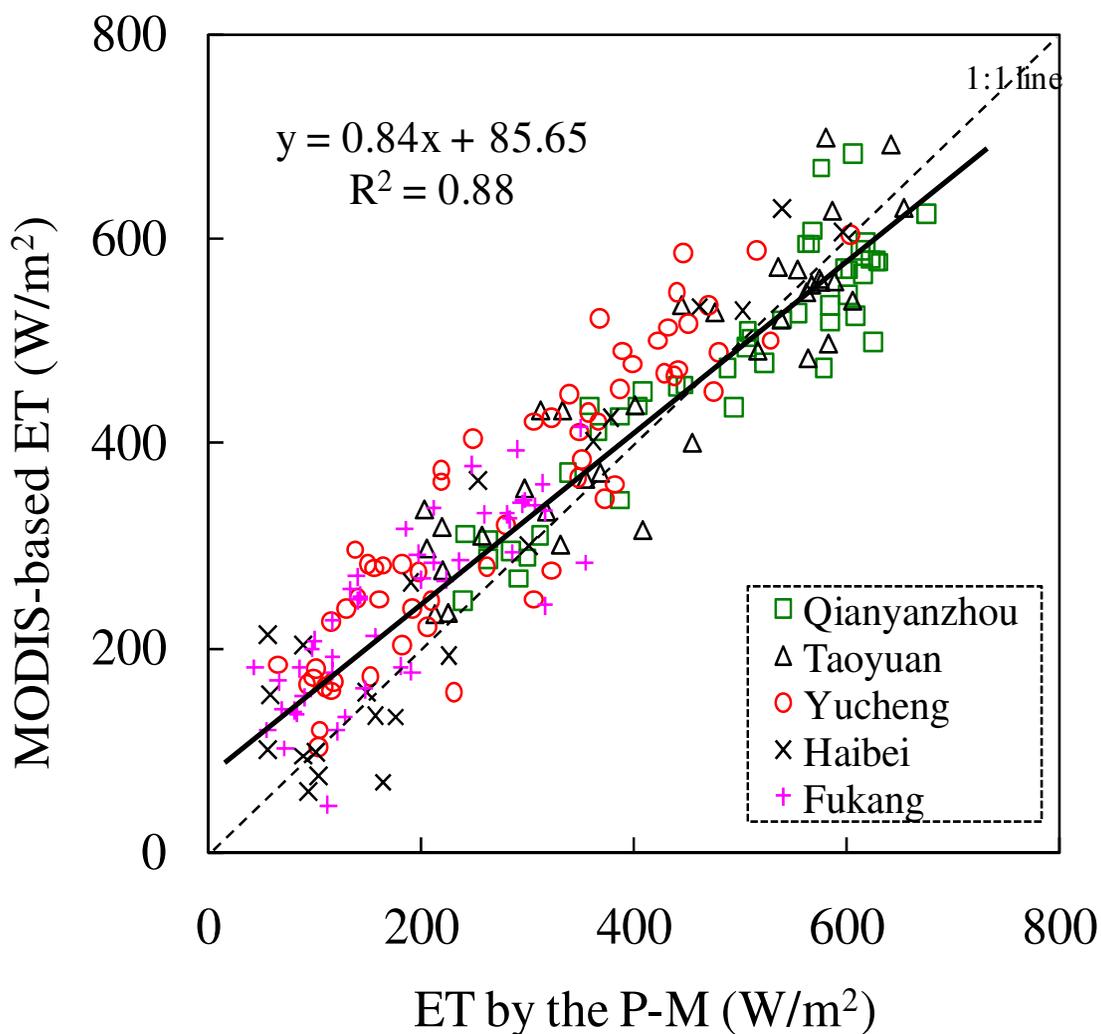


Fig. 5. Comparison of MODIS-based ET and ET by the P-M method at the five stations

5. Conclusions and discussions

A dual-source Simple Remote Sensing EvapoTranspiration model (Sim-ReSET) has been developed based solely 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 laterally homogenous, but the aerodynamic characters are 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 RS data, which allows obtaining regular RS-driven ET products.

