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Actual daily evapotranspiration estimated from MERIS and AATSR data over the Chinese Loess Plateau

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Abstract

The Loess Plateau is located in north of China and has a significant impact on the climate and ecosystem evolvement over the East Asian continent. Based on the land surface energy balance theory, the potential of using Medium Resolution Imaging Spectrometer (onboard sensor of the Environmental Satellite) remote sensing data on 7, 11 and 27 June 2005 is explored. The "split-window" algorithm is used to retrieve surface temperature from the Advanced the Along-Track Scanning Radiometer, another onboard senor of the Environmental Satellite. Then the near surface net radiation, sensible heat flux and soil heat flux are estimated by using the developed algorithm. We introduce a simple algorithm to predict the heat flux partitioning between the soil and vegetation. Combining the sunshine hours, air temperature, sunshine duration and wind speed measured by weather stations, a model for estimating daily ET is proposed. The instantaneous ET is also converted to daily value. Comparison of latent heats flux retrieved by remote sensing data with ground observation from eddy covariance flux system during Loess Plateau land surface process field Experiment, the maximum and minimum error of this approach are 10.96% and 4.80% respectively, the cause of the bias is also explored and discussed.

1 Introduction

Regional water exchange between the land and atmosphere is linked to many hydrological, meteorological, agricultural and environmental models (Huntington, 2006). It can assess the impact of re-vegetation activities on regional hydrology requiring a spatially distributed measure of evapotranspiration (ET) (Donohue et al., 2007). Estimation of ET at a regional scale is useful for various aims. First, latent heat flux, together with sensible heat flux and soil heat flux, is used for solving energy balance equations and has implications in micrometeorological and agroclimatological studies. Next, it is useful in hydrology for estimation of regional water balance.

Since the 1802, the concept of ET was first presented by Dalton, it has been increasingly used by more disciplines for different purposes, with the number of empirical definitions growing (Allen et al., 1998; Oudin et al., 2005). Many of them were only calibrated at local scale. To encourage the use of a standard ET, the concept of crop reference ET was proposed, which was calculated using four approaches in the mid 1970s (Doorenbos and Pruitt, 1977). Following extensive analysis of these algorithms in many locations world-wide, the Penman-Monteith approach is unanimously accepted as the sole endorsed approach by Food and Agricultural Organization (FAO) to estimate ET, culminating in publication of Allen's FAO-56 report (Allen et al., 1998).

As the improvement of ground observation and turbulent flux monitoring, the routines for estimating ET were conducted from point data of operational weather station to wide scale area by remote sensing. Remote sensing has proven to be the only suitable approach for large-area estimates of ET, because satellite remote sensing is the only technology that can provide representative parameters such as radiometric surface temperature, albedo, and vegetation index in a globally consistent and economically feasible manner. Moreover, advancements in sensors, improved retrieval algorithms and tremendous increases in data distribution, storage and processing have greatly promoted the use of remote sensing data in estimating ET. In the past decades, many algorithms using remote sensing information to estimate ET have been developed, and these can be put into two groups broadly: (1) to calculate the sensible heat flux first and then to obtain the latent heat flux as the residual of the energy balance equation (Kustas and Norman, 1996; Su et al., 1999); (2) to estimate ET by means of an index using a combination equation (Index, 1994; Boegh, 2002). An advanced algorithm, the surface energy balance system (SEBS) for estimation of turbulent heat fluxes and ET has been developed (Su, 2002). SEBS was developed for the estimation of atmospheric turbulent fluxes and surface evaporative fraction using remote sensing data. Pan tested a number of previously developed assimilation techniques, including Ensemble Kalman Filter (EnKF), Particle Filter (PF), water balance constrainer, and copula error model, and as well as physically based models, including the Variable Infiltration Capacity (VIC), as well as Land Surface Microwave Emission Model (LSMEM), and SEBS in the water budget estimation experiments over Red-Arkansas River basin (Pan et al., 2008).

