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**Estimating surface  
fluxes**

W. Ma et al.

# Estimating surface fluxes over the north Tibetan Plateau area with ASTER imagery

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## Abstract

Surface fluxes are important boundary conditions for climatological modeling and Asian monsoon system. The 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. 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), 30 m in the short wave infrared (SWIR), and 90 m in the thermal infrared (TIR). A parameterization method based on ASTER data and field observations has been proposed and tested for deriving surface albedo, surface temperature, Normalized Difference Vegetation Index (NDVI), Modified Soil Adjusted Vegetation Index (MSAVI), vegetation coverage, Leaf Area Index (LAI), net radiation flux, soil heat flux, sensible heat flux and latent heat flux over heterogeneous land surface in this paper. As a case study, the methodology was applied to the experimental area of the Coordinated Enhanced Observing Period (CEOP) Asia-Australia Monsoon Project (CAMP) on the Tibetan Plateau (CAMP/Tibet), which located at the north Tibetan Plateau. The ASTER data of 24 July 2001, 29 November 2001 and 12 March 2002 was used in this paper for the case of summer, winter and spring. To validate the proposed methodology, the ground-measured surface variables (surface albedo and surface temperature) and land surface heat fluxes (net radiation flux, soil heat flux, sensible heat flux and latent heat flux) were compared to the ASTER derived values. The results show that the derived surface variables and land surface heat fluxes in three different months over the study area are in good accordance with the land surface status. Also, the estimated land surface variables and land surface heat fluxes are in good accordance with ground measurements, and all their absolute percent difference (APD) is less than 10% in the validation sites. It is therefore concluded that the proposed methodology is successful for the retrieval of land surface variables and land surface heat fluxes using the ASTER data and field observation over the study

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area.

## 1 Introduction

The energy and water cycles play an important role in the Asian Monsoon system over the Tibetan Plateau. The Tibetan Plateau contains the world's highest elevation with average elevation about 4000 m relief features. It represents an extensive mass extending from subtropical to middle latitudes and is spanning over 25 degrees of longitude. Because of its topographic character, the plateau surface absorbs a large amount of solar radiation energy (much of which is redistributed by cryospheric processes), and undergoes dramatic seasonal changes of surface heat and water fluxes (e.g., Ye and Gao, 1979; Ye, 1981; Yanai et al., 1992; Ye and Wu, 1998; Ma et al., 2002a; Ma et al., 2006; Ma and Tsukamoto, 2002). The study on the energy exchanges between the land surface and atmosphere was also of paramount importance for the CAMP/Tibet (Ma et al., 2003a; Ma et al., 2005; Ma et al., 2006). Some interesting detailed studies concerning the land surface heat fluxes have been reported (e.g., Yang et al., 2002, 2003, 2004; Ma et al., 2002a; Choi et al., 2004; Zuo et al., 2005). These researches were, however, on point-level or a local-patch-level. Since the area the information of land-surface atmosphere interaction is required, the aggregation of the individual results into a regional scale is necessary.

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  $\varepsilon$  is 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;

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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; Ma et al., 2003b; Oku and Ishikawa, 2004; Kato, 2005). The regional heat fluxes is 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 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 high altitudes (e.g., the Tibetan Plateau area) were 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; Ma et al., 2003b; Ma et al., 2005; Ma et al., 2006; Oku et al., 2007). However, the resolution of the NOAA/AVHRR and GMS data is about 1 km×1 km, and heterogeneity, the scale of which is less than 1 km×1 km over the Tibetan Plateau area, has been omitted. So does Landsat-7 ETM data. This research is to upscale the point or patch scale field observations of land surface variables and land surface heat fluxes to regional distribution of them with the aid of high-resolution (15 m×15 m) ASTER data and in situ data.

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## 2 Data and methodology

### 2.1 Data

The intensive observation period (IOP) and long-term observation of the CAMP/Tibet have been done successfully in the past seven years. A large amount of data has been collected, which is the best data set so far for the study of energy and water cycle over the Tibetan Plateau. The experimental region, about  $150 \times 250 \text{ km}^2$ , includes variety of land surfaces such as a large area of grassy marshland, some desertification grassland areas, many small rivers and several lakes (Fig. 1).

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,  $0.52\text{--}0.86 \mu\text{m}$ ), 30 m in the short wave infrared (SWIR,  $1.6\text{--}2.43 \mu\text{m}$ ), and 90 m in the thermal infrared (TIR,  $8.1\text{--}11.6 \mu\text{m}$ ) (Yamaguchi, 1998).

