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Estimating surface fluxes over middle and upper streams of the Heihe River Basin with ASTER imagery

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Abstract

Surface fluxes are important boundary conditions for climatological modeling and the Asian monsoon system. Recent availability of high-resolution, multi-band imagery from the ASTER (Advanced Space-borne Thermal Emission and Reflection Radiometer) sensor has enabled us to estimate surface fluxes to bridge the gap between local scale flux measurements using micrometeorological instruments and regional scale land-atmosphere exchanges of water and heat fluxes that are fundamental for the understanding of the water cycle in the Asian monsoon system. A Surface Energy Balance System (SEBS) method based on ASTER data and field observations has been proposed and tested for deriving net radiation flux (R_n), soil heat flux (G_0), sensible heat flux (H) and latent heat flux (λE) over heterogeneous land surface in this paper. As a case study, the methodology was applied to the experimental area of the WATER (Watershed Allied Telemetry Experimental Research), located at the mid-to-upstream sections of the Heihe River, northwest China. The ASTER data of 3 May and 4 June in 2008 was used in this paper for the case of mid-to-upstream sections of the Heihe River Basin. To validate the proposed methodology, the ground-measured land surface heat fluxes (net radiation flux (R_n), soil heat flux (G_0), sensible heat flux (H) and latent heat flux (λE)) were compared to the ASTER derived values. The results show that the derived surface variables and land surface heat fluxes in different months over the study area are in good accordance with the land surface status. It is therefore concluded that the proposed methodology is successful for the retrieval of land surface heat fluxes using the ASTER data and filed observation over the study area.

1 Introduction

Among many land surface experiments having been carried out so far, arid and cold regions were paid little attention. The land surface observations in arid and cold regions, both remotely sensed and in-situ, need to be strengthened for a better understanding of hydrological and ecological processes at different scales. The Watershed Allied Telemetry Experimental Research (WATER) is a simultaneous air-borne, satellite-borne, and ground-based remote sensing experiment conducted in the Heihe Basin, the second largest inland river basin in the northwest arid regions of China. The WATER is aiming at the research on water cycles, eco-hydrological and other land surface processes in catchment-scale. Data sets with high-resolution and spatiotemporal consistency will be generated based on this experiment. An integrated watershed model and a catchment-scale land/hydrological data assimilation system is proposed to be developed. The mission of WATER is to improve the observability, understanding, and predictability of hydrological and related ecological processes at catchmental scale, accumulate basic data for the development of watershed science and promote the applicability of quantitative remote sensing in watershed science studies (Li, 2008).

Remote sensing offers the possibility to derive regional distribution of land surface heat fluxes over heterogeneous land surface in combination with sparse field experimental stations. Remote sensing data provided by satellites are a means of obtaining consistent and frequent observations of spectral albedo and emittance of radiation at elements in a patch landscape and on a global scale (Sellers et al., 1990). The land surface variables and vegetation variables, such as surface temperature T_{sfc}, surface hemispherical albedo r_0, NDVI, MSAVI, LAI and surface thermal emissivity ε can be derived directly from satellite observations (e.g., Susskind et al., 1984; Che'din et al., 1985; Tucker, 1986; Wan and Dozier, 1989; Menenti et al., 1989; Becker and Li, 1990, 1995; Watson et al., 1990; Baret and Guyot, 1997; Price, 1992; Kahle and Alley, 1992; Li and Becker, 1993; Qi et al., 1994; Norman et al, 1995; Schmugge et al., 1995; Kustas and Norman, 1997; Sobrino and Raissouni, 2000; Su, 2002; Ma et al., 2003a, b; Oku and Ishikawa, 2004; Kato, 2005; Ma, 2006b, 2007, 2009). The regional heat fluxes can be determined indirectly with the aid of these land surface variables and vegetation variables (Pinker, 1990).

Studies have explored several approaches to estimate the regional distribution of surface heat fluxes in recent years. These methods require specification of the vertical

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temperature difference between the surface temperature and the air temperature and an exchange resistance (e.g., Kustas et al.,1989; Kustas, 1990; Wang et al., 1995; Menenti et al., 1991; Menenti and Choudhury, 1993; Bastiaanssen, 1995; Kustas and Norman, 1997; Su, 2002). However, these remote sensing retrieval methods have been performed in homogeneous moist or semiarid regions, and investigations in heterogeneous landscape of arid and cold regions (e.g., the WATER area) are rare.

