Validating MODIS-derived land surface evapotranspiration with in situ measurements at two AmeriFlux sites in a semiarid region

Ronglin Tang,1,2,3 Zhao-Liang Li,1,2 and Kun-Shan Chen4

Received 28 May 2010; revised 1 October 2010; accepted 13 October 2010; published 22 February 2011.

[1] Reducing uncertainties in the estimation of land surface evapotranspiration (ET) from remote-sensing data is essential to better understand earth-atmosphere interactions. This paper demonstrates the applicability of temperature-vegetation index triangle (T–VI) method in estimating regional ET and evaporative fraction (EF, defined as the ratio of latent heat flux to surface available energy) from MODIS/Terra and MODIS/Aqua products in a semiarid region. We have compared the satellite-based estimates of ET and EF with eddy covariance measurements made over 4 years at two semiarid grassland sites: Audubon Ranch (AR) and Kendall Grassland (KG). The lack of closure in the eddy covariance measured surface energy components is shown to be more serious at MODIS/Aqua overpass time than that at MODIS/Terra overpass time for both AR and KG sites. The T–VI–derived EF could reproduce in situ EF reasonably well with BIAS and root-mean-square difference (RMSD) of less than 0.07 and 0.13, respectively. Surface net radiation has been shown to be systematically overestimated by as large as about 60 W/m². Satisfactory validation results of the T–VI–derived sensible and latent heat fluxes have been obtained with RMSD within 54 W/m². The simplicity and yet easy use of the T–VI triangle method show a great potential in estimating regional ET with highly acceptable accuracy that is of critical significance in better understanding water and energy budgets on the Earth. Nevertheless, more validation work should be carried out over various climatic regions and under other different land use/land cover conditions in the future.


I. Introduction

[2] Water and energy budgets at the soil-vegetation-atmosphere interface control the physical, chemical, and physiological processes occurring on the Earth’s surface. Estimation of evapotranspiration (ET) at regional/global scale is essential to better understand the mechanism of climate change and plays a crucial role in the water resources management, especially in arid and semiarid areas. Though some instruments have been designed to measure turbulent heat fluxes regularly (e.g., Bowen ratio system, eddy covariance system, and large aperture scintillometer system) or occasionally (aircraft- and radiosonde-based turbulence measurement sensors) over scales of hundreds to thousands of meters, these direct measurements are only conducted by flux network sparsely distributed on this planet or in large field programs. Furthermore, these measurements are generally spatially discontinuous and consequently cannot meet the requirement of a variety of ET-related studies. It is therefore necessary to make effort to estimate regional ET from various empirical and physical models. However, estimation of ET over regional scale is complicated by surface heterogeneity and is subject to the capability of acquiring spatially representative surface variables/parameters.

[3] Satellite remote sensing technology is recognized as the only viable means to be able to map temporally and spatially continuous patterns of regional ET on the Earth’s surface in a globally consistent and economically feasible manner [Kustas and Norman, 1996]. It can provide land surface parameters/variables required in the remotely sensed ET models, such as surface temperature (Ts), vegetation indices, and albedo. However, satellite remote sensing cannot measure ground-based aerodynamic resistance, surface roughness, air temperature, and wind speed, which are indispensible for estimating sensible heat flux at high to moderate pixel resolution from the commonly applied remotely sensed models. Therefore, evaluation of land ET as the residual of surface energy balance over large heterogeneous surfaces will inevitably incur a large degree of uncertainty and errors. In recent years, a parameterization of
Figure 1. A schematic $T_s$-$F_r$ triangular space (from Tang et al. [2010], reprinted with permission from Elsevier). Upper and lower blue solid lines represent observed dry and wet edges, respectively, from remotely sensed data; upper and lower red solid lines represent true dry edge with water stressed conditions in root zone soil water for different vegetation covers and true wet edge with sufficient water conditions, respectively (see section 2.1 for the meanings of symbols).

regional evaporative fraction (EF, defined as the ratio of latent heat flux to surface available energy) and ET based on primarily remotely sensed data has been proposed by Jiang and Islam [1999, 2001], namely the surface temperature-vegetation index ($T_s$-$VI$) triangle method. This $T_s$-$VI$ triangle method originates from the constructed triangle shape, when $T_s$ is plotted against VI under a full range of soil-moisture availability and fractional vegetation cover. The idea behind the $T_s$-$VI$ triangle method is that variation of surface temperatures from maxima to minima for a given VI is mainly due to the evaporative cooling effects when surface soil volumetric water content increases from 0 to 1.