The most relevant data, collected at the CAMP/Tibet 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, vertical profiles of air temperature, humidity, wind speed and direction measured at the Atmospheric Boundary Layer (ABL) towers, Automatic Weather Stations (AWSs), radio sonde, turbulent fluxes measured by eddy correlation technique, soil heat flux, soil temperature profiles, soil moisture profiles, and the vegetation state.

### 2.2 Theory and scheme

The general concept of the methodology is shown in a diagram (Fig. 2). The surface albedo for short-wave radiation ( $r_0$ ) is retrieved from narrowband-broadband conversion by Liang (Liang, 2001). ASTER has nine bands. It is expected that so many

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bands should enable us to convert narrowband to broadband albedos effectively. Liang found that the conversions are quite linear. The land surface temperature ( $T_{sfc}$ ) is derived from Hook's method (Hook, 1992). Hook evaluates land surface temperature ( $T_{sfc}$ ) technique developed to extract  $T_{sfc}$  information from multispectral thermal infrared data. The radiative transfer model MODTRAN (Berk et al., 1989) computes the downward short-wave and long-wave 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  $R_n$ . The sensible heat flux ( $H$ ) is estimated from  $T_{sfc}$ , and regional latent heat flux ( $\lambda E$ ) is derived as the residual of the energy budget theorem (Liou, 2004; MA, 2006) for land surface.

### 2.2.1 Net radiation

The regional net radiation flux is derived from

$$R_n(x, y) = K_{\downarrow}(x, y) - K_{\uparrow}(x, y) + L_{\downarrow}(x, y) - L_{\uparrow}(x, y) \quad (1)$$

$$= (1 - r_0(x, y)) \cdot K_{\downarrow}(x, y) + L_{\downarrow}(x, y) - \varepsilon_0(x, y) \sigma T_{sfc}^4(x, y)$$

where  $\varepsilon_0(x, y)$  is surface emissivity,  $K_{\downarrow}(Wm^{-2})$  represents the short-wave ( $0.3-3\mu m$ ) and  $L_{\downarrow}(Wm^{-2})$  is the long-wave ( $3-100\mu m$ ) radiation components, respectively. Surface albedo  $r_0(x, y)$  is derived from narrowband-broadband conversion method by Liang (Liang, 2001). ASTER has nine bands. It is expected that so many bands should enable us to convert narrowband to broadband albedos effectively. Liang (Liang, 2001) found that the conversions are quite linear. The resultant linear equations are collated in following.

$$r_0 = 0.484\alpha_1 + 0.335\alpha_3 - 0.324\alpha_5 + 0.551\alpha_6 + 0.305\alpha_8 - 0.367\alpha_9 - 0.0015 \quad (2)$$

where  $\alpha_i (i=1-9)$  were corresponded each ASTER band surface reflection.

The incoming short-wave radiation flux  $K_{\downarrow}(x, y)(Wm^{-2})$  in Eq (1) is derived from radiative transfer model MODTRAN (Kenizys et al., 1996), The incoming long-wave radiation flux  $L_{\downarrow}(x, y) (Wm^{-2})$  in Eq. (1) is derived from MODTRAN directly as well (Ma

and Tsukamoto, 2002; Ma et al., 2006). Surface temperature  $T_{sfc}(x, y)$  (K) in Eq. (1) is derived from ASTER thermal infrared spectral radiance(Hook, 1992).

## 2.2.2 Soil heat flux

The regional soil heat flux density  $G_0(x, y)$  ( $\text{Wm}^{-2}$ ) is determined through (Choudhury, 1988)

$$G_0(x, y) = \rho_s C_s ((T_{sfc}(x, y) - T_s(x, y)) / r_{sh}(x, y)) \quad (3)$$