NOAA/AVHRR, GMS and Landsat-7 ETM data were used to determine regional land surface heat fluxes over heterogeneous landscape of the Tibetan Plateau (Ma et al., 2003a, b, 2005, 2006; Oku et al., 2007). However, the resolution of the NOAA/AVHRR and GMS data is about 1 km×1 km and sub-pixel heterogeneity has been omitted. So have Landsat-7 ETM data. The aim of this research is to upscale in-situ point observations of land surface variables and land surface heat fluxes to the regional scale using high-resolution (15 m×15 m) ASTER data.

2 Data and methodology

2.1 Data

The recent availability of high-resolution, multi-band imagery from the ASTER sensor has enabled us to estimate surface fluxes. ASTER covers a wide spectral region with 14 bands from the visible to the thermal infrared with high spatial, spectral and radiometric resolution. The spatial resolution varies with wavelength: 15 m in the visible and near-infrared (VNIR, 0.52–0.86 μm), 30 m in the short wave infrared (SWIR, 1.6–2.43 μm), and 90 m in the thermal infrared (TIR, 8.1–11.6 μm) (Yamaguchi, 1998).

The most relevant data, collected at the WATER (Fig. 1) surface stations (sites) to support the parameterization of land surface heat fluxes and analysis of ASTER images in this paper, consist of surface radiation budget components, surface radiation temperature, surface albedo, humidity, wind speed and direction measured at the Atmospheric Boundary Layer (ABL) towers, Automatic Weather Stations (AWSs), turbu-

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lent fluxes measured by eddy correlation technique, soil heat flux, soil temperature profiles, soil moisture profiles, and the vegetation state.

2.2 Theory and scheme

A Surface Energy Balance System (SEBS, Su, 2002) is proposed for the estimation of atmospheric turbulent fluxes and evaporative fraction using satellite earth observation data, in combination with meteorological information at proper scales. SEBS consists of: a set of tools for the determination of the land surface physical parameters, such as albedo, emissivity, temperature, vegetation coverage etc., from spectral reflectance and radiance measurements; a model for the determination of the roughness length for heat transfer (Su, 2002).

In this study, the Surface Energy Balance System (SEBS) retrieval algorithm is used for the ASTER data (Su, 2002). The general concept of the methodology is shown in a diagram (Fig. 2). The surface albedo for shortwave radiation (r_0) is retrieved from narrowband-broadband conversion by Liang (Liang, 2001). The land surface temperature (T_{sfc}) is derived using a method developed by Juan (2006) from multispectral thermal infrared data. Juan (2006) also evaluated a technique to extract emissivity information from multispectral thermal infrared data adding vegetation information. The radiative transfer model SMAC (Rahman and Dedieu, 1994) computes the downward shortwave and longwave radiation at the surface. With these results the surface net radiation flux (R_n) is determined. On the basis of the field observations, the soil heat flux (G_0) is estimated from the net radiation flux (R_n). The sensible heat flux (H) is estimated from T_{sfc}, and regional latent heat flux (λE) is derived as the residual of the energy budget theorem (Liou, 2004; Ma, 2006) for land surface.

The net radiation flux R_n is estimated as

$$\begin{aligned} R_n(x,y) &= K_{\downarrow}(x,y) - K_{\uparrow}(x,y) + L_{\downarrow}(x,y) - L_{\uparrow}(x,y) \\ &= (1 - r_0(x,y)) \cdot K_{\downarrow}(x,y) + L_{\downarrow}(x,y) - \varepsilon_0(x,y)\sigma T_{sfc}^4(x,y) \end{aligned} \qquad (1)$$

where ε_0 (x, y) is surface emissivity, $K_\downarrow$ (Wm^{-2}) represents the shortwave (0.3–3 μm) and $L_\downarrow$ (Wm^{-2}) is the longwave (3–100 μm) radiation components, respectively. Surface albedo r_0 (x, y) is derived from narrowband-broadband conversion method by Liang (2001). Since ASTER has nine bands, it is expected that so many bands should enable us to convert narrowband to broadband albedos effectively. Liang (2001) found that the conversions are quite linear. The resultant linear equations are collated in the following.

$$r_0 = 0.484\alpha_1 + 0.335\alpha_3 - 0.324\alpha_5 + 0.551\alpha_6 + 0.305\alpha_8 - 0.367\alpha_9 - 0.0015 \tag{2}$$

Where i (i=1–9) are the correspondent ASTER band surface reflectance.