A number of papers have shown that the $T_s$-$VI$ triangle method is reliable in estimating regional ET from a series of remote sensors, such as AVHRR, MODIS and MSG [Stisen et al., 2008; Wang et al., 2006; Batra et al., 2006; Venturini et al., 2004; Jiang and Islam, 2001, 2003; Jiang et al., 2009; Carlson, 2007]. Similar or better results in the estimates of regional ET have been achieved using the $T_s$-$VI$ triangle method, when compared with aerodynamic resistance energy balance method [Jiang and Islam, 2003; Jiang et al., 2004]. Using a semiempirical error analysis, Jiang et al. [2004] showed that the upper bound of absolute error in the $T_s$-$VI$–derived ET from the surface temperature-normalized difference vegetation index ($T_s$-SNDVI) triangle is within about 0.25 and decreases with an increase in SNDVI. The root-mean-square difference (RMSD) in validating the $T_s$-$VI$–derived ET is generally within 60 W/m² for most of the studies [Jiang and Islam, 1999, 2003; Batra et al., 2006; Stisen et al., 2008; Carlson, 2007] and Petropoulos et al. [2009] concluded from exclusive overviews that $T_s$-$VI$ triangle is capable of producing land surface energy fluxes and surface soil moisture availability, and has attracted continuous attention from the scientific community though some limitations exist. The notable advantage of this approach lies in the minimum data requirement in the model inputs, as well as simplicity and easiness to parameterize EF. The $T_s$-$VI$ triangle method has shown a great potential in the estimates of regional ET and EF over large heterogeneous surfaces for its easiness, simplicity, and relatively high accuracy.

Numerous studies [Price, 1990; Moran et al., 1994; Gillies and Carlson, 1995; Jiang and Islam, 1999] have concentrated on the study of spatial contextual information of remotely sensed $T_s$ and VI with an attempt to estimate regional ET and soil moisture content in the $T_s$-$VI$ triangular/trapezoidal diagram. Uncertainty in the $T_s$-$VI$ triangle method for ET estimation mainly comes from the determination of physics-based dry and wet edges (see Figure 1). Several papers [Jiang and Islam, 2001; Carlson, 2007] have reported identifying the wet edge (a nearly horizontal line representing potential ET and minimum surface temperature under different vegetation indices) from the average of inland water body $T_s$ or $T_s$ of well watered dense vegetation, whereas determination of dry edge (an oblique line representing minimum ET and maximum surface temperature under different vegetation indices) from the scatterplot of $T_s$ versus VI has been seldom mentioned in detail. However, determination of dry and wet edges in the $T_s$-$VI$ triangular space generally requires a large number of pixels indicative of two limiting conditions of ET and surface soil moisture. An iterative process, which can filter out spurious dry points and make the observed dry edge approach the true dry edge more closely, was proposed by Tang et al. [2010] to determine both dry and wet edges of the $T_s$-$VI$ triangle in arid and semiarid areas, where potentially evaporating pixels...
are not readily available over satellite pixel resolutions. An agreement was observed with RMSD of about 25 W/m² in the work by Tang et al. [2010], when the T_{s}-VI-derived sensible heat flux (H) was compared with in situ large aperture scintillometer measurements conducted during the Heihe field experiment from May to August 2008 in Northwest China. However, as indicated by Tang et al. [2010], more work on T_{s}-VI triangle method needs to be carried out to verify EF and relevant intermediate variables (surface net radiation, soil heat flux, H, and LE).