where  $\rho_s$  ( $\text{kgm}^{-3}$ ) is soil dry bulk density,  $C_s$  ( $\text{Jkg}^{-1}\text{K}^{-1}$ ) is soil specific heat,  $T_s(x, y)$  (K) represents soil temperature of a determined depth, and  $r_{sh}(x, y)$  ( $\text{sm}^{-1}$ ) stands for resistance of soil heat transportation. The regional soil heat flux  $G_0(x, y)$  ( $\text{Wm}^{-2}$ ) cannot directly be mapped from satellite observations through Eq. (3) for the difficulty to derive the soil heat transportation resistance  $r_{sh}(x, y)$  ( $\text{sm}^{-1}$ ) and the soil temperature at a determined depth  $T_s(x, y)$  (K) (e.g., Bastiaanssen, 1995; Ma et al., 2002b). Many investigations have shown that the midday  $G_0/Rn$  ratio,  $\Gamma$ , is reasonably predictable from special vegetation indices (Daughtry et al., 1990).  $\Gamma$  is considered as a function  $F$  which relates  $G_0/Rn$  to other variables (Ma and Tsukamoto, 2002). Some researchers have concluded that  $G_0/Rn = \Gamma = F(\text{NDVI})$  (Clothier et al., 1986; Kustas and Daughtry, 1990). A better ratio of  $G_0/Rn = \Gamma = F(r_0, T_{sfc}, \text{NDVI})$  was also found (Choudhury et al., 1987; Menenti et al., 1991; Bastiaanssen, 1995). The relationship between  $G_0(x, y)$  ( $\text{Wm}^{-2}$ ) and  $R_n(x, y)$  ( $\text{Wm}^{-2}$ ) found in the Tibetan Plateau area (Ma et al., 2003b) will be used to determine regional soil heat flux over the CAMP/Tibet area here. It means that  $G_0(x, y)$  ( $\text{Wm}^{-2}$ ) is:

$$G_0(x, y) = R_n(x, y) \cdot \frac{T_{sfc}(x, y)}{r_0(x, y)} \cdot (0.00029 + 0.00454 \bar{r}_0 + 0.00878 \bar{r}_0^2) \cdot (1 - 0.964 \text{MSAVI}(x, y)^4) \quad (4)$$

where  $\bar{r}_0$  is the average albedo.

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### 2.2.3 Sensible heat flux

The regional distribution of sensible heat flux is calculated from

$$H(x, y) = \rho C_p \frac{T_{sfc}(x, y) - T_a(x, y)}{r_a(x, y)} \quad (5)$$

where aerodynamic resistance is

$$r_a(x, y) = \frac{1}{\kappa u_* (x, y)} \left( \ln \left( \frac{z - d_0(x, y)}{z_{0m}(x, y)} \right) + kB^{-1}(x, y) - \psi_h(x, y) \right) \quad (6)$$

where  $\kappa$  is Von-Karman constant;  $u_*$  ( $\text{ms}^{-1}$ ) is friction velocity,  $z$  (m) is reference height,  $d_0$  (m) is zero-plane displacement height,  $z_{0m}$  (m) is the aerodynamic roughness,  $kB^{-1}$  is the excess resistance for heat transportation,  $\psi_h$  is the stability correction function for heat. The friction velocity  $u_*$  is derived from

$$u_* (x, y) = \kappa u(x, y) \left( \ln \left( \frac{z - d_0(x, y)}{z_{0m}(x, y)} \right) - \psi_m(x, y) \right)^{-1} \quad (7)$$

where  $\psi_m$  is the stability correction function for momentum. From Eq. (5)–(7)

$$H(x, y) = \rho C_p \kappa^2 u(x, y) \frac{(T_{sfc}(x, y) - T_a(x, y))}{\left( \ln \frac{z - d_0(x, y)}{z_{0m}(x, y)} + kB^{-1} - \psi_h(x, y) \right) \cdot \left( \ln \frac{z - d_0(x, y)}{z_{0m}(x, y)} - \psi_m(x, y) \right)} \quad (8)$$

where  $z$  is the reference height and  $u$  is the wind speed at the reference height. In the study,  $z$  and  $u$  are determined with the aid of field measurements of AWS (Automatic Weather Stations) system at the same height.  $z_{0m}(x, y)$  in Eq. (8) over the Northern Tibetan area is calculated using Jia et al.'s model (Jia et al., 1999).  $d_0$  is the zero-plane displacement, which is calculated using Stanhill's model (Stanhill, 1969).  $T_a(x, y)$  in Eq. (8) is the regional distribution of air temperature at the reference height, it is derived from a linear method (Ma, 2007):

$$T_a(x, y) = 0.7784T_{sfc}(x, y) + 60.1706 \quad (9)$$

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Values of the excess resistance to heat transfer,  $kB^{-1}$  versus  $u(T_{sf_c} - T_a)$  over the Northern Tibetan Plateau is following equation, (Ma, 2006)

