Combining satellite and in-situ data for evapotranspiration estimates over heterogeneous landscape of the Tibetan Plateau

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Abstract

In this study, a new parameterization method based on MODIS (Moderate Resolution Imaging Spectroradiometer) data, AVHRR (Advanced Very High-Resolution Radiometer) data and *in-situ* data is constructed and tested for estimating the regional evaporative fraction (*EF*) over heterogeneous landscape. As a case study, the algorithm was applied to the Tibetan Plateau area. Eight images of MODIS data (17 January 2003, 14 April 2003, 23 July 2003 and 16 October 2003; 30 January 2007, 15 April 2007, 1 August 2007 and 25 October 2007) and four images of AVHRR data (17 January 2003, 14 April 2003, 23 July 2003 and 16 October 2003) were used in this study for the inter-comparison among winter, spring, summer and autumn and the annual variation analysis. The results were also validated by using the ‘‘ground truth’’ measured in the stations of the Tibetan Observation and Research Platform (TORP) and the CAMP/Tibet (CEOP (Coordinated Enhanced Observing Period) Asia-Australia Monsoon Project (CAMP) on the Tibetan Plateau). The results show that the estimated *EF* in four different seasons over the Tibetan Plateau area is in good accordance with the land surface status. The *EF* show a wide range due to the strong contrast of surface features over the Tibetan Plateau. Also, the estimated *EF* is in good agreement with the ground measurements, and their absolute percent difference (*APD*) is less than 10.0% in the validation sites. The results from AVHRR were also in agreement with MODIS, with the latter usually displaying a higher level of accuracy. It is therefore concluded that the proposed algorithm is successful for the retrieval of *EF* using the MODIS data, AVHRR data and *in-situ* data over the Tibetan Plateau area, and the MODIS data is the better one and it should be used widely for the evapotranspiration (*ET*) research over this region.

1. Introduction

As the most prominent and complicated terrain on the Earth, the Tibetan Plateau, with an elevation of more than 4000 *m* on average above mean sea leave (*msl*) makes up approximately one fourth of the land area of China (Fig.1). Due to its topographic character, the plateau surface absorbs a large amount of solar radiation energy, and undergoes dramatic seasonal changes of surface heat and water fluxes (e.g., Yanai et al., 1992; Ye and Wu, 1998; Hsu and Liu, 2003; Sato and Kimura, 2007). Evapotranspiration (*ET*) between the land surface and atmosphere of the Tibetan Plateau play an important role in the Asian Monsoon system, which in turn are major components of the energy and water cycles of the global climate system. Some interesting detailed studies concerning the *ET* (or latent heat flux) have been reported in the different sites and land surface types over the Tibetan Plateau in the past years (e.g.Tanaka et al. 2001; Ma et al., 2005; Li et al., 2006; Zhong et al., 2009). These researches were, however, on point-level or a local-patch-level. Remote sensing from satellites however offers the possibility to derive *ET* regional (or areal) distribution over heterogeneous land surface in combination with sparse field experimental stations. And the regional *ET* distributions have been reported over the Tibetan Plateau in the past years (e.g. Ma et al., 2003; Ma et al., 2009), but the results were still in a meso-scale area. To understand the effect of the Tibetan Plateau on the climatic change over China, East Asia, and even the globally, the regional distribution of *ET* distribution of over whole Tibetan Plateau must been determined.

[Insert Fig.1 about here]

Our objective in this study is to estimate the regional distribution of *ET* and its seasonal variation over the whole Tibetan Plateau with the aid of MODIS data, AVHRR data and *in-situ* data. It is because the *ET* from land is essential for understanding climate dynamics and ecosystem productivity (e.g. Churkina et al., 1999) and it also has applications in areas such as water resource management. We will introduce “evaporative fraction (*EF*)” as an index for *ET* after Shuttleworth et al. (1989). *EF* is defined here as:

$$\Lambda = \frac{\lambda E}{H + \lambda E} = \frac{\lambda E}{R_n - G_0} \qquad (1)$$

Where H is the sensible heat flux, λE the latent heat flux, R_n the net radiation flux and G_0 the soil heat flux.