The objective of this paper is to test the robustness and to explore the applicability of the edges determination algorithm proposed by Tang et al. [2010] to different climatic regions through a thorough comparison with the tower-based eddy covariance measurements made at two AmeriFlux sites in Arizona. Eddy covariance measurements of sensible and latent heat fluxes have been conducted pervasively from global water and flux monitoring network, which provides good opportunity for validating regional ET derived from remotely sensed models. One concern with eddy covariance measurements is the energy closure problem, which will also be assessed in this paper. In addition, as estimation of EF is independent of surface net radiation estimates in the T_{s}-VI triangle method, evaluation of the algorithm used in this paper for the surface radiation estimation will be our another objective.

2. Parameterization of EF and ET
2.1. Overview of T_{s}-VI Triangle

In the work by Jiang and Islam [1999, 2001], a simple parameterization of EF and ET on the basis of an extension of Priestley-Taylor equation [Priestley and Taylor, 1972] with primarily remotely sensed data was proposed in the T_{s}-NDVI triangle space to estimate surface ET over the heterogeneous Southern Great Plains (SGP). Latent heat flux (ET in W/m²) in the T_{s}-VI triangle space can be expressed with the following equation:

$$\text{LE} = \phi \left[ (R_n - G) \frac{\Delta}{\Delta + \gamma} \right]$$  \hspace{1cm} (1)

where \(\phi\) is a parameter that absorbs the effects of aerodynamic and canopy resistances (dimensionless), \(R_n\) is the surface net radiation (W/m²), \(G\) is soil heat flux (W/m²), \(\Delta\) is the slope of saturated vapor pressure versus air temperature (kPa/°C), and \(\gamma\) is the Psychrometric constant (kPa/°C). Unlike the parameter \(\alpha\) in the Priestly Taylor equation \((\text{LE}_{\text{PT}} = \alpha(R_n - G)\Delta/(\Delta + \gamma))\), which is generally applicable under equilibrium wet surface conditions, parameter \(\phi\) in equation (1) can take a wider range of values extending from 0 (no evaporation) to \((\Delta + \gamma)/\Delta\) (maximum evaporation), when no significant advection and convection is present. Jiang and Islam [1999] demonstrated that the upper bound of \(\phi\) for each NDVI is very close to 1.26. Furthermore, Wang et al. [2006] has shown that in equation (1), an error of 1 K in air temperature merely results in an error of 0.0127\(\phi\) in EF. Taking into account the fact that large difference between \(T_s\) and air temperature will be concurrent with small value of \(\phi\), uncertainty of EF caused by the use of \(T_s\) instead of air temperature in the estimation of \(\Delta\) will generally be less than 5%. Parameter \(\phi\) is estimated according to a two-step linear interpolation scheme proposed by Jiang and Islam [1999] in the T_{s}-VI triangular space. From equation (1), EF, defined as the ratio of latent heat flux to surface available energy, can be easily derived as:

$$EF = \frac{\Delta}{\Delta + \gamma}$$  \hspace{1cm} (2)

Theoretical interpretation of the conceptual T_{s}-VI triangle method for the estimation of regional ET has been given in detail by Jiang et al. [2004], Stisen et al. [2008], and Tang et al. [2010], and will be discussed briefly as follows. For a surface pixel, ET can be decomposed into surface evaporation from the soil and transpiration of water from the vegetation. When pixels for different VIs are under sufficient water conditions, they will evaporate (transpire) potentially under given atmospheric forcing and form the wet edge with similar surface temperatures in the T_{s}-VI triangle. For a given VI, as a result of stressed surface soil water content, evaporation from the surface soil decreases progressively from the maximum value at wet edge to become negligible at dry edge, whereas transpiration does not change in a similar fashion because of the capability of green vegetation to extract water from the root zone. The integrated effects of the different physical processes in evaporation and transpiration result in a decreasing dry edge when the surface varies from bare soil to fully covered vegetation. However, in arid and semiarid areas, surface temperatures at the observed wet edge are generally higher than those at the true wet edge because of the unavailability of sufficient surface soil water content at the spatial scale of satellite pixel, while the observed dry edge can approach close to the true dry edge without consideration of water stress in the root zone soil. Under water stress conditions in the root zone soil, the surface temperature at dry edge will be much higher as a result of stoma closure from the vegetation, making the T_{s}-VI triangle more likely to be a trapezoid shape. Jiang et al. [2004] introduced a correction parameter in the transpiration of vegetation to consider the water stress conditions in the root zone soil. In arid and semiarid areas, it is feasible to take the observed dry edge in the remotely sensed T_{s}-VI triangle as the true dry edge, whereas the observed wet edge may not be representative of potentially evaporating pixels.