In China, the SEBS has been applied to calculate the energy partitioning at the regional scale with minimum ground data and has been verified at many places to estimate ET according to NOAA data in the Yellow River Delta (YRD) in Shandong province (Zhang, 2005). Considering the complex of surface transpiration and ET, Chen developed a daily ET model over large areas by combining remote sensing data and ground-based meteorological variables (Chen, 2005). Although successful estimations of ET have been obtained over small-scale homogeneous surfaces, difficulties remain in estimations for partial canopies which are geometrically and thermally heterogeneous over the Chinese Loess Plateau.

The Chinese Loess Plateau has inhomogeneous geographic features with elevation ranging from 1000 m to 1800 m. It consists of diverse landscapes including the loess mesa, lowlands, gullies, hills, the loess ridge, continuous knolls, dry gulches, flat ground, loess terraces, and other land surface type (Yang et al., 2000). The ET of the Loess Plateau, is well related to the surface soil moisture content, and also has a significant impact on the water resources in eastern Asia. However, it is difficult to measure, especially in heterogeneous terrain which includes species and canopy diversity, topographical exposure and horizontal extension. Unfortunately, some of the established proxies were only based on very limited experimental data.

Therefore, the motivation of the presented research here is to develop an algorithm that uses multi-sensor remote sensing measurements to improve the estimation of the daily ET, especially in regions characterized by heterogeneous landscapes over the Chinese Loess Plateau. Mixed pixel was parameterized with considering of the vegetation canopy and bare land surface characteristics. The daily ET model is derived based on the land surface energy balance equation. The Medium Resolution Imaging Spectrometer (MERIS) and Advanced Along-Track Scanning Radiometer (AATSR) data were proposed using Integrated Simplified Method for Atmospheric Correction

(SMAC) and Meris Toolbox (BEAM). Then, the net radiation, sensible heat flux and soil heat flux were calculated in the Loess Plateau mesa regions. The daily ET model can also transform instantaneous to daily value and the causes of the bias were also explored and discussed.

2 Methodology

2.1 Estimate of instantaneous ET

Near surface net radiation is the balance of the upwelling and downwelling streams of shortwave and longwave radiation, which is the source fundamental quantity of energy budget at the earth's surface. Most ET models require *Rn* as the core input parameter, and an accurate estimation of *Rn* is essential for regional water resource management (Ryu et al., 2008). As sum of latent heat flux consumed by ET, sensible heat flux increases air temperature, storage heat flux (including storage heat flux in water and soil, and the negligible components of photosynthetic term, metabolic term and storage term in vegetation), *Rn* is the source energy of land-atmosphere exchange in land surface process. The energy balance equation is given by the following equation

$$LE = Rn - H - G \tag{1}$$

where *Rn* is the net radiation ($\mathrm{W\,m^{-2}}$), *H* is the sensible heat flux ($\mathrm{W\,m^{-2}}$) and *G* is the soil heat flux ($\mathrm{W\,m^{-2}}$); *LE* is the latent heat flux (*L* is latent heat of vaporization, $2.49\times10^6\ \mathrm{J\,kg^{-1}}$; *E* is ET (mm)). The accuracy of this model for estimating *LE* is dependent not only on the estimate of *Rn*, but also on the algorithm used for estimating *H* and *G*, and all residual errors are incorporated in the estimate of *LE*. Considering the difference of the vegetation fraction, we discriminate ET between bare soil surface and vegetation canopy. Therefore, according to this configuration, the addition between the soil and canopy contributions (values per unit area of component) to the total ET, LE_v

and LE_g are weighted by their respective partial areas as follows

$$LE_v = Rn_v - H_v - G_v \quad (2)$$

$$LE_g = Rn_g - H_g - G_g \quad (3)$$

where Rn_v is the net radiation over the vegetation canopy; Rn_g is the net radiation over the soil surface; H_v andH_g can be described as the turbulent flux heat exchange partitioning between soil and vegetation. G_v andG_g can be described as the flux heat exchange in vegetation and soil inside. Thus, the ET over the whole area can be partition of composite heat flux into soil and canopy.