$$kB^{-1} = 0.062u(T_{sf_c} - T_a) + 0.599 \quad (10)$$

$\psi_h(x, y)$  and  $\psi_m(x, y)$  in Eq. (8) are the integrated stability functions. For an unstable condition, the integrated stability functions  $\psi_h(x, y)$  and  $\psi_m(x, y)$  is written as (Paulson, 1970)

$$\begin{cases} \psi_m(x, y) = 2 \ln\left(\frac{1+X}{2}\right) + \ln\left(\frac{1+X^2}{2}\right) - 2 \arctan(X) + 0.5\pi \\ \psi_h(x, y) = 2 \ln\left(\frac{1+X^2}{2}\right) \end{cases} \quad (11)$$

Where  $X = \{1 - 16 \times (z - d_0(x, y)) / L(x, y)\}^{0.25}$ . For a stable condition, the integrated stability function  $\psi_h(x, y)$  and  $\psi_m(x, y)$  become (Webb, 1970)

$$\psi_m(x, y) = \psi_h(x, y) = -5 \cdot \frac{z - d_0(x, y)}{L(x, y)} \quad (12)$$

The stability function  $(z - d_0(x, y)) / L(x, y)$  is calculated by Businger's method (Businger, 1988):

$$\begin{cases} \frac{z - d_0(x, y)}{L(x, y)} = R_i(x, y) \quad (\text{unstable}) \\ \frac{z - d_0(x, y)}{L(x, y)} = R_i(x, y) / (1 - 5.2R_i(x, y)) \quad (\text{stable}) \end{cases} \quad (13)$$

where  $R_i(x, y)$  is the Richardson number; and according to the definition of the Richardson number, the approximate analytical solutions of  $R_i$  found by Yang (Yang, 2001) will be used here.

#### 2.2.4 Latent heat flux

The regional latent heat flux  $\lambda E(x, y)$  ( $\text{Wm}^{-2}$ ) is derived as the residual of the energy budget theorem (Ma, 2006) for land surface based on the condition of zero horizontal advection at  $z < z_{\text{sur}}$ , i.e.,

$$\lambda E(x, y) = R_n(x, y) - H(x, y) - G_0(x, y) \quad (14)$$

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### 3 Case Studies and Validation

As a case study, 3 scenes of ASTER data over Tibetan Plateau are used (see Table 1). Figure 3 shows the distribution maps of surface albedo and surface temperature around the CAMP/Tibet area. Their frequency distributions are shown in Fig. 4.

Figure 5 shows the distribution maps of surface heat fluxes around the CAMP/Tibet area. Their frequency distributions are shown in Fig. 6. Figures 3 and 5 are based on 4980×4200 pixels of the ASTER data. The derived land surface heat fluxes are validated by using field measurements. The land surface variables (surface albedo and surface temperature) and land surface heat fluxes (net radiation flux, soil heat flux, sensible heat flux and latent heat flux) derived from satellite data were compared with the field measurements at BJ site. The measured surface soil heat fluxes were calculated from soil heat flux measured at -10 cm and the soil temperature measured at surface and -10 cm. The absolute percent difference (APD) can quantitatively measure the difference between the derived results ( $H_{\text{derived}(i)}$ ) and measured values ( $H_{\text{measured}(i)}$ ) as

$$\text{APD} = \frac{|H_{\text{derived}(i)} - H_{\text{measured}(i)}|}{H_{\text{measured}(i)}} \quad (15)$$

The results show the following:

1. The derived surface variables (land surface albedo and surface temperature) and surface heat fluxes (net radiation flux  $R_n$ , soil heat flux  $G_0$ , sensible heat flux  $H$  and latent heat flux  $\lambda E$ ) in three different months over the study area are in good accordance with the land surface status. The experimental area includes variety of land surfaces such as a large area of grassy marshland, some desertification grassland areas, many small rivers and several lakes; therefore these derived parameters show a wide range due to the strong contrast of surface features. Surface albedo is from 0.01 to 0.34 in July and from 0.08 to 0.55 in March and November. Surface temperature ranged from 0°C to 51.65°C in July and