As described by Tang et al. [2010], in this paper, NDVI will also be replaced by \(F_r\) to construct the T_{s}-F_{r} triangular space. \(F_r\) can be expressed as a function of NDVI with the following equation [Carlson and Ripley, 1997]:

$$F_r = \left( \frac{NDVI - NDVI_{\text{min}}}{NDVI_{\text{max}} - NDVI_{\text{min}}} \right)^2$$  \hspace{1cm} (3)

where NDVI_{min} and NDVI_{max} are the minimum and maximum NDVIs corresponding to bare soil and fully vegetated surface, respectively. NDVI_{min} and NDVI_{max} are assigned to be 0.2 and 0.86, respectively, in this work as done by Prihodko and Goward [1997].

The processes to establish the T_{s}-F_{r} triangular space using MODIS data and determine both the dry and wet edges from the iterative algorithm can be found in the work by Tang et al. [2010]. Accordingly, once the dry and wet
edges in the $T_s$-$F_r$ triangle space are determined according to the algorithm developed by Tang et al. [2010], parameter $\phi$ can be obtained through a two-step linear interpolation scheme as follows (see also Figure 1). First, set the global minimum $\phi (\phi_{\text{min}})$ at $F_r = 0$ and maximum of $\phi (\phi_{\text{max}})$ at $F_r = 1$ to be 0 and 1.26, respectively, namely, $\phi_{\text{min}} = 0$, $\phi_{\text{max}} = 1.26$; then, determine $\phi$ value along the dry and wet edges by assuming that the minimum $\phi_{\text{min},i}$ at pixel $i$ ($F_r, T_s$) varies linearly with $F_r$ and that the maximum $\phi_{\text{max},i}$ is a constant along the wet edge, i.e., $\phi_{\text{min},i} = 1.26 F_r$ and $\phi_{\text{max},i} = \phi_{\text{max}} = 1.26$. Second, determine $\phi_i$ value for a given pixel $i$ whose position in the $T_s$-$F_r$ triangle space is ($F_r, T_s$), by assuming that the variation of $\phi_i$ from $\phi_{\text{min},i}$ to $\phi_{\text{max},i}$ is linear with the variation of surface temperature from $T_{\text{max},i}$ ($T_s$ on the dry edge at given $F_r$) to $T_{\text{min},i}$ ($T_s$ on the wet edge at given $F_r$), namely:

$$\phi_i = \frac{T_{\text{max},i} - T_s}{T_{\text{max},i} - T_{\text{min},i}} (\phi_{\text{max},i} - \phi_{\text{min},i}) + \phi_{\text{min},i}. \quad (4)$$

2.2. Estimation of Surface Net Radiation and Soil Heat Flux From MODIS Data

In this work, algorithms (hereafter referred to as Tang’s algorithm) proposed by Tang et al. [2006] and Tang and Li [2008], based fully on MODIS/Terra (or MODIS/Aqua) products, are employed to estimate the surface net shortwave ($R_{nsw}$) and longwave ($R_{lnw}$) radiation, respectively. Tang’s algorithm can be expressed as follows:

$$R_{nsw} = \frac{E_0 \cos \theta_s}{D^2} (\alpha' - \beta' r) \quad (5)$$

with $r = b_0 + \sum_{i=1}^{7} b_i \rho_i$

where $E_0$ is the solar irradiance at the top of atmosphere (TOA), $\theta_s$ is the solar zenith angle extracted from MODIS geolocation product (MOD03/MYD03), $D$ is the earth–sun distance in astronomical unit, $\alpha'$, $\beta'$ are parameters dependent on solar zenith angle and atmospheric precipitable water extracted from MODIS atmospheric precipitable water product (MOD05/MYD05) over land surface, $b_0$-$b_7$ are the coefficients depending on the view zenith angle and the solar zenith angle, both retrieved from MOD03/MYD03, and $\rho_i$ is the TOA narrowband reflectance measured by MODIS band $i$ ($i = 1$–7) retrieved from MODIS calibrated radiances product (MOD02/MYD02).