2.1.1 The net radiation over the vegetation canopy and the bare soil surface

In digital satellite imagery, each pixel usually represents a large area on the ground. Thus, it is possible that a pixel is a mixture of some typical ground objects in proportions. The existence of mixed pixels reduces the accuracy of recognition and classification of ground objects based on pixel-level, and handicaps the development of the quantitative remote sensing technology. How to decompose the mixed pixels precisely and effectively for multispectral remote sensing images is a critical issue for the quantitative remote sensing research. Thus, this paper provides a holistic systematic approach aparting the contribution of vegetation canopy and ground from the mixed pixel. Because temperature of vegetation area is lower than that of soil surface, the upward long-wave is exiguous in vegetation canopy. The net radiation in vegetation canopy and soil surface can be expressed as

$$Rn_v = f_v Rn \quad (4)$$

$$Rn_g = (1 - f_v)Rn \quad (5)$$

where Rn_v and Rn_g are contributions of the canopy and soil to the total net radiation flux, respectively. They are estimated by establishing a balance between the long-wave

HESSD

6, 921–942, 2009

MERIS and AATSR data over the Chinese Loess Plateau

R. Liu et al.

and the short-wave radiation separately for each component. The vegetation fraction is expressed according to $f_v = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}$ (Gutman and Ignatov, 1998).

The net radiation is given by the following equation

$$Rn = (1 - \alpha)Q + L\downarrow - L\uparrow \tag{6}$$

where α is the surface albedo, and can be elicited by SMAC model and satellite remote sensing data; Q is the solar global radiation (W m^{-2}); $L\downarrow$ is the downward longwave radiation (W m^{-2}), and can be obtained by the ground observation data from weather station when ignore the effect of cloud (Holtslag and Vanulden, 1983)

$$L\downarrow = 5.31 \times 10^{-13} T_a^6 \tag{7}$$

where T_a is the air temperature over canpoy or bare soil . The experimental fields were characterized by cornfield and fallow during the experiment period. In order to properly validate remote sensing air temperature, the flux measurement device which is typically a tower-based eddy covariance system with a source-area/flux-footprint of a few 100 m or less was considered. So in this study, the air temperature measured by the eddy covariance system at a 2.9 m-high can represent the mean temperatures over cornfield and fallow farmland.

$L\uparrow$ is the outgoing long-wave radiation flux density (W m^{-2}) governed by the surface temperature by the Stefan-Boltzmann law

$$L\uparrow = \varepsilon \sigma T_s^4 \tag{8}$$

where ε=1.0094 × 0.047 ln(NDVI) is the land surface effective emissivity; σ is the Stefan-Boltzmann constant (5.669×10^{-8} W m^{-2} k^{-4}); T_s is the land surface temperature. As there is difference existed between vegetation canopy and soil surface, land surface temperature is underestimated by remote sensing during daytime compared to ground measurements. In this study, the split-window algorithm is used for soil moisture estimate by using the AATSR 10.85 μm and 12.50 μm bands measurement, another sensor of ENVISAT. Based on the difference of vegetation fraction, the land surface temperatures of vegetation and soil surface were calculated respectively (Watson, 1992).

2.1.2 The near surface sensible heat flux

The near surface sensible heat flux (H, $\mathrm{W\,m^{-2}}$) is calculated according to the following equation (Spittlehouse and Black, 1980)

$$H = \rho Cp(T_s - T_a)/r_a \tag{9}$$

where ρ is the air density; Cp is the specific heat capacity of air; normally ρCp is constant ($1205\,\mathrm{Ws\,m^{-3}\,K^{-1}}$); T_s and T_a is the instantaneous land surface temperature and air temperature. The land surface temperature was estimated using the AATSR measurement, and air temperature was collected by the eddy covariance measurement system. Definitely, the "point" observations have a limited regional representative. So the estimates of the air temperature from the eddy covariance system can be considered as the air temperature over the soil surface and vegetation. Aerodynamic resistance r_{ah} is a function of wind speed and crop roughness characteristics and can be estimated from the surface similarity theory as (Thom and Oliver, 1977)