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from  $-10.3^{\circ}\text{C}$  to  $36.8^{\circ}\text{C}$  in March and November. Net radiation flux changed from  $570\text{Wm}^{-2}$  to  $830\text{Wm}^{-2}$  in July and from  $80\text{Wm}^{-2}$  to  $655\text{Wm}^{-2}$  in March and November. Soil heat flux varied from  $100\text{Wm}^{-2}$  to  $220\text{Wm}^{-2}$  in July and from  $0\text{Wm}^{-2}$  to  $180\text{Wm}^{-2}$  in March and November. Sensible heat flux is from  $0\text{Wm}^{-2}$  to  $540\text{Wm}^{-2}$  in July and from  $0\text{Wm}^{-2}$  to  $520\text{Wm}^{-2}$  in March and November, and latent heat flux varied from  $0\text{Wm}^{-2}$  to  $736\text{Wm}^{-2}$  in July and  $0\text{Wm}^{-2}$  to  $288\text{Wm}^{-2}$  in March and November (see Figs. 3 and 5). Surface albedo, surface temperature and sensible heat flux around the lake in the distribution maps are much higher in July, and at the same time, net radiation flux, soil heat flux and latent heat flux are lower in the area. The reason is that most of around lake area is the desertification grass land, and it was dry and has low moisture.

2. The derived pixel value (Figs. 3 and 5) and average value (see Fig. 4 and 6) of surface temperature, net radiation flux, soil heat flux and latent heat flux in July are higher than that in March and November. It means that there is much more evaporation in summer than in winter in the north Tibetan Plateau area. It is also pointed out that the heating density ( $H+\lambda E=R_n-G_0$ ) in summer is much higher than that in winter in the central Tibetan Plateau area. The reason is that most the land surface is covered by green grass in summer and it is covered by snow and ice during winter on the experimental area.
3. The derived net radiation flux over the study area is very close to the field measurement with APD less than 3.1% (Table 2). It is caused by the improvement on surface albedo and surface temperature.
4. 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 CAMP/Tibet area, and the APD is less than 9.8% at validation sites (Table 2). As a result of the relationship itself was derived from the same area (Ma et al., 2002b).
5. The derived regional sensible heat flux and latent heat flux with APD less than

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9.8% at validation sites in the CAMP/Tibet area is in good agreement with field measurements (Table 2). The reason is that the process of atmospheric boundary layer was considered in more detail in our methodology. It is pointed that the proposed parameterization methodology for sensible heat flux and latent heat flux is reasonable, and it is used over the north Tibetan Plateau area.

4 Concluding remarks

In this study, the regional distributions of land surface variables (surface albedo and surface temperature), vegetation variables (NDVI, MSAVI, vegetation coverage and LAI) and land surface heat fluxes (net radiation flux, soil heat flux, sensible heat flux and latent heat flux) over heterogeneous north Tibetan Plateau area were derived with the aid of ASTER data and the field observation. Reasonable results of land surface variables, vegetation variables and land surface fluxes were gained in this study.

Derived the regional land surface heat fluxes over heterogeneous landscape is not an easy task. The parameterization method presented in this study is still in developing stage:

1. Only three ASTER images at a specific time of specific day are used in this study. To obtain more accurate regional land surface fluxes, their seasonal variations and even variation day by day over the CAMP/Tibet area, and even the whole Tibetan Plateau area, 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 another satellite such as MODIS (Moderate Resolution Imaging Spectroradiometer) and NOAA (National Oceanic and Atmospheric Administration)/AVHRR (Advanced Very High Resolution Radiometer) have to be used. It is also worth trying SEBI (Surface Energy Balance Index; Menenti and Choudhury, 1993) method and SEBS (Surface Energy Balance System; Su, 2002).

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

5 Vegetation variables cannot be validated in this study because there were no such measurements during the experiments. More attention should be paid to the measurements of vegetation variables in the coming experiments.

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**Table 1.** The solar zenith angles information of 3 ASTER scenes.

Date	HH:MM:SS(Beijing Time)	solar zenith angle(degree)
24 Jul 2001	12:47:59	19.64792
29 Nov 2001	12:44:03	54.80759
12 Mar 2002	12:47:25	38.96375

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**Table 2.** Comparison of the derived results (RS results) versus those measured values (Observations) at the CAMP/Tibet site with APD.