$$R_{lnw} = \varepsilon_s L_d - 5.67 \times 10^{-8} \varepsilon_s T_s^4 \quad (6)$$

where $L_d = c_0 + c_1 \times M_{29} + c_2 \times M_{34} + c_3 \times M_{33} + c_4 \times M_{36} + c_5 \times M_{28} + c_6 \times M_{31}$,

$$\varepsilon_s = 0.273 + 1.778 \varepsilon_{s1} - 1.807 \varepsilon_{s1} \varepsilon_{s2} - 1.037 \varepsilon_{s2} + 1.774 \varepsilon_{s2}^2 \quad (7)$$

in which $T_s$ is the surface temperature ($K$), $\varepsilon_{s1}$ and $\varepsilon_{s2}$ are the surface emissivity in MODIS channels 31 and 32 retrieved with $T_s$ from MOD11/MYD11, respectively, $c_i$ ($i = 0$–6) are coefficients depending on the view zenith angle and surface altitude, both extracted from MOD03/MYD03, $M$ is the TOA radiance measured by the MODIS thermal infrared channel extracted from MOD02/MYD02, and the number in the subscript indicates the thermal channel of MODIS sensor.

[11] The scheme of $Su$ [2002] relating the ratio of $G$ to $R_n$ ($F$) to fractional vegetation cover ($F_v$) is adopted to estimate soil heat flux ($G$):

$$\Gamma = G/R_n = \Gamma_v + (1 - F_v)(\Gamma_i - \Gamma_v) \quad (7)$$

where $\Gamma_v$ and $\Gamma_i$ are the fractions for the full vegetation cover and dry bare soil, respectively. According to the in situ point measurements, $\Gamma$ ranges from 0.05 for full vegetative cover ($F_v = 1$) to a maximum of 0.3 to 0.5 for dry bare soil ($F_v = 0$), depending on the types of soils [Daughtry et al., 1990; Li and Lyons, 1999]. In this work, as used by Tang et al. [2010], $\Gamma_v = 0.05$ and $\Gamma_i = 0.4$ (average of 0.3 and 0.5) are assumed.

[12] To objectively evaluate the performance of the $T_s$-$F_r$ triangle method in the estimates of regional ET using our proposed edges determination algorithm and by taking into account the large uncertainties in the estimated available surface energy, a comparison of EF between model estimates and in situ measurements is more descriptive of the validation results, as $T_s$-$F_r$ triangle derived EF is independent of the estimation of surface net radiation and soil heat flux in this work. Once the $T_s$-$F_r$ triangle space is established and dry and wet edges are determined based on the iterative process proposed by Tang et al. [2010] for each of the clear sky remotely sensed data sets, regional ET over the study area can be directly derived using equation (2) from the constructed $T_s$-$F_r$ triangular space without resorting to the estimation of surface available energy. With surface net radiation and soil heat flux estimated from remotely sensing products or measured at ground, latent heat flux (LE) can be calculated from equation (1) and sensible heat flux (H) can be measured as the residual of surface energy balance equation. Estimation of EF in the $T_s$-VI triangle method is obviously independent of $R_h - G$ estimation, as shown in equation (2). This is a notable advantage over surface energy balance residual method for regional ET estimates, because this method allows us to evaluate the model performance directly from the validation of EF with in situ measurements.