$$r_a = 4.72[\ln(Z/Z_0)]^2/(1 + 0.54U_x) \tag{10}$$

where Z is reference height (in this experiment 2.9 m is available from the eddy covariance system); Z_o is roughness length (Z_0=$0.04h^{1.417}$, h is the vegetation height (Dong et al., 1996); U_x is the wind speed at reference height. Among the various Loess Plateau landscapes, the loess mesa that the field experiment was conducted is characterized by a large flat mountain top area, where width ranging from a few to 10 km and 40 km in length. So the wind speed measured by the eddy covariance system represents the wind speed over the whole territory approximately, and satellite passes through the loess mesa at that moment.

2.2 The soil heat flux over the vegetation canopy and the soil surface

The soil heat flux over the vegetation canopy is given by (Reginato et al., 1985)

$$G_v = (0.1 - 0.042 \times 2.5\,\mathrm{NDVI})R_n \tag{11}$$

The soil heat flux can expressed as

$$G_g = 0.1R_n \tag{12}$$

Substitute the results of the net radiation, sensible heat flux and soil heat flux into the expression (2) and (3), then the estimation of instantaneous ET was conducted.

2.3 Daily ET

ET estimated from remote sensing data are usually instantaneous values, it is necessary to convert these values into daily amount. By using the data obtained during the experiment, an algorithm of converting instantaneous ET into daily amount was used (Zhang and Lemeur, 1995). Based on the assumption that the diurnal course of ET is similar to that of solar irradiance and can be approximated by a sine function, the daily ET can be obtained from one instantaneous measurement by the following expression

$$\frac{LE_d}{LE} = \frac{2N_E}{\pi \sin(\pi/N_E)} \tag{13}$$

where LE_d is daily ET; LE is instantaneous ET; N_E is daily effective sunlight hours. The ET value is very small around sunrise and sundown period, so effective ET time is the sunshine hours minus two.

3 Observation sites and data resources

3.1 Observation sites

The Chinese Loess Plateau is situated in the northwest China between the Taihang Mountain to Riyue Mountain in West-East and Ordos Plateau to Qinling Mountain in North-South with an altitude ranging from 1000 to 1800 m (The region consists of parts of Gansu, Qinghai, Ningxia, Shannxi and Inner Mongolia provinces with a total area of 620 000 km^2, approximately 6% of the Chinese territory). It has a temperate continental climate with cold winters, a windy and dry spring, and a warm and rainy summer followed by a short, cool autumn. One major river run through the region: the Yellow River, with the highest levels of silt anywhere in its reaches, flows through this region and carries away more than 1.4 billion tons of silt annually. Around 430 000 km^2 of land is suffering from soil erosion in this area (Zhang, 2000). It has complex geomorphic features, consists of diverse landscapes including the loess mesa, lowlands, gullies, hills, the loess ridge, continuous knolls, dry gulches, flat ground, loess terraces, and other land surface types (Yang and Shao, 2000). Dry land crop occupies 80% of the cultivated land, and predominant winter wheat together with the summer fallow after the wheat harvest between July and September and extensive stubble removal and cultivation, leads to the lower soil water use and water erosion, which is the major threat to sustainable crop production on the loosely structured sandy loams of Loess origin (Li et al., 2002).

Few land-atmosphere interaction studies have been conducted on the Loess Plateau because of its complex underlying surface. However, a land-atmosphere interaction study in this loess mesa region would provide a significant contribution toward understanding the characteristics of land surface energy balance, land surface parameterization, and water and soil conservation over the Chinese Loess Plateau (Wen et al., 2007). With a summer-dominant rainfall pattern over the Loess Plateau, there is a need to evaluate the impact of ET on the crop-soil water balance and explore the consequent management implications. In this paper, the summer daily characteristics of land surface energy over the Chinese Loess Plateau mesa region is evaluated by using data collected during the LOess Plateau land-atmosphere interaction pilot Experiment 05 (LOPEX05), which was conducted from 15 July to 25 August 2005 near PingLiang city, Gansu Province of China.