Date	Items	$Rn(Wm^{-2})$	$H(Wm^{-2})$	$G_0(Wm^{-2})$	$\lambda E(Wm^{-2})$
24 Jul 2001	Observations	620.15	262.07	123.14	234.94
	RS results	637.03	268.24	133.16	243.60
	APD	2.6%	2.3%	7.5%	3.6%
29 Nov 2001	Observations	297.94	214.87	4.8	25.58
	RS results	307.40	201.22	4.69	27.20
	APD	3.1%	6.8%	2.1%	6.0%
12 Mar 2002	Observations	391.77	327.57	48.57	15.64
	RS results	387.64	350.74	53.74	17.35
	APD	1.0%	6.6%	9.6%	9.8%

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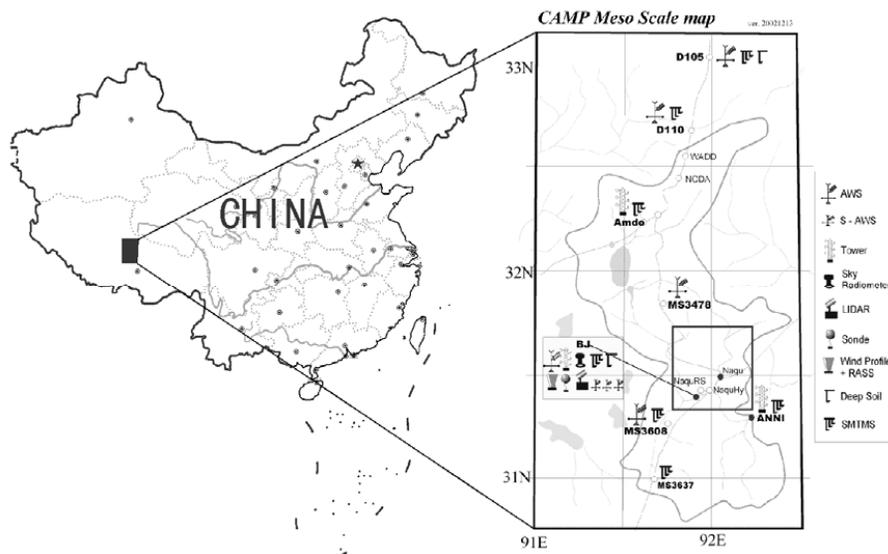
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**Fig. 1.** Study area map and the sites during the CAMP/Tibet.

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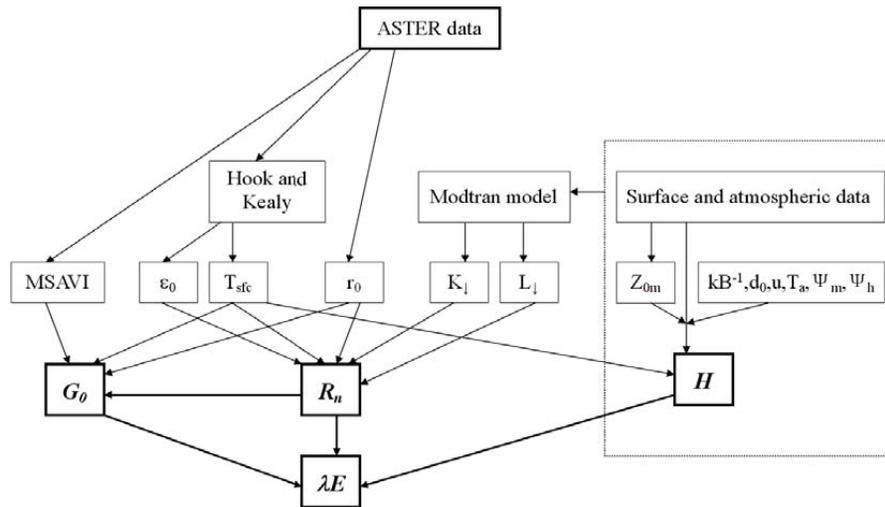


Fig. 2. Diagram of parameterization procedure by combining ASTER data with field observations.