The equation to calculate soil heat flux is parameterized as (Su, 2002):

$$G_0 = R_n[\Gamma_c + (1 - f_c) \bullet (\Gamma_s - \Gamma_c)] \tag{3}$$

in which it is assumed that the ratio of soil heat flux to net radiation Γ_c=0.05 for full vegetation canopy (Monteith, 1973) and Γ_s=0.315 for bare soil (Kustas and Daughtry, 1989). An interpolation is then performed between these limiting cases using the fractional canopy coverage, f_c.

In order to derive the sensible and latent heat flux, the similarity theory will be made use of. In ASL (Atmospheric Surface Layer), the similarity relationships for the profiles of the mean wind speed, u, and the mean temperature, $\theta_0 - \theta_a$, are usually written in integral form as

$$u = \frac{u_*}{k}\left[\ln\left(\frac{z-d_0}{z_{0\,m}}\right) - \Psi_m\left(\frac{z-d_0}{L}\right) + \Psi_m\left(\frac{z_{0\,m}}{L}\right)\right] \tag{4}$$

$$\theta_0 - \theta_a = \frac{H}{ku_*\rho C_p}\left[\ln\left(\frac{z-d_0}{z_{0\,h}}\right) - \Psi_h\left(\frac{z-d_0}{L}\right) + \Psi_h\left(\frac{z_{0\,h}}{L}\right)\right] \tag{5}$$

where z is the height above the surface, $u_*=(\tau_0/\rho)^{1/2}$ is the friction velocity, τ_0 is the surface shear stress, ρ is the density of air, k=0.4 is von Karman's constant, d_0 is the zero plane displacement height, $z_{0\,\mathrm{m}}$ is the roughness height for momentum transfer, θ_0 is the potential temperature at the surface, θ_a is the potential air temperature at height z, $z_{0\,\mathrm{h}}$ is the scalar roughness height for heat transfer, ψ_m and ψ_h are the stability correction functions for momentum and sensible heat transfer respectively, and L is the Obukhov length defined as:

$$L = \frac{\rho C_p u_*^3 \theta_v}{kgH} \tag{6}$$

where g is the acceleration due to gravity and θ_v is the potential virtual temperature near the surface.

The latent heat flux $\lambda\, E$ is the residual resulting from an application of the energy budget theorem to the land surface (Ma, 2006):

$$\lambda E = R_n - H - G_0 \tag{7}$$

3 Case studies and validation

As a case study, 4 scenes of ASTER data over the mid-to-upstream sections of the Heihe River Basin are used. Figure 3 shows the distribution maps of surface heat fluxes around the WATER area. Figure 4 shows the validation of the derived net radiation R_n, soil heat flux G_0, sensible heat flux H and latent heat flux $\lambda\, E$ against ground measurements over the Watershed Airborne Telemetry Experimental Research (WATER) stations, Yingke, Huazhaizi, Guantan, Maliantan, A'rou, Binggou and Yakou with 1:1 line.

The results show the following:

1. The derived surface heat fluxes (net radiation flux R_n, soil heat flux G_0, sensible heat flux H and latent heat flux $\lambda\, E$) in different months over the study area are in good accordance with the land surface status. The experimental area includes a variety of land surfaces, such as a large area of grassy marshland, some

desertification grassland areas, many small rivers; therefore these derived parameters show a wide range due to the strong contrast of surface features. Net radiation flux changed from 410 $\mathrm{Wm^{-2}}$ to 830 $\mathrm{Wm^{-2}}$ in May and from 410 $\mathrm{Wm^{-2}}$ to 870 $\mathrm{Wm^{-2}}$ in June. Soil heat flux varied from 30 $\mathrm{Wm^{-2}}$ to 260 $\mathrm{Wm^{-2}}$ in May and from 25 $\mathrm{Wm^{-2}}$ to 270 $\mathrm{Wm^{-2}}$ in June. Sensible heat flux is from 30 $\mathrm{Wm^{-2}}$ to 480 $\mathrm{Wm^{-2}}$ in May and from 10 $\mathrm{Wm^{-2}}$ to 470 $\mathrm{Wm^{-2}}$ in June, and latent heat flux varied from 60 $\mathrm{Wm^{-2}}$ to 430 $\mathrm{Wm^{-2}}$ in May and 10 $\mathrm{Wm^{-2}}$ to 560 $\mathrm{Wm^{-2}}$ in June (Fig. 3).