Our goal is to estimate *ET* but rather *EF* in whole Tibetan Plateau area. This is due to two reasons. First, *EF* is more suitable as an index for surface moisture condition than *ET*. Because *ET* itself is a function not only of the land surface conditions (e.g., soil moisture and vegetation) but also surface available energy R_n-G_0 (=H+λE), *ET* cannot be easily interpreted for soil moisture condition or drought status. On the contrary, *EF* can be more directly related to these land surface conditions. Secondly, *EF* is useful for scaling up instantaneous observations to longer time periods. As one knows, a satellite (except for geostationary satellite) observes each land surface very instantaneously during a day. *ET*, however, can generally change drastically during a day mainly due to changes in sun angle and cloud coverage. Therefore, even if we can accurately estimate *ET* at the moment of satellite overpass, it cannot be directly related to daily or daytime average *ET*. On the contrary, *EF* is well known to be nearly constant during most of daytime (e.g. Shuttleworth et al., 1989; Sugita and Brutsaert, 1991; Crago, 1996a; Crago, 1996b). We also find that *EF* is also nearly constant from sunrise to sunset during the clear days in BJ station (31.37^{0}N, 91.90^{0}E; elevation:4509 m; land-cover: sparseness meadow) of the CAMP/Tibet (CEOP (Coordinated Enhanced Observing Period) Asia-Australia Monsoon Project (CAMP) on the Tibetan Plateau) (Ma et al., 2005), NAMOR(Nam Co Station for

Multisphere Observation and Research, Chinese Academy of Sciences; 30.46^{0}N, 90.59^{0}E; elevation: 4730 m; land-cover: sparseness meadow), QOMS(Qomolangma Station for Atmospheric and Environmental Observation and Research, Chinese Academy of Sciences; 28.21^{0}N, 86.56^{0}E; elevation: 4276 m; land-cover: sparse grass-Gobi) and SETS(Southeast Tibet Station for Alpine Environment Observation and Research, Chinese Academy of Sciences; 29.77^{0}N, 94.73^{0}E; elevation: 3326 m; land-cover: grass land) in the Tibetan Observation and Research Platform (TORP, Ma et al., 2008) (see Fig.2). Therefore, if we can estimate daytime average R_n-G_0 or $H+\lambda E$, daytime average *ET* will be estimated from Eq.(1) by using instantaneous *EF* derived by satellite. There are some cases for the estimation by using the satellite and in-situ data. A similar spatial variation of broadband albedo and surface temperature was proposed to estimate *EF* (Su, 1999; Roerink et al., 2000). Jiang and Islam (2001) estimated *EF* by interpolating the Priestley–Taylor parameter. Venturini et al.(2004) did the comparison of *EF* estimated from AVHRR and MODIS sensors over South Florida of USA. Verstraeten et al. (2005) estimated *EF* from NOAA-imagery at satellite overpass time over European forests area. Wang et al. (2006) estimated *EF* from a combination of day and night land surface temperatures and NDVI. But no any study of *EF* over heterogeneous landscape of whole Tibetan Plateau till now.

[Insert Fig.2 about here]

The regional distribution of *EF* over the Tibetan Plateau will be estimated and validated in this study. We first propose the algorithm in section 2. The usage of satellite data and in-situ data for the validation are shown in section 3. The application of the methodology to the Tibetan Plateau area is presented in section 4, where the distribution of *EF* are estimated for four different phases, spring, summer, autumn and winter by using eight scenes of MODIS data and four scenes of AVHRR data. Discussions are given in the section 5.

2. Theory and scheme

The general concept and procedure of the methodology are shown in a diagram (Fig. 3). The surface reflectance for short-wave radiation $r_0(x,y)$ is retrieved from MODIS data by using Zhong's method (Zhong,2007) and AVHRR data by using the method of Ma et al. (2003) with the atmospheric correction, using land surface and aero-logical observation data. The land surface temperature $T_{sfc}(x,y)$ is also derived from MODIS data by using the method of Zhong et al.(2010) and AVHRR data by using the method of Ma et al. (2003) with the atmospheric correction, using land surface and aero-logical observation data. The radiative transfer model MODTRAN (Berk et al., 1989) computes the downward short-wave and long-wave radiation at the surface by using satellite data, land surface and aero-logical observation data and the atmospheric correction (Ma and Tsukamoto, 2002). With these results the regional surface net radiation flux $R_n(x,y)$ is determined by using the surface radiation energy budget theorem for land surface. The regional soil heat flux $G_0(x,y)$ is estimated from $R_n(x,y)$ and field observations over the Tibetan Plateau (Ma et al., 2002). It means that based on the field observation data from the key stations over the Tibetan

Plateau, a good relationship between G_0 and R_n can be found over the area. And the relationship will be used for the determination of $G_0(x,y)$ from $R_n(x,y)$. The regional sensible heat flux $H(x,y)$ is estimated from $T_{sfc}(x,y)$, surface and aero-logical data with the aid of so-called "tile approach" (Ma et al., 2010). The procedure to determine $R_n(x,y)$ and $H(x,y)$ in detail will be found in Ma's paper (Ma et al., 2011). The regional latent heat flux $\lambda E(x,y)$ can be derived as the residual of the energy budget theorem for land surface. If the evaporative fraction (*EF*) defining equation (Eq.(1)) is used to the MODIS and AVHRR pixel scale, it will be become:

$$\Lambda(x,y) = \frac{\lambda E(x,y)}{H(x,y) + \lambda E(x,y)} \tag{2}$$

EF value is between 0.0 and 1.0. Λ equaling 0.0 means that the surface is very dry, and no *ET* from surface. Λ equaling 1.0 means that surface is very wet, and there are maximum *ET* from the surface.