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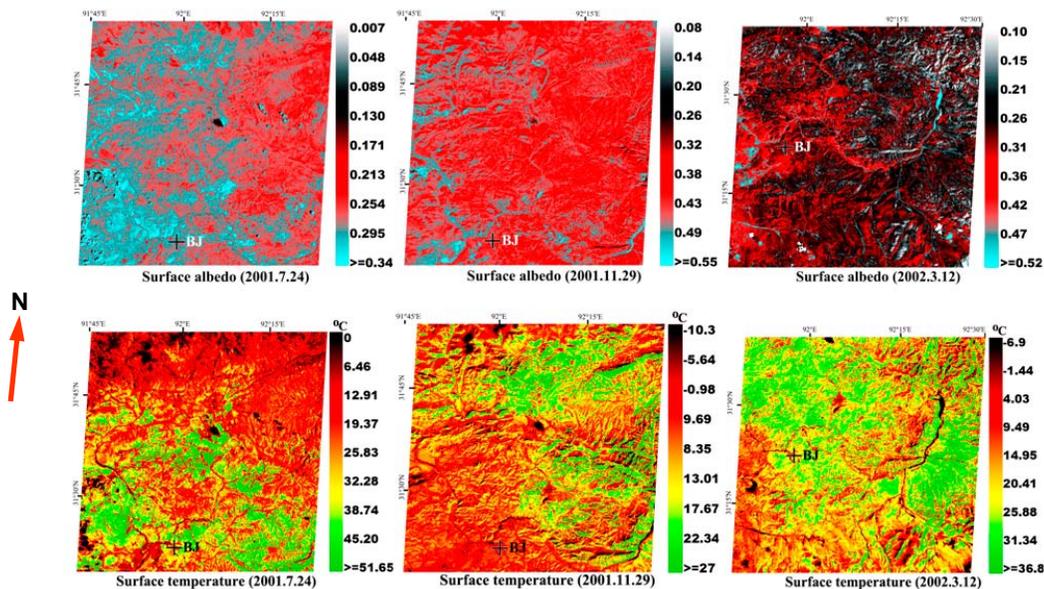


Fig. 3. Distribution maps of land surface variables over the CAMP/Tibet area.

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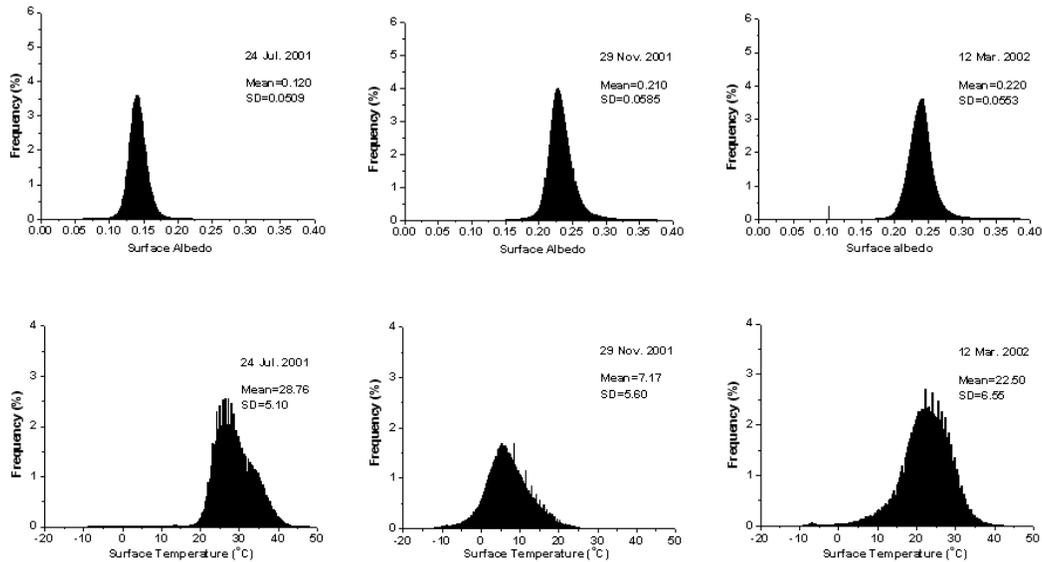
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**Fig. 4.** Frequency distribution of surface albedo and surface temperature for the CAMP/Tibet area at 12:45 Beijing Time.