3. Study Area and Data

3.1. Study Area and In Situ Surface Energy Fluxes Measurements

[13] The study area in this work is located in the arid and semiarid region in the southwest of America. The area of the study region is about 77,000 km², and the latitude and longitude range from 30.5° to 32.5°N and 108° to 111.5°W, respectively. The main land cover types from MOD12 over this area are classified as shrublands, grasslands, and woody savannas. The surface elevation of the study area ranges mostly from 1000 to 1800 m. There are four AmeriFlux sites operating in this area. Surface elevation of these four sites varies from 991 to 1531 m. As variation of $T_s$ is assumed to be caused only by the evaporative cooling effects in $T_s$-VI
triangle method, pixels used to construct the triangular space should have similar surface elevations. Therefore, only measurements from two of the four AmeriFlux sites are employed in this work, namely Audubon Research Ranch (AR) (31.591°N, 110.509°W) and Kendall Grassland (KG) (31.737°N, 109.942°W).

[14] Surface energy flux measurements during years 2004–2007 from AR and KG sites located in Arizona in the study area (Figure 2) were collected for the purpose of evaluation and validation of the Tₚ–VI triangle method in the estimates of regional EF and ET, respectively. Table 1 gives the attribute of these two sites used in this work. Both the sites have been providing continuous observations of exchanges of energy, water, and CO₂ from a suite of instrumentations at ecosystem level since their establishment. Sensible and latent heat fluxes are estimated with eddy covariance analysis using data from 3-D sonic anemometer and temperature/humidity probe while surface net radiation and soil heat flux are estimated from measurements using net radiometer and soil heat flux plate, respectively. Mean annual precipitation, minimum temperature, and maximum temperature at AR (KG) site based on observations during years 2004–2007 were nearly 355 (235) mm, −8.1°C (−5.0°C) and 37.3°C (35.9°C), respectively. Vegetation type at AR site is desert grassland and tower height is about 4 m above the ground. Surface elevation of AR site is about 1469 m above the sea level. The KG site is located in a small intensively studied, experimental watershed within USDA-ARS’s Walnut Gulch Experimental Watershed. It is covered by warm desert C₄ grassland with a few shrubs interspersed. Surface elevation at this site is about 1531 m and instrumentation is mounted at a 6.4 m height above the ground. Level 3 and Level 2 (Level 3 files contain the same values as Level 2 files, but with quality flags assigned and NEE calculated using standardized techniques) 30 min averaged surface fluxes and meteorological data measured by eddy covariance system during years 2004–2006 at AR site and during years 2004–2007 at KG site were retrieved from the Carbon Dioxide Information Analysis Center (CDIAC) (ftp://cdiac.ornl.gov/pub/ameriflux/data/). In addition to surface energy (net radiation, soil heat flux, sensible heat flux and latent heat flux) and CO₂ fluxes, a number of meteorological variables were also measured by the site investigators and their associates, including air temperature, wind speed, and relative humidity [Scott et al., 2010].

3.2. Correction Methods

[15] Extensive studies [Twine et al., 2000; Massman and Lee, 2002; Anderson et al., 2000, 2008; Norman et al., 2003; Sánchez et al., 2008; Li et al., 2008] have reported the lack of closure in surface energy budget measured by eddy covariance technique. The sum of the measured sensible (H) and latent (LE) heat fluxes is generally less than the surface available energy (Rₐ − G), namely H+LE < Rₐ − G. The accuracy of eddy covariance measurements of LE at KG site has been evaluated by comparing them with those derived from water balance method on a seasonal or yearly basis [Scott, 2010]. However, LE (as well as H and EF) estimated in this paper will be an instantaneous (or 30 min averaged) value at satellite overpass time on different clear-sky days. It has been realized that at this point, it is impossible to assess the energy closure ratio at instantaneous (or 30 min averaged) scale because of the immeasurable water components in the water balance equation at such a short time scale. However, model estimates of turbulent fluxes on the basis of the surface energy balance by definition do enforce closure among fluxes. Therefore, the measured surface energy components balance should be ensured to make meaningful and convincible comparisons between the estimated and measured EF and energy components.