[Insert Fig.3 about here]

3. Satellite data and field observation data

Eight swath of MODIS data (17 January 2003, 14 April 2003, 23 July 2003 and 16 October 2003; 30 January 2007, 15 April 2007, 1 August 2007 and 25 October 2007) and four swath of AVHRR data (17 January 2003, 14 April 2003, 23 July 2003 and 16 October 2003) was chosen in this study for the comparison among winter, spring, summer and autumn. Same day images of AVHRR and MODIS data in 2003 (17 January 2003, 14 April 2003, 23 July 2003 and 16 October 2003) are used here to find which satellite data is better for the determination of *EF* over heterogeneous landscape of the Tibetan Plateau. More four images of MODIS data in 2007 is used here for the more validations of methodology due to more validation sites set up in 2007 over the Tibetan Plateau (Ma et al., 2008).

The most relevant in-situ data, collected at the key stations over the Tibetan Plateau to support the parameterization of *EF* and analysis of the MODIS and AVHRR images, consist of surface radiation budget components, surface radiation temperature, surface reflectance, vertical profiles of air temperature, humidity, wind speed and direction measured at the PBL towers, Wind Profiler and RASS, radiosonde and tethersonde, turbulent fluxes measured by eddy-correlation technique, soil heat flux, soil temperature profiles, soil moisture profiles, and the vegetation state. The key stations in the TORP are including BJ station (31.37^{0}N, 91.90^{0}E; elevation:4509m; land-cover: sparseness meadow), NAMOR(Nam Co Station for Multisphere Observation and Research, Chinese Academy of Sciences; 30.46^{0}N, 90.59^{0}E; elevation: 4730m; land-cover: sparseness meadow), QOMS(Qomolangma Station for Atmospheric and Environmental Observation and Research, Chinese Academy of Sciences; 28.21^{0}N, 86.56^{0}E; elevation: 4276m; land-cover: sparse grass-Gobi), SETS(Southeast Tibet Station for Alpine Environment Observation and Research, Chinese Academy of Sciences; 29.77^{0}N, 94.73^{0}E; elevation: 3326m; land-cover: grass land), Haibei (37.62°N, 101.30°E; elevation: 3220m; land-cover: grassy marshland), Maqu(33.89°N, 102.14°E; elevation: 3423m; land-cover: grassy marshland), D105 (33.06^{0}N, 91.94^{0}E; elevation: 5039m; land-cover: sparseness meadow), Amdo(32.14^{0}N, 91.37^{0}E; elevation: 4695m; land-cover: grassy marshland), NPAM (31.93^{0}N, 91.71^{0}E; elevation: 4620m; land-cover: grassy marshland) and ANNI(31.25^{0}N, 92.17^{0}E; elevation: 4480m; land-cover: grassy marshland).

4. Cases study and validation

Fig.4 and Fig.5 shows the distribution maps of net radiation flux R_n and evaporative fraction *EF* over the Tibetan Plateau area. The distribution maps of net radiation flux are shown here due to their key position in the procedure of determination of *EF* (Fig.3). The R_n and *EF* distribution maps are based on 2875×1487 pixels with a size about 1×1km^2. The estimated R_n and *EF* can be validated by the field measurements. In-situ data observed in nine stations of Haibei, Maqu, D105, Amdo, NPAM, BJ, NAMOR, QOMS and SETS in the TORP(Ma et al., 2008) are used for the validation in 2007 and four stations of D105, NPAM, ANNI and BJ of the CAMP/Tibet (Ma et al., 2005) are used for the validation in 2003. In Fig.6, the estimated results are validated against the measured values in the stations. The absolute percent difference (*APD*) was quantitatively measures the difference between the estimated results ($H_{derived(i)}$) and measured value($H_{measured(i)}$) here, and

$$APD = \frac{\left| H_{derived(i)} - H_{measured(i)} \right|}{H_{measured(i)}} . \quad (3)$$