The experiment was carried out in the loess mesa that located in a semiarid climate zone, shown as the shaded area in Fig. 1. It has an average temperature of 6°, a maximum recorded temperature of 34°, a lowest recorded temperature of −24°, average annual precipitation of 510 mm, 2425 h of sunshine per year, and 170 days free of frost obtained from local meteorological data (Wen et al., 2007). The geographic locations of sampling fields are illustrated in Fig. 1, coordinates of the central point are 35.35° N, 106.42° E, with a 1592 m altitude above the sea.

The principle vegetation in the Loess Plateau includes farm land, shrub, deciduous forest and broad-leaved forest, and cultivation is mainly located in the loess mesa (Fig. 1). The major crops include maize, wheat, vigna, broomcorn and millet. A very small area is utilized for human settlements ranging from river Jing to thruway, which was a region of sparse population. The soil texture of the pilot experimental sampling fields is typical medium loam with a high proportion of silt, and the soil color is characterized by yellow brown and cinnamon (Yang and Shao, 2000).

The sites of eddy covariance systems deployed in the Loess Plateau land surface process field experiment are also showed in Fig. 1. The region in the middle of the map with green color was covered by corn and winter wheat, and our sites were installed there. All the winter wheat was harvested before the experiment, so only the site is fallow. ⋆ represents the PL station (a village); • represents the eddy covariance station at the Mesa bare soil surface and the mesa corn field; ▲ represents the automatic weather station installed at the edge of the mesa. The white part was Pingliang city, and grassland in the northwest on the map was Pengyang village. Chongxin village and the Mountain Kongtong covered by woodland were at the south and west of the map respectively. Blue line represents the River Jing which is the anabranch of the Yellow River but dry perennial. Black line represents the thruway that parallels with the watercourse of the River Jing.

3.2 Data recourses

3.2.1 Remote sensing data

Many advances in instrumental design and processing algorithms for earth observation purposes have been achieved in the last decade. Those advances have enabled the launch of the ENVIronmental SATellite (ENVISAT) mission by the European Space Agency (ESA) in March 2002. Currently, ENVISAT is the ESA core mission for earth observation and different instruments were onboard ENVISAT. Medium Resolution Imaging Spectrometer Instrument (MERIS) and Advanced Along-Track Scanning Radiometer (AATSR) are two of them.

MERIS measures the solar radiation reflected by the earth surface in 15 spectral channels distributed within the visible and near-infrared spectral domain and offers a complete global coverage every 3 days. It is a multidisciplinary instrument operating in the 390 nm to 1040 nm spectral range. It was originally designed for marine applications and this predominance can also be used for land applications (Verstraete et al., 1999). The AATSR instrument is a self-calibrating infrared, near-infrared and visible radiometer, using two highly stable onboard blackbody reference targets to calibrate the thermal channels and an opal diffuser for calibration of the visible and near-infrared channels. These data can be used to derive the surface albedo and surface temperature which are essential for the ET estimate of a particular interesting region. The AATSR was initially designed to provide regional sea surface temperature (SST). However, AATSR data are being used more frequentlly to obtain land surface temperature (LST) on a global scale (Coll et al., 2005). The Large volumes of ENVISAT-MERIS/AATSR data are available on-line now. Users with an on-going project can register and order the MERIS/AATSR data under the ESA earth observation data policy.

With the daily ground observations, a relationship between the ground vegetation water content measurement and satellite remotely sensed indices was established and validated (Liu et al., 2007). But there are few researches on estimation of ET over the Loess Plateau by using MERIS and AATSR data. An algorithm for the derivation of vegetation fraction, ableo and NDVI parameters data from MERIS and LST from AATSR on board ENVISAT have been developed in this investigation.

The land surface albedo was derived by using the BEAM toolbox. BEAM is a toolbox for viewing, analyzing and processing of remote sensing data. Originally developed to facilitate the utilization of image data from ENVISAT's optical instruments, BEAM now supports a growing number of other sensors such as MODIS, AVHIR, PRISM and CHRIS/Proba. The reflectance image, as well as the other atmospheric correction outputs, can be geometrically corrected. But as a consequence, the MERIS L2 reflectance product was delivered without aerosol correction. The map projection processor, supplied with the BEAM software, can be triggered by user command in order to obtain the images geo-rectified into the latitude/longitude projection for converting L2 "Top-Of-Aerosols" reflectance to actual surface reflectance. Thus, the step of atmospheric correction of land surface reflectance in L2 data can be accomplished.