The 16-day Asian MODIS-based ET maps from 2000 to 2010 were generated using the Sim-ReSET model. The ET maps are capable of showing the spatial and temporal variations of ET on a continental scale. Extensive ground data from a variety of ecosystems across China were used to validate the MODIS-based ET product. The MODIS-based ETs are in agreement with the ETs estimated by the P-M method for homogeneous forest, paddy, and grass lands, and the MADs are less than or equal to 52.36 W/m². Mainly because a 1km×1km heterogeneous MODIS pixel does not match the fetch of a micrometeorological / flux tower, the MODIS-based ETs show relatively large biases for heterogeneous desert and irrigated crop lands, and the MADs are larger than or equal to 66.95 W/m². These biases might come from assumptions in the model, mismatches of spatial scale in validations, and remote sensing input data. The ET accuracies vary between different stations and are mainly related to land covers and spatial scales. There are homogeneous forest, rice paddies, and grass from the observational sites to 1 km MODIS-pixel scales at the Qianyanzhou, Taoyuan, and Haibei stations, respectively, so ET estimations by the P-M method on the site scale can agree with the ET estimations by our model on the corresponding 1 km MODIS-pixel scale. However, within the range of 1 km around the observational site in the Yucheng station, there are not only cotton but also winter wheat, summer maize, and other crops. Near the observational site in the Fukang station, there is sparse shrub. Hence, ET estimations or observations on the site scale cannot well represent the ET on the 1 km MODIS-pixel scale at the Yucheng and Fukang stations. This might be the main reason for larger ET biases at the Yucheng and Fukang stations.

The ET accuracy depends on remote sensing input data. Compared with the ground-truth observations, remote sensing data still have uncertainties and errors due to their retrieving algorithms and the atmospheric effect on remote sensing observations. Of course, these uncertainties and errors in remote sensing inputs will be mitigated by the application of more new technologies for retrieving remote sensing data. Many of MODIS land products have been updated to new versions with more accuracy. These new data products will contribute to improving the ET accuracy.

The ET accuracy also depends on the derivative parameters from the remote sensing inputs, such as the surface temperature of reference dry bare soil (T_{sd}), air temperature (T_a), and canopy height (h). Our sensitivity analysis of the Sim-ReSET model showed that the model is sensitive to variables related to temperature, but insensitive to the heights of canopy and the atmospheric surface layer (Sun et al., 2009). Hence, the improvements of T_{sd} and T_a estimations will enhance the accuracy of ET product. We used a triangular VI- T_s diagram to obtain T_{sd} and T_a in this study. However, an ideal triangular VI- T_s diagram sometimes cannot be well constructed using 1 km MODIS data if the ranges of land surface moisture and VI are incomplete within a sampling window. This will result in more uncertainties and errors in the determinations of T_{sd} and T_a , and then in ET estimations

Although a daily ET is more useful in the applications of hydrology and water resources, only instantaneous ET products at the overpass time of the Terra satellite were generated using MODIS/Terra data in this study. Similar to the sinusoidal variation of solar radiation in the daytime on cloudless days, a daily ET can be estimated from an instantaneous ET at the satellite overpass time (Sun et al., 2009). This up-scaling method seems invalid on cloudy days. Li et al. (2009) tried to use the microwave difference vegetation index (EDVI) and ground data to estimate ET in a mid-latitude forest. The EDVI can be obtained under both clear and cloudy sky conditions, but the land surface temperature is still unavailable from remote sensing under cloudy sky conditions. Therefore, it is still an attractive challenge to obtain actual daily ET directly from remote sensing.

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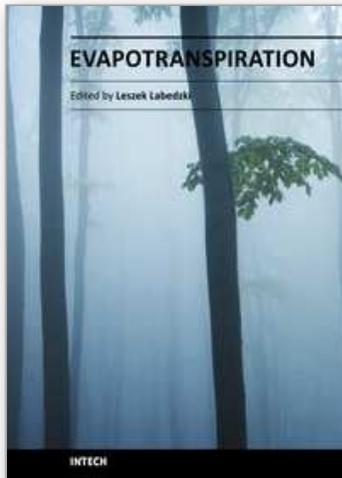
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Evapotranspiration

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Evapotranspiration is a very complex phenomenon, comprising different aspects and processes (hydrological, meteorological, physiological, soil, plant and others). Farmers, agriculture advisers, extension services, hydrologists, agrometeorologists, water management specialists and many others are facing the problem of evapotranspiration. This book is dedicated to further understanding of the evapotranspiration problems, presenting a broad body of experience, by reporting different views of the authors and the results of their studies. It covers aspects from understandings and concepts of evapotranspiration, through methodology of calculating and measuring, to applications in different fields, in which evapotranspiration is an important factor. The book will be of benefit to scientists, engineers and managers involved in problems related to meteorology, climatology, hydrology, geography, agronomy and agricultural water management. We hope they will find useful material in this collection of papers.

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