The results show that: (1) The estimated R_n and *EF* in four different months over the Tibetan Plateau area are in good accordance with the land surface status. The Tibetan Plateau includes variety of land surfaces such as a large area of grassy marshland, some desertification grass-land areas, sparse grass-Gobi, sparseness meadow, many small rivers and lakes, snow (glacier) mountains, forest, and farmland etc. Therefore, these estimated parameters show a wide range due to the strong contrast of surface features over whole Tibetan Plateau. (2) The estimated pixel value (Fig.5) of *EF*s in summer(1 August 2007 and 23 July 2003)and autumn(25 October 2007 and 16 October 2003) are higher than that in winter(30 January 2007 and 17 January 2003) and spring (15 April 2007 and 14 April 2003). *EF*s in summer are mostly from 0.70 to 1.0, *EF*s in autumn are mostly around 0.60, *EF*s in spring are mostly around 0.50, *EF*s in winter are mostly around 0.30 (some of the *EF*s are 1.0 in the distribution maps indicating cloud-covering). The differences between 2007 image and 2003 image seem to be large is due to day-to-day variability. It means that there are much more evapotranspiration in summer and autumn than it in winter and spring in the Tibetan Plateau area. The reason is that most the land surface is wet and covered by green grass and growing vegetations in summer and autumn and it is dry and most the mountain ranges is covered by snow and ice during winter and spring on the Tibetan Plateau area. In other words, sensible heat and latent heat fluxes play different roles in the partition of net radiation flux in different month in the Tibetan Plateau: sensible heat flux plays the main role in winter and spring and latent heat flux plays the main role in summer and autumn**.** (3) The mean *EF* from MODIS data over the Tibetan Plateau area is increasing from January to April and August, then decreasing from October (Fig.5(b) and Fig.5(c)). They are 0.275, 0.415, 0.567 and 0.406 for 2007 and 0.271, 0.342, 0.569 and 0.347 for 2003. The mean *EF* from AVHRR data over the Tibetan Plateau area is also increasing from January to April and July, then decreasing from October. They are 0.267, 0.335, 0.502, and 0.331(Fig.5(a)). (4) Because of the land surface cover and property in spring (April) is much complex (there are ice, snow, seasonal and long-living permafrost, grass land and lakes etc existing in this month), therefore the *EF*s distribution in this month is also complicated (Fig.5). (5) The most estimated regional *EF*s with *APD* less than 10.0% at validation sites in the Tibetan Plateau are in good agreement with field measurements, except *EF*s estimated from AVHRR in ANNI (*APD*=13.0%) and D105(*APD*=11.0%) in 23 July 2003 (Fig.6). The reason is that the radiation transportation processes, using MODTRAN model, land surface and aero-logical data and the process of atmospheric boundary layer, such as using “tile approach” and the measuring and calculating accurately of wind speed u, air temperature T_a and specific humidity q at the reference height, zero-plane displacement d_0, aerodynamic roughness length z_{0m} and thermodynamic roughness length z_{0h}, the excess resistance for heat transportation kB^{-1} etc. in each tile were considered in more detail in our method (Fig.3). It is pointed that our proposed parameterization algorithm for *EF* is reasonable, and it can be used over the Tibetan Plateau area. (6) The retrieval *EF* and net radiation from MODIS are superior to those from AVHRR even the same methodology are used (Fig.4, Fig.5 and Fig.6). It means that the estimated values from MODIS are more closed to the “ground truth” measured in the validation stations (Fig.6). Many reasons might account for this, such as the image quality itself, the different Split Window Algorithms (SWAs), or the different algorithms for water vapor. It is therefore concluded that the MODIS data is the better one and it should be used widely for the determination of surface heat fluxes and *ET* over the Tibetan Plateau area.

[Insert Fig.4 about here]

[Insert Fig.5 about here]

[Insert Fig.6 about here]

5. Concluding remarks

In this study, the regional distributions of evaporative fraction (*EF*) over heterogeneous landscape of the Tibetan Plateau are estimated with the aid of MODIS data, AVHRR data and the *in-situ* data. And the MODIS data are the better one than AVHRR data for the estimating *EF* over heterogeneous landscape. Compared with the field measurements, the proposed *EF* has been proved to be a better index to getting related evapotranspiration (*ET*) over heterogeneous landscape.

Regionalizing the evapotranspiration (*ET*) over heterogeneous landscape is not an easy issue. The parameterization methodology presented in this research is still in developing stage due to only a single set of values at a specific time of specific day are used in this research. To reach more accurate regional *ET* and seasonal and annual variations of evapotranspiration over the Tibetan Plateau area, more field observations, more accurate radiation transfer models to determine the surface reflectance and surface temperature, more MODIS data, and other satellites such as ASTER (Advanced Spaceborne Thermal Emission and Reflection radiometer), Landsat-5 TM, Landsat-7 ETM, GMS (Geo-stationary Meteorological Satellite), and ATSR (Along

Track Scanning Radiometer) have to be used. These researches will be done in the next step.