2. The derived net radiation flux over the study area is very close to the field measurement. It is the result of the improvement on surface albedo and surface temperature.

3. The regional soil heat flux derived from the relationship between soil heat flux and net radiation flux is suitable for heterogeneous land surface of the WATER area, because the relationship itself was derived from the same area.

4. The derived regional sensible heat flux and latent heat flux at the validation sites in the WATER area is in good agreement with field measurements (Fig. 4). This is due to the fact that atmospheric boundary layer processes have been considered in more detail in our methodology and the proposed parameterization for sensible heat flux and latent heat flux can be used over the upper streams of the Heihe River Basin area.

4 Concluding remarks

In this study, the regional distributions of land surface heat fluxes (net radiation flux, soil heat flux, sensible heat flux and latent heat flux) over middle and upper streams of the Heihe River Basin were derived with the aid of ASTER data and field observations. Reasonable results of land surface heat fluxes were gained in this study.

HESSD

6, 4619–4635, 2009

The retrieval of regional land surface heat fluxes over heterogeneous landscape is not an easy task.

1. Only three ASTER images are used in this study. To obtain more accurate regional land surface fluxes (daily to seasonal variations) over a larger area (the Heihe River Basin), more field observations (ABL tower and radiation measurement system, radiosonde system, turbulent fluxes measured by eddy correlation technique, soil moisture and soil temperature measurement system, etc.) and other satellite sensors such as MODIS (Moderate Resolution Imaging Spectroradiometer) and NOAA (National Oceanic and Atmospheric Administration)/AVHRR (Advanced Very High Resolution Radiometer) with more frequent temporal coverage have to be used.

2. This study implies the SEBS method is only applicable to clear-sky days. In order to extend its applicability to cloudy skies, we should consider using microwave remote sensing data to derive surface temperature and other land surface variables.

SEBS has been developed to estimate atmospheric turbulent fluxes using satellite earth observation data, in combination with meteorological data from a proper reference height given by either in-situ measurements for application to a point, and radiosonde or meteorological forecasts for application at larger scales. On the basis of these experimental validations, SEBS can be used to estimate turbulent heat fluxes at different scales with acceptable accuracy.

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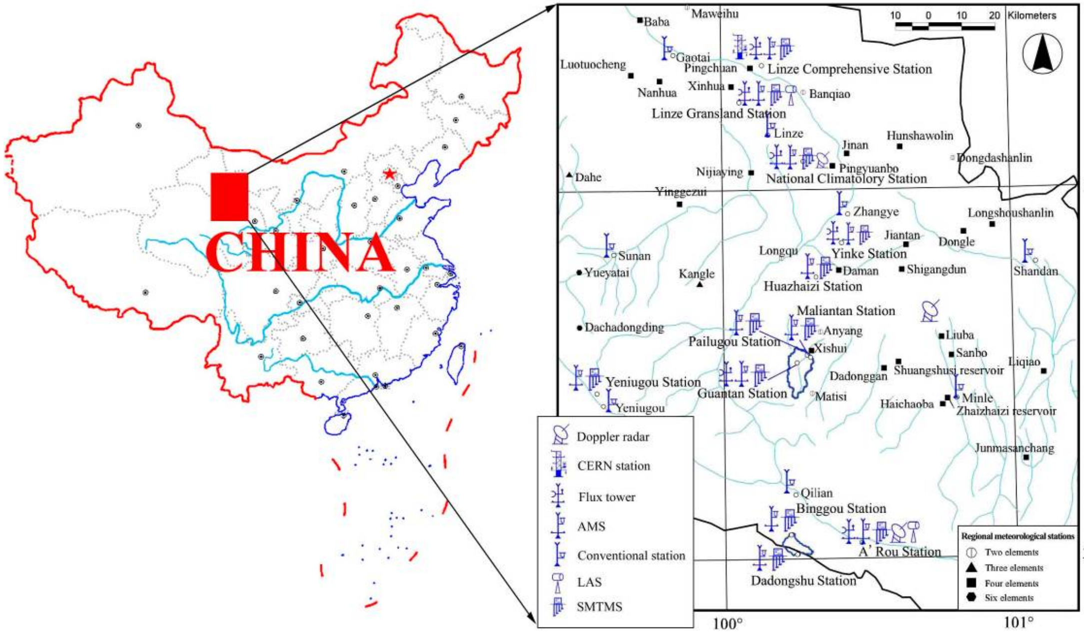