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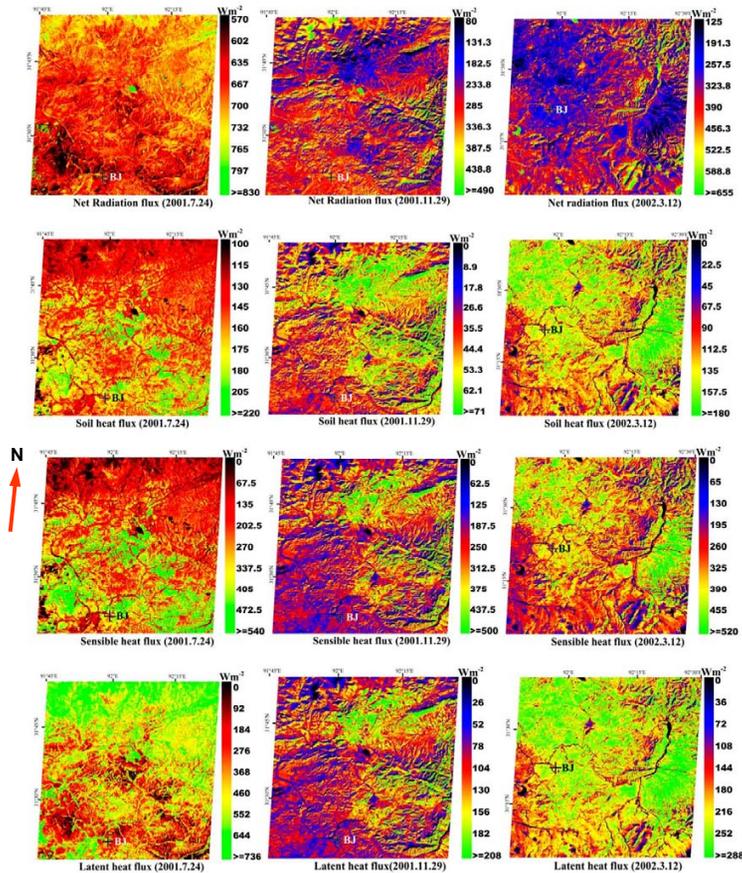
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**Fig. 5.** Distribution maps of land surface heat fluxes over the CAMP/Tibet area.

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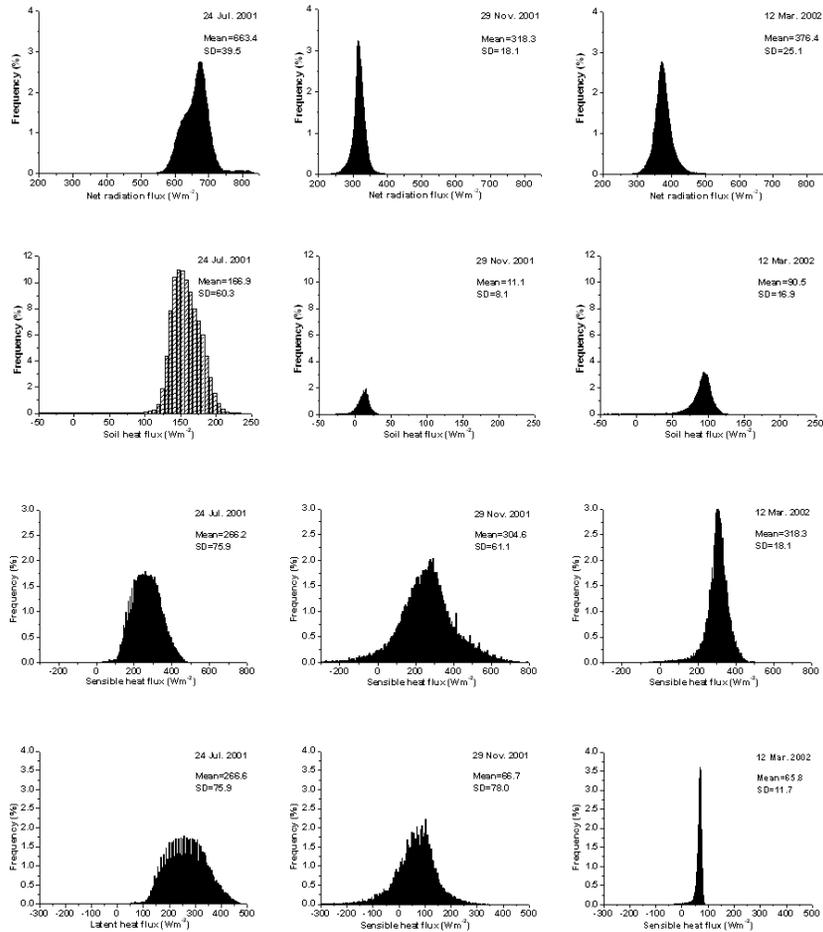
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**Fig. 6.** Frequency distribution of land surface heat fluxes for the CAMP/Tibet area at 12:45 Beijing Time.

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