3.2.2 Ground observation data

Three field observation sites were installed during the LOPEX05, the Tazhan site at the mesa corn field, the Yuanxia site at the bottom flat of the mesa, the landuse type are corn fields, the coordinates were 35°34′36″ N, 106°42′6.1″ E and 35°31′50.3″ N, 106°44′0.3″ E. The Chaisi site was at the mesa bare soil surface with central coordinates 35°35′24″ N, 106°40′48″ E. In addition, an Automatic Weather Station was installed at the edge of the mesa observing the air temperature, air humidity and wind speed. Beside these, the vegetation height, category, fraction, sunshine duration and weather conditions were measured and recorded during the experiment period. In particular, data collected on 7, 11 and 27 June 2005 were used to assess the ET in particular. The vegetation height were 90 cm, 120 cm and 190 cm, average air temperature were 21.8°, 23.1° and 25.7°, respectively. The measured sunshine duration was approximately 8 h during these separate days.

3.3 Results and validation

The specific routines for ET estimate are: firstly, vegetation fraction was estimated from the MERIS data, the land surface albedo was estimated by using SMAC and MREIS data, and the solar radiation is estimated from the exist algorithm (Wang, 1988). Secondly, the "split-window" algorithm was used to retrieve the surface temperature from the data of AATSR two infrared bands (10.85 μm and 12.50 μm). Finally, with the aid of meteorological variables, the daily ET over the Loess Plateau heterogeneous region was estimated from Eqs. (2) to (13).

The Fig. 2 shows that the estimated ET decreases from south to north, which is corresponding to the land cover classification. The regions of higher value are concentrated at the Kongtong Mountain, and its ET values could reach more than 1.00 mm, while in the Northeast regions the values are less than 0.10 mm. The values in the Chaisi site, the Tazhan site and the Yuanxia site are 0.10 mm, 0.50 mm and 0.50 mm respectively, The Chaisi site is situated in bare soil surface mesa, it is different from the Tazhan site and the Yuanxia site. The average vegetation fraction of mesa area is 0.3 that lies between the value of grassland in the northern part and the woodland in the western part, so the surface albedo is also lower than that of the grassland, and higher than that of the woodland. As the temperatures of three land surface types are significantly different, the near surface sensible heat exchange is weaker than that of grassland but stronger than that of woodland. The soil heat flux and surface latent flux are higher in the vegetable area, and the net radiation is lower than the bare soil, thus the corresponding value of ET of mesa ranges between the grassland and woodland.

The LOPEXs were conducted successively in 2004–2007. In this paper, we used the MERIS and AATSR data from the first ten days of June 2005. The loess mesa is agricultural lands, planted primarily with corn and winter wheat. After the harvest of winter wheat, the land surface becomes bare soil. The corn is in the silking stage during the experimental period and the condition of annual growing and reaping are basically the same, so the measurement data of the eddy covariance system on 7, 11 and 27 June 2006 are conducted to validate the instantaneous ET data from remote sensing retrieval (Fig. 3).

The remote sensing estimated latent heat flux shows a consistent relationship with simultaneous value of the ground eddy covariance measurement (Fig. 3). The minimum and maximal relative errors of this approach are 10.96% and 4.80% on 7 and 27 June 2006, respectively. We can also draw conclusions that the error is smaller in high vegetation coverage area. The above comparisons imply that the ET assessed by using MERIS and AATSR data are approximately in accordance with the field observations. As the special geomorphology and inhomogeneity of the Loess Plateau mesa region landscape, and defects on the eddy covariance system, inevitably the evaluation precision of flux would be reduced, brief explanations are listed as follow:

1. Oversimplification of the energy conservation model lead to error in this study. The land surface energy imbalance terms over the Chinese Loess Plateau mesa region cornfield were large indeed, which implied that the magnitudes of the storage terms were considerable in the Loess Plateau Soil-Plant-Atmosphere Continuum (SPAC) system (Wen et al., 2007). Although estimate result of the ET was acceptable, the storage terms and advection terms and aerodynamic resistance could cause errors.