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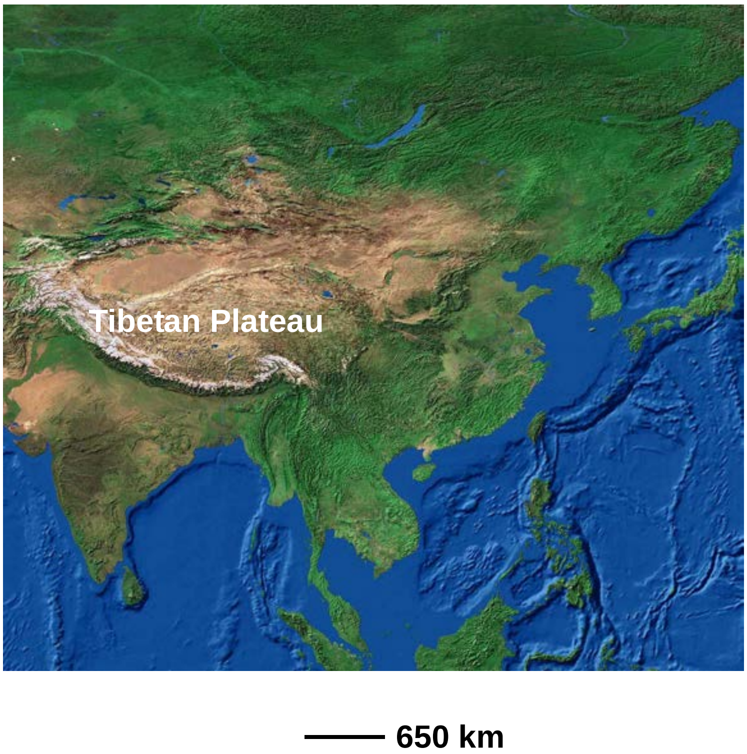


Fig.1 The location and landscape of the Tibetan Plateau.

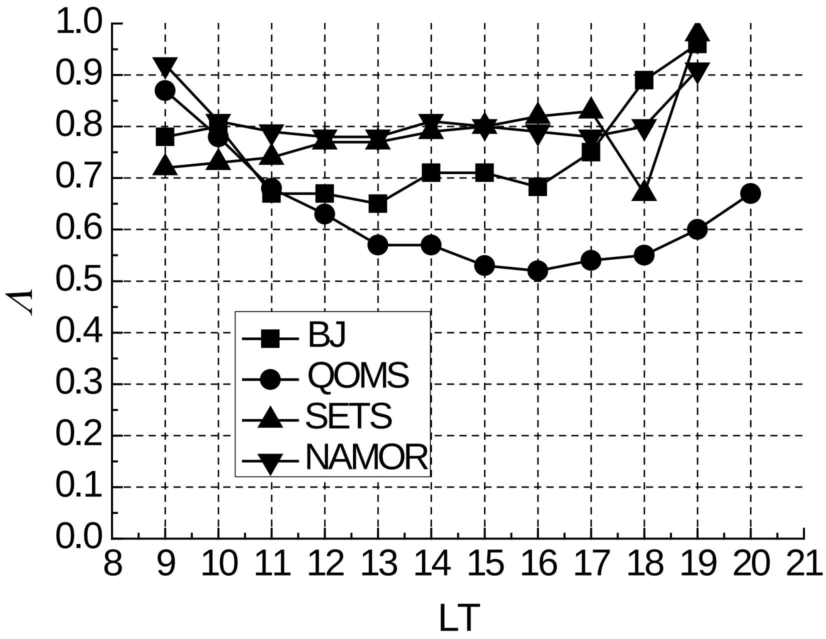


Fig.2 Diurnal variation of evaporative fraction (*EF*) at four stations of the Tibetan Plateau. LT is local time.