Fig. 1. Sketch map of studying area and the sites during the WATER. Network of the automatic meteorological stations and flux towers in WATER (For regional meteorological stations, two elements indicate air temperature and precipitation; three elements indicate wind direction plus two elements; four elements indicate wind speed plus three elements; six elements indicate air pressure, global radiation plus four elements. SMTMS: Soil Moisture and Temperature Measurement System).

HESSD
6, 4619–4635, 2009

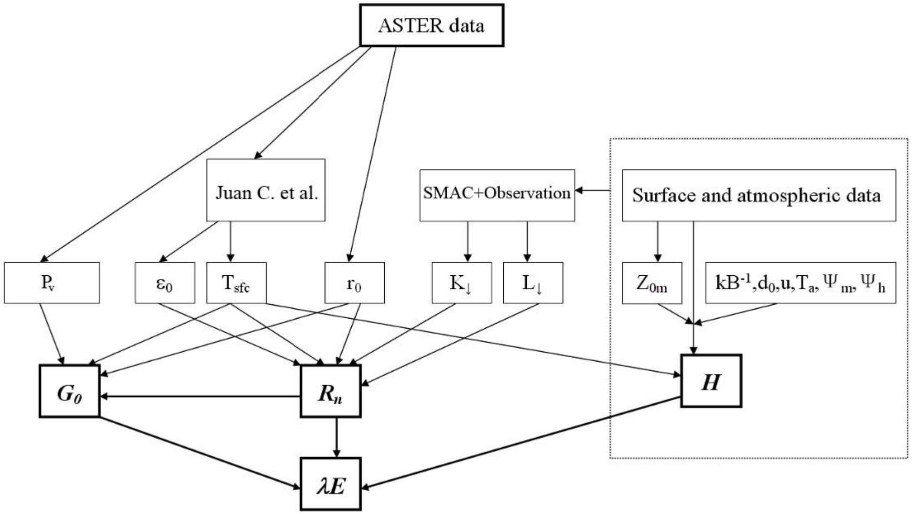

Fig. 2. Diagram of parameterization procedure by combining ASTER data with field observations.

HESSD
6, 4619–4635, 2009

Estimating surface fluxes over the Heihe River Basin with ASTER imagery

W. Ma et al.

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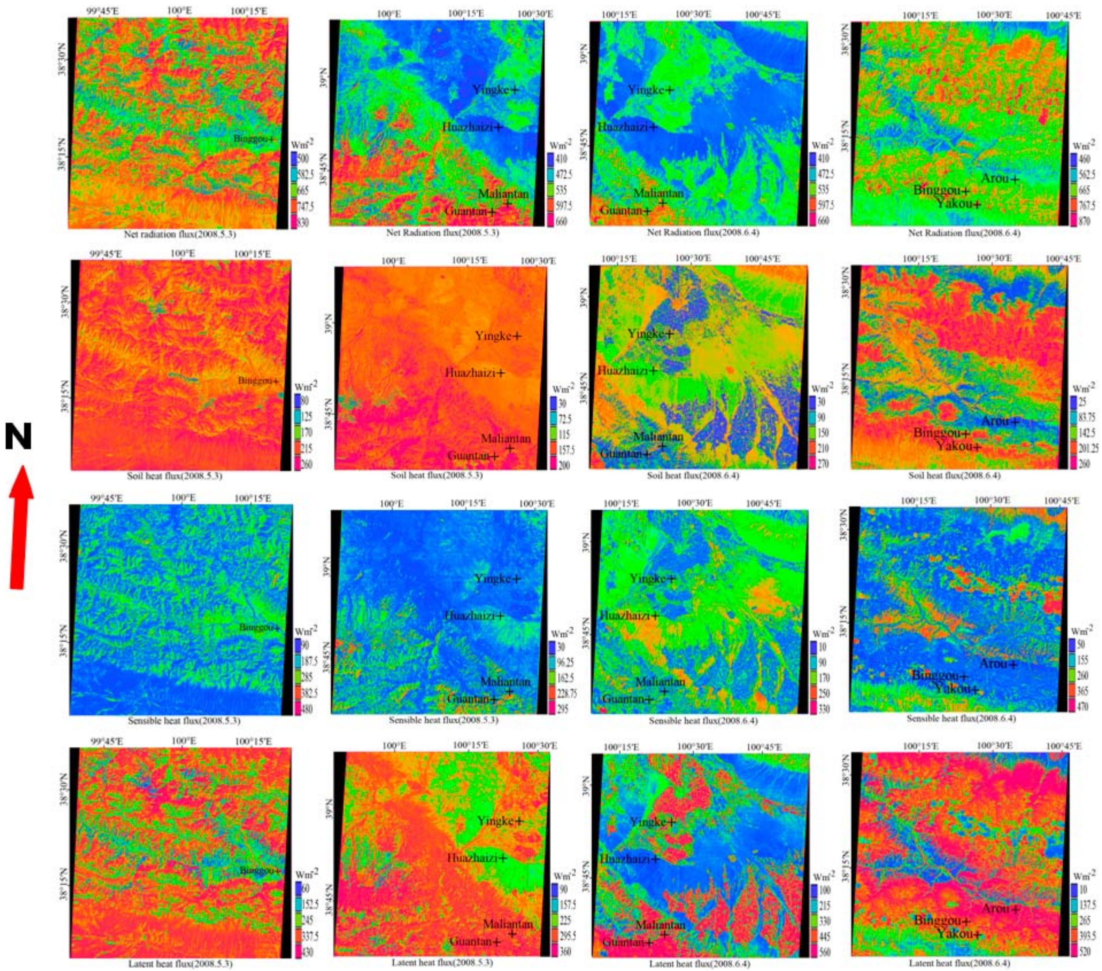