2. The observation accuracy of the eddy covariance system is influenced by meteorological conditions. The maximal uncertainty of the eddy covariance system measurement can reach 20% (Baldocchi et al., 2001). Moreover, in the semi-arid areas with sparse vegetation cover, the error in energy fluxes tends to be even higher, around 25% (Were et al., 2007). In addition, although the errors are estimated as less than 15.0%, within the data from different instruments are compared and calibrated (Wei et al., 2005), it was calibrated during a prior period that was considered representative enough of the variability found in surface and

climate variables at longer time scales.

4 Conclusion and discussion

With the collected ground measurement and satellite remote sensing data during the LOPEXs, the land surface albedo, vegetation coverage fraction were derived from MERIS data, and the surface temperature was retrieved by using the "split-window" algorithm with the AATSR data. Based on the land surface energy balance theory, a simple algorithm was proposed for estimating the ET by using MERIS and AATSR data and available meteorological data on 7, 11 and 27 June 2005 over the Loess Plateau heterogeneous region. The instantaneous latent heat fluxes estimated from satellite remote sensing data were converted to daily ET amount by using an algorithm, and the results were validated by using the ground measurements.

In the developed simple algorithm for daily ET estimate, the only required variables are land surface albedo, vegetation fraction, land surface temperature and relevant ground meteorological data. The estimated daily ET values were ranged 0.0 to 1.0 mm in the study area, and the average error was around 7.7%, and it was smaller in the area with high vegetation coverage. This shows that energy balance modeling is a feasible algorithm for irrigation management and monitoring crop water requirement in the arid regions. Further work is needed to improve the precision of land surface temperature retrieved from AATSR, and implement sensitivity test for ET under different land surface characteristics and explore error source in the land surface energy balance model.

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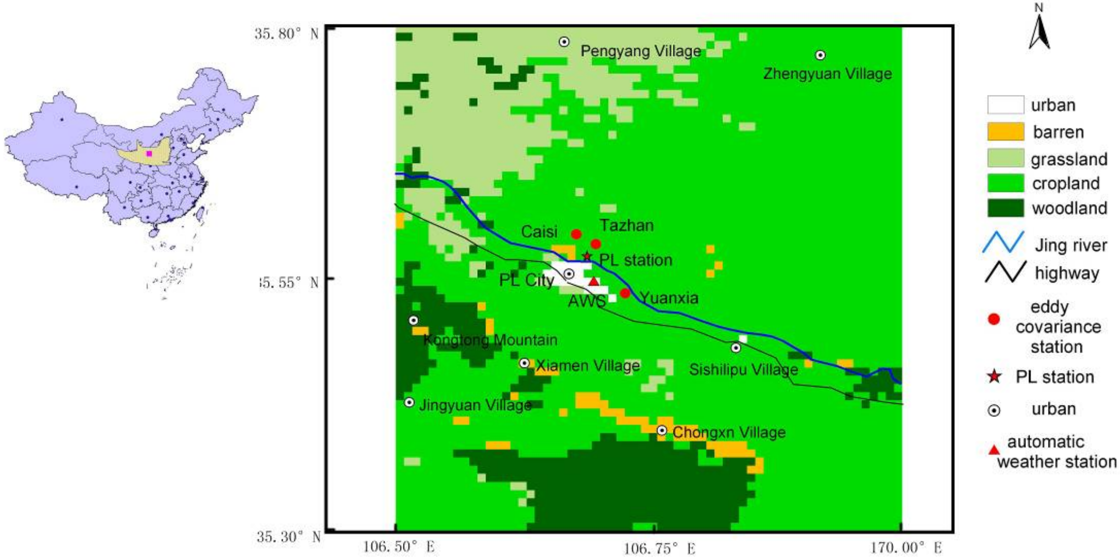

Fig. 1. Geographic location and landuse information of the Loess Plateau mesa regions.