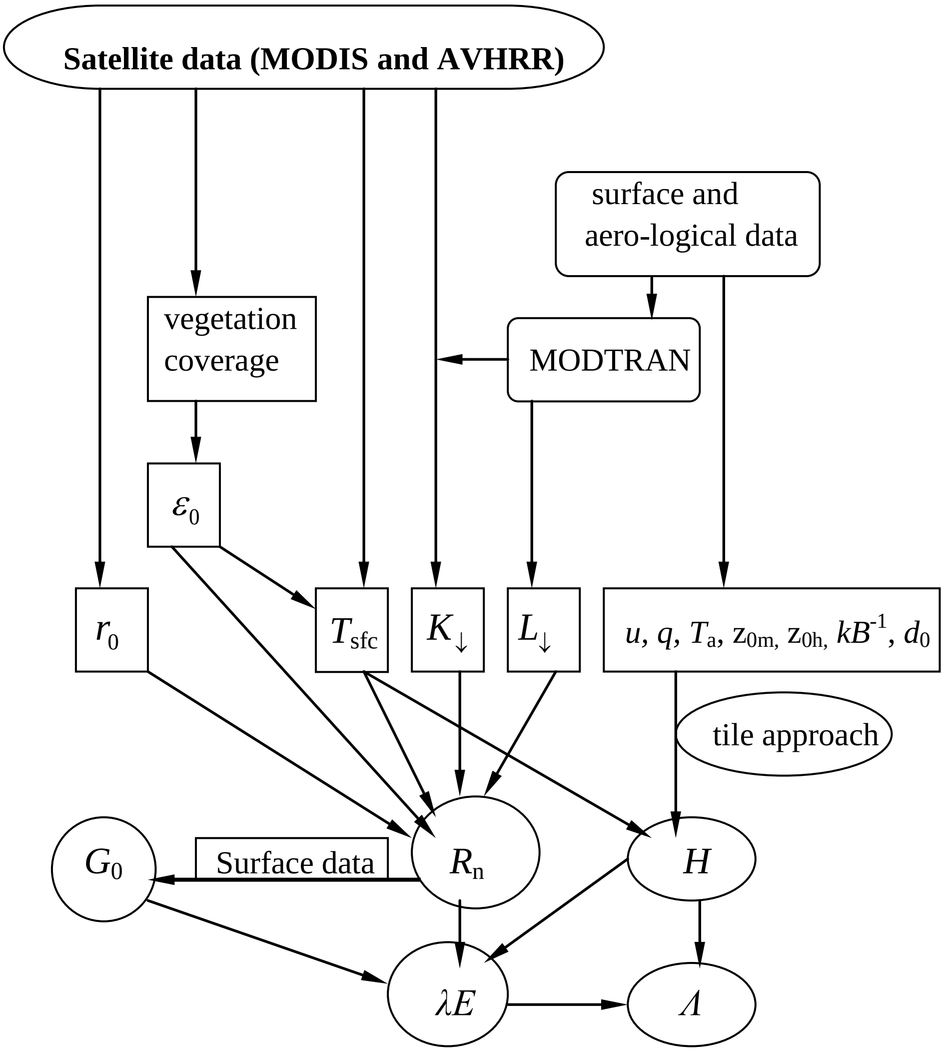
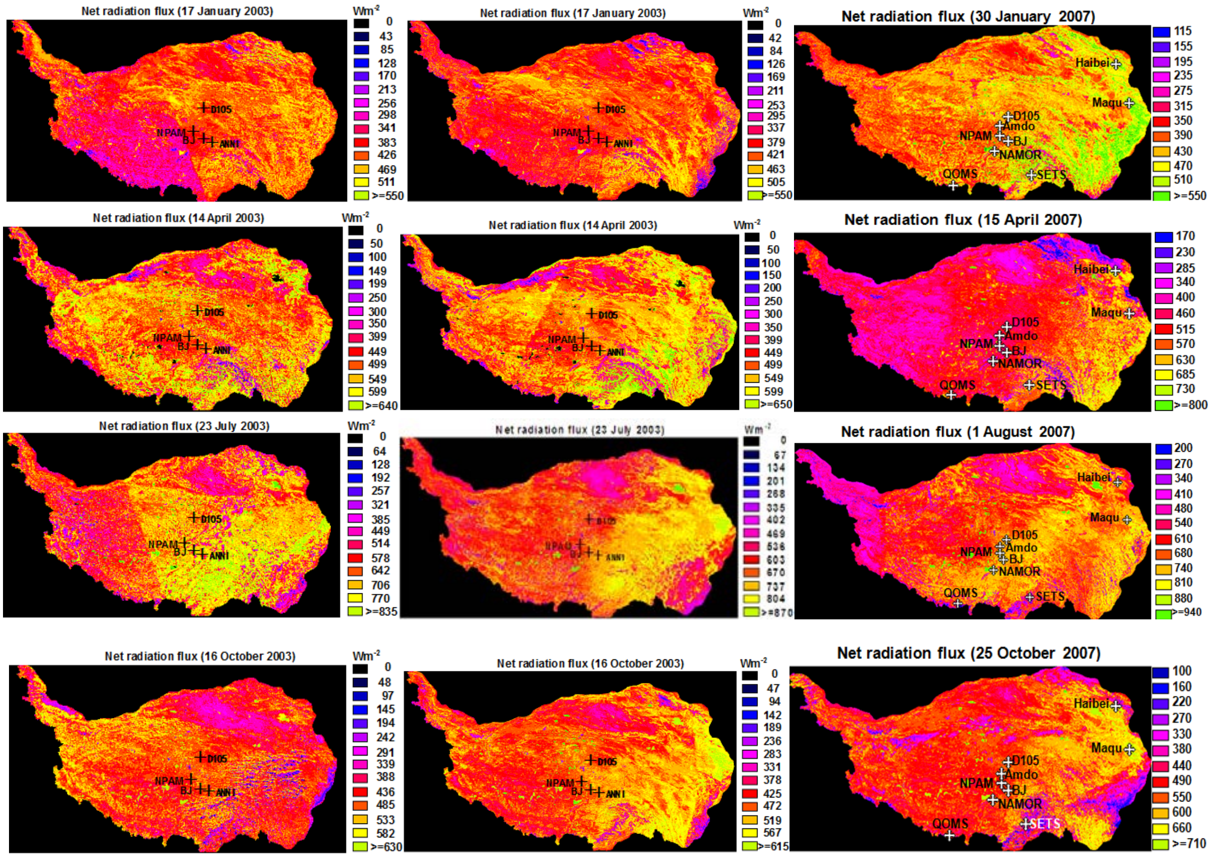