Fig. 3. Distrubution maps of land surface heat fluxes over the WATER area.

HESSD
6, 4619–4635, 2009

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀ | ▶
Back | Close
Full Screen / Esc
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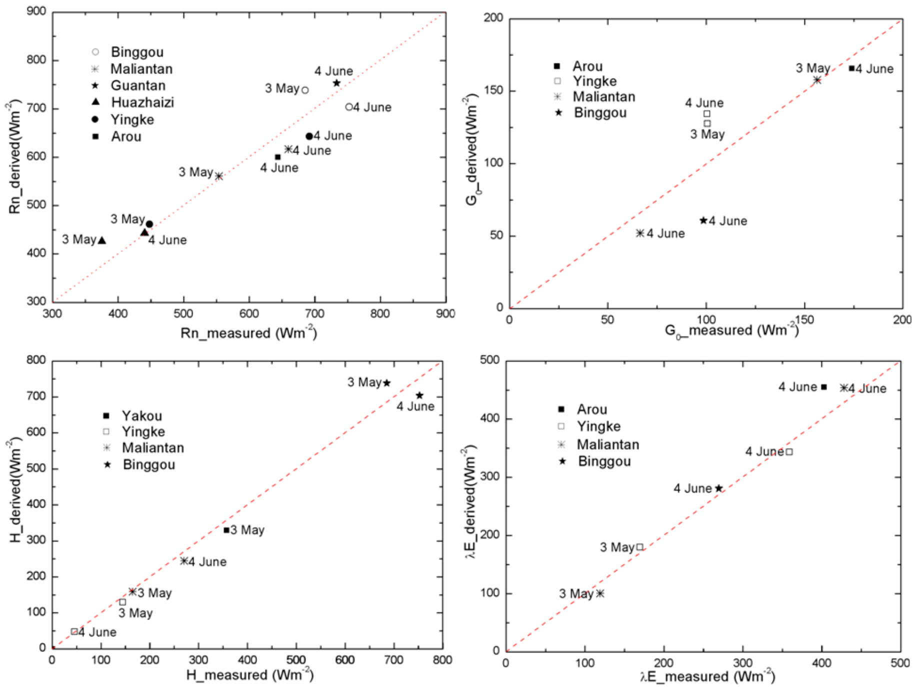

Fig. 4. Validation of the derived net radiation R_n, soil heat flux G_0, sensible heat flux H and latent heat flux λE against ground measurements over the Watershed Airborne Telemetry Experimental Research (WATER) stations, Yingke, Huazhaizi, Guantan, Maliantan, A'rou, Binggou and Yakou with 1:1 line.

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