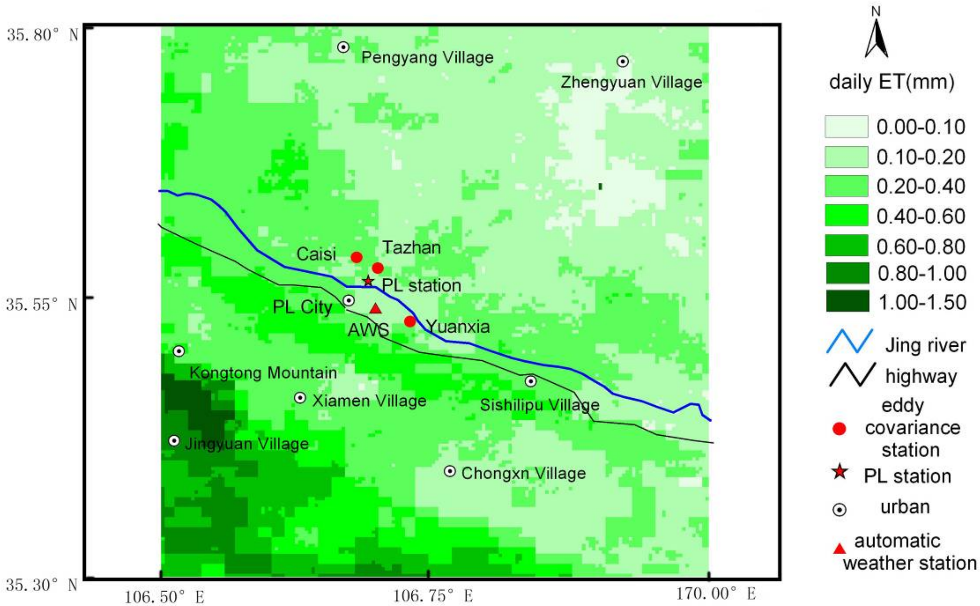

Fig. 2. Regional distribution of daily ET over the Loess Plateau mesa regions retrieved based on the land surface energy balance theory on 27 June 2005.

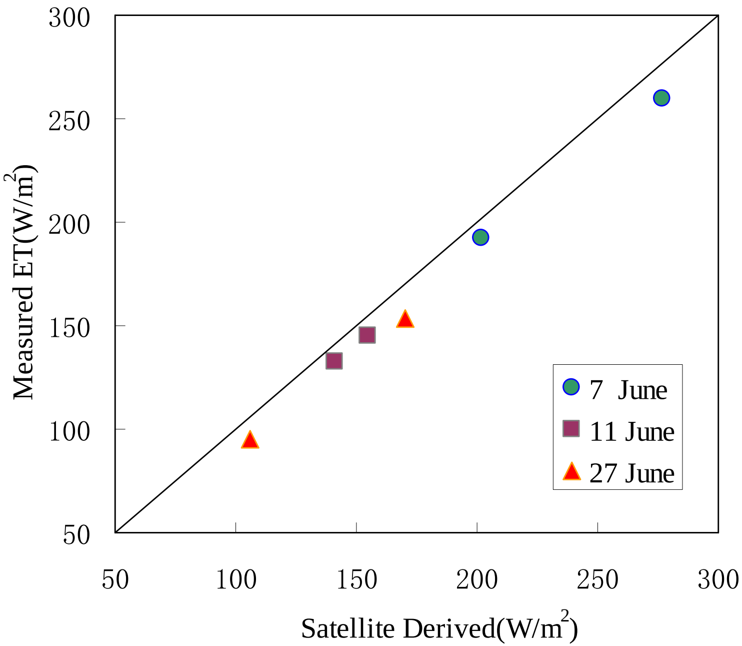

Fig. 3. Intercompassion of remote sensing estimates and ground measured latent heat flux on June 7, 11 and 27 June 2005.