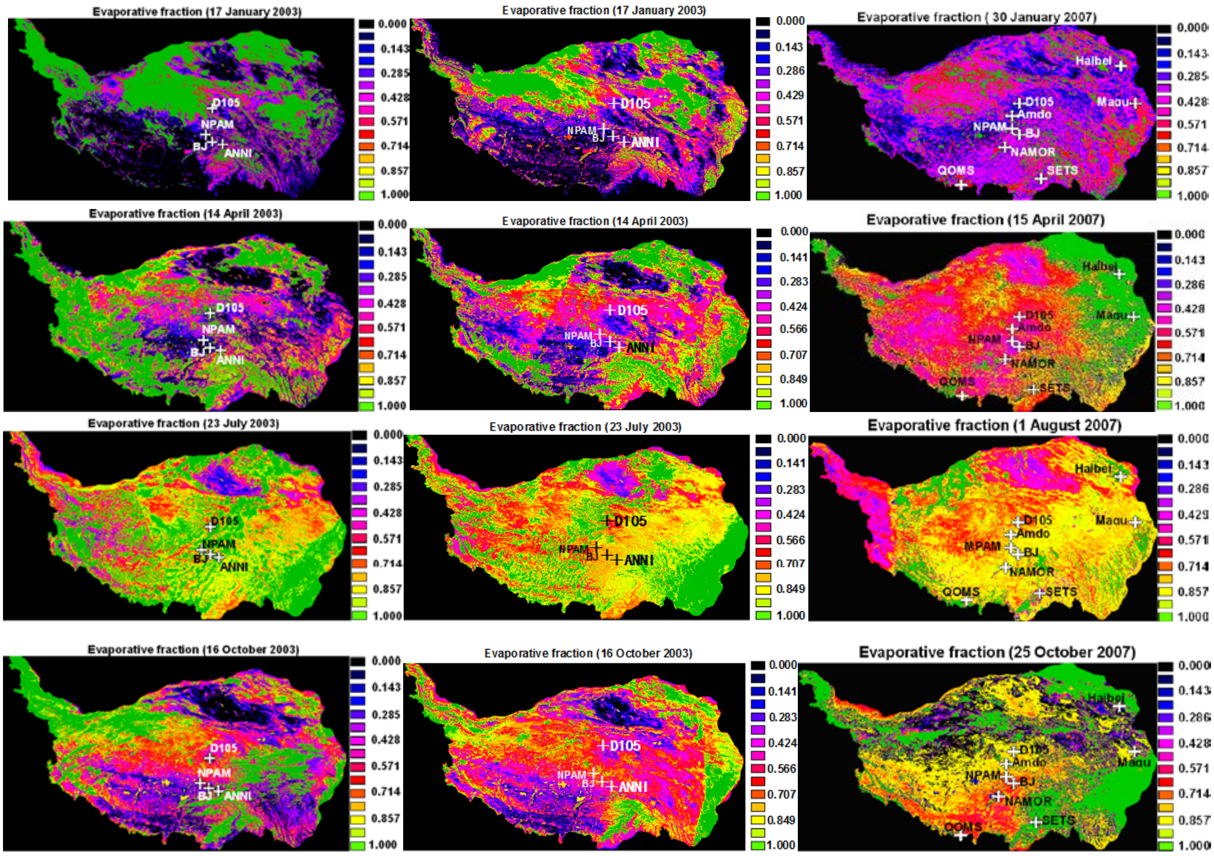
Fig.3 The diagram of parameterization procedure to determine evaporative fraction (*EF*) by combining satellite data with field observations.