[16] In this study, we have applied two methods to correct the in situ eddy covariance measured turbulent heat fluxes to constrain closure in surface energy components. One is the Bowen ratio (BR) correction method and the other is the residual energy (RE) correction method [Twine et al., 2000; Anderson et al., 2000, 2008; Norman et al., 2003; Sánchez et al., 2008; Li et al., 2008]. In the BR correction method, the surface available energy is repartitioned into H and LE by conserving the measured Bowen ratio with the assumption that both the measured H and LE by eddy covariance system are underestimated proportionately, while in the RE correction method, the imbalance energy totally goes into latent heat flux by assuming that eddy covariance measured H is reliable and lack of closure is just because of the underestimation of LE. Comparisons of H, LE, and EF estimated from satellite data with in situ measurements will be conducted in this work with closure enforced using the BR and RE correction methods, respectively.

Table 1. Attribute of the Two AmeriFlux Sites Used in This Work

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Latitude, Longitude</th>
<th>Elevation (m)</th>
<th>Soil Type</th>
<th>Land Cover</th>
<th>Tower Height (m)</th>
<th>Annual Precipitation (mm)</th>
<th>Min/Max Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audubon Ranch</td>
<td>31.591°N, 110.509°W</td>
<td>1469</td>
<td>sandy loam</td>
<td>desert grassland</td>
<td>4</td>
<td>355</td>
<td>−8.1 37.3</td>
</tr>
<tr>
<td>Kendall Grassland</td>
<td>31.737°N, 109.942°W</td>
<td>1531</td>
<td>course loam</td>
<td>C₄ grassland</td>
<td>6.4</td>
<td>235</td>
<td>−5.0 35.9</td>
</tr>
</tbody>
</table>

Data involved are measured in situ from year 2004 to 2006 at Audubon Ranch site and from 2004 to 2007 at Kendall Grassland site, respectively.
3.3. Remote-Sensing Data

Remote-sensing data used in this paper were derived from MODIS sensors onboard both Terra and Aqua satellites. Terra and Aqua were launched in December 1999 and May 2002, respectively, and both have been collecting a variety of global data sets about Earth’s changing climate. MODIS sensor can provide data covering the entire surface of the Earth every 1–2 d in 36 discrete spectral bands ranging from visible, near-infrared, to thermal infrared with corresponding spatial resolution at 250, 500, and 1000 m, respectively. A total of 44 distinct products in HDF (Hierarchical Data Format) format produced from MODIS/Terra (Aqua) by the MODIS Science Team are available for the study of interactions among the Earth’s atmosphere, lands, and oceans.

MODIS/Terra (Aqua) data/products used in this paper include land surface temperature/emissivity (MOD11_L2 for Terra, MYD11_L2 for Aqua), surface reflectance (MOD09GA, MYD09GA), calibrated radiances (MOD02), geolocation (MOD03), and precipitable water (MOD05_L2) products. As mentioned earlier, the algorithm of 

\[ R_n \]

estimation applied in our study requires MOD02 (or MYD02 from Aqua) product as one of the inputs. However, there are many stripes in MODIS/Aqua band 6 in all of MYD02 data (Aqua data) because of the large number of dead detectors in band 6 of MODIS/Aqua instrument, thus making our 

\[ R_n \]

estimates unreliable from MODIS/Aqua data. Therefore, only land surface temperature/emissivity (MYD11_L2) and surface reflectance (MYD09GA) products from MODIS/Aqua satellite are used to estimate surface EF, which is independent of 

\[ R_n \]

estimation and can be directly derived from 

\[ T_e - VI \]

triangle space. Totally, 147 and 152 clear-sky (clear sky at satellite overpass time) daytime MODIS/Terra and Aqua products, respectively, from May to September during the years 2004–2007 over our study area were used to estimate surface fluxes of regional 

\[ R_n \]

, G, sensible and latent heat fluxes, and EF.

Both MOD11_L2 (MYD11_L2) and MOD09GA (MYD09GA) products were retrieved from Land Processes Distributed Active Archive Center (LP DAAC) (https://lpdaac.usgs.gov/). Level 2 MOD11_L2 (MYD11_L2) swath product was generated daily at 5 min increments using the generalized split window algorithm at 1000 m spatial resolution. Surface temperature, emissivity at channels 31 and 32, and view time (local solar time) were extracted from MOD11_L2 product for estimation of upward longwave radiation. MOD09GA (MYD09GA) provides 500 m surface spectral reflectance and 1 km observation and geolocation statistics for bands 1–7 in a daily gridded L2G product in the sinusoidal projection. These data are corrected for atmospheric gases and aerosols, and have been assessed over a widely distributed set of locations and time periods via several ground truth and validation efforts, and are ready for scientific applications. MODIS surface spectral reflectances at bands 1 (red band) and 2 (near-infrared band) were extracted from MOD09GA (MYD09GA) over the study area to estimate regional NDVI with a nominal spatial resolution of 500 m. The estimated NDVI was then resampled to spatial resolution of 1000 m by nonweighted average of the four nearest-sampled data.

MOD02, MOD03, and MOD05_L2 can be downloaded from LAADS (Level 1 and Atmosphere Archive and Distribution System) Web (http://ladsweb.nascom.nasa.gov/).

3.4. Statistical Measure

A number of quantitative indices of Willmott [1982] have been adopted in this study to evaluate the model performance. These indices are

\[
\text{Mean bias error} : BIAS = \frac{1}{n} \sum_{i=1}^{n} (P_i - O_i) / n
\]

(8a)

\[
\text{Root – mean – square difference} : RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (P_i - O_i)^2} / n^{1/2}
\]

(8b)

\[
\text{Mean absolute difference} : MAD = \frac{1}{n} \sum_{i=1}^{n} |P_i - O_i| / n
\]

(8c)

where \( n \) is the number of observations, and \( P_i \) and \( O_i \) are the model-predicted and observed variables, respectively.

4. Results and Discussions

4.1. Energy Closure of In Situ Measurements

Energy closure of in situ measurements was examined only on clear-sky days when MODIS/Terra or MODIS/Aqua passed over AR and KG sites. During MODIS/Terra overpass time period, there were 89 clear-sky days available for AR site and 131 clear-sky days for KG site. During MODIS/Aqua overpass time period, there were 92 clear-sky days available for AR site and 129 clear-sky days for KG site.

On the whole, \( H + LE < (R_n - G) \) could generally be observed at both the sites (Figure 3). The slope (S) and coefficient of determination (\( R^2 \)) from the linear least squares fit at the MODIS/Terra (Aqua) overpass times at AR site were 0.94 (0.27) and 0.46 (0.07), whereas at KG site, S = 0.71 (0.63) and \( R^2 = 0.31 (0.23) \), respectively. Closure ratio (CR) ranged from 0.30 to 1.13 with energy residual (\( E = R_n - G - H - LE \)) varying from -41.4 to 341.9 W/m² at AR site, and CR ranged from 0.56 to 1.21 with an energy residual varying from -70.2 to 204.3 W/m² at KG site. From Figure 3, one can see that at AR site, \( H + LE \) approaches more closely to \( R_n - G \) with the mean energy residual (\( E \)) of 59.4 W/m² and mean CR (\( \bar{C}R \)) of 0.86 at MODIS/Aqua overpass time, when compared with the observations at MODIS/Terra overpass time with \( E = 126.7 \) W/m² and \( \bar{C}R = \).
Figure 3. Closure of surface energy budget from eddy covariance measurements at (a) Audubon Research Ranch and (b) Kendall Grassland sites (E with an overline, E\text{max}, and E\text{min} represent the mean, maximum, and minimum of E defined as surface available energy (surface net radiation minus soil heat flux, R\text{n} − G) minus the sum of sensible heat flux and latent heat flux (H+LE), respectively).

For the KG site, E = 57.4 W/m\textsuperscript{2} and \text{CR} = 0.87 at MODIS/Aqua overpass time and E = 94.3 W/m\textsuperscript{2} and \text{CR} = 0.76 at MODIS/Terra overpass time. Furthermore, \text{CR} derived from the combination of Terra and Aqua overpass-time observations at AR site was 0.79 with a standard deviation (SD) of about 0.12, whereas at KG site, \text{CR} was 0