(a) (b) (c)

Fig.4 The distribution maps of net radiation flux over the Tibetan Plateau area (73.5^0E—107.1^0E, 25.0^0N—40.1^0N).

(a)AVHRR-2003; (b) MODIS-2003; (c) MODIS-2007



(a) (b) (c)

Fig.5 The distribution maps of evaporative fraction (*EF*) over the Tibetan Plateau area (73.5^0E－107.1^0E, 25.0^0N－40.1^0N).

(a)AVHRR-2003; (b) MODIS-2003; (c)MODIS-2007

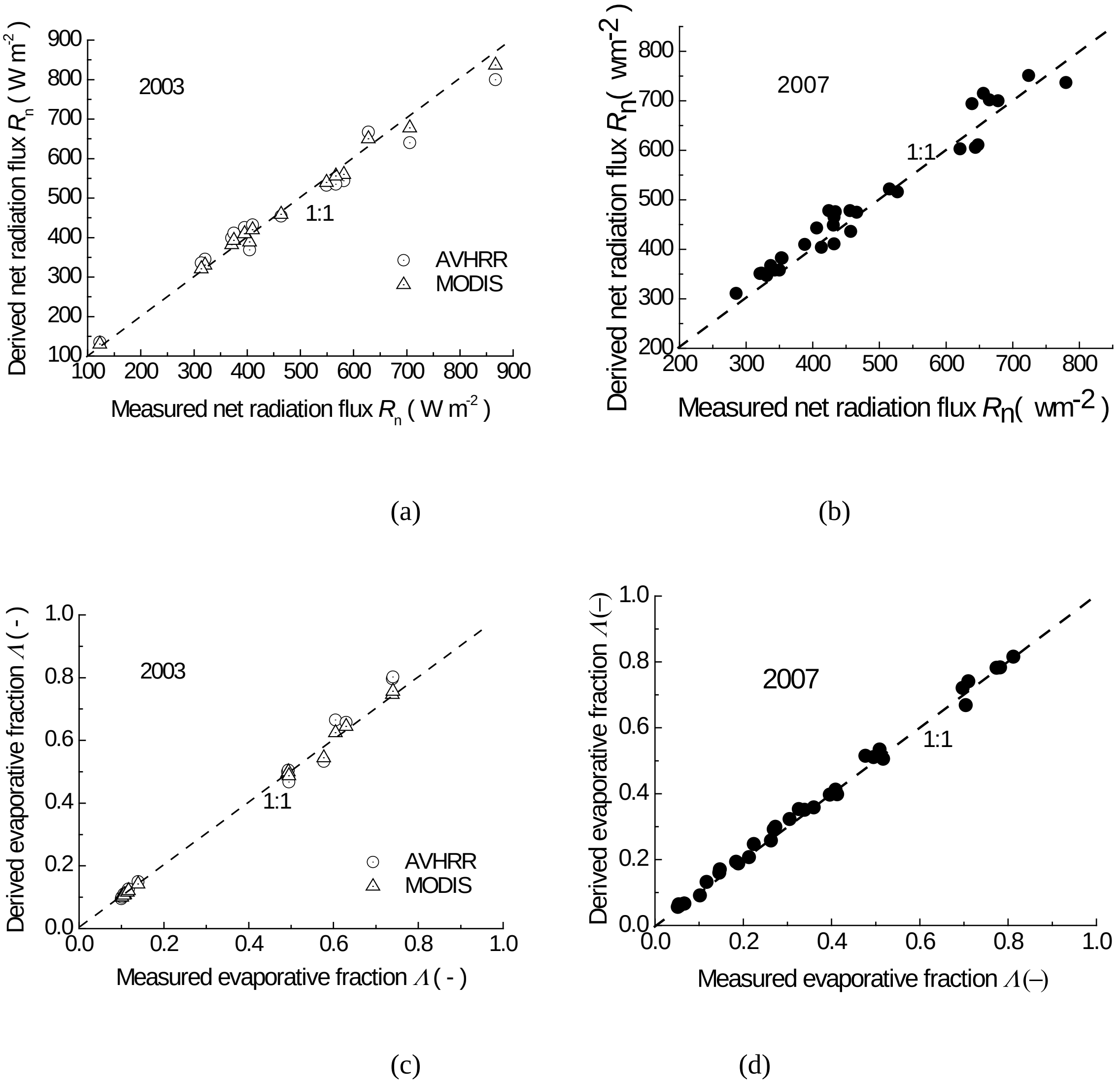


Fig.6 Comparison between the derived net radiation flux, evaporative fraction, and the field measurement values, together with a 1:1 line in 2003 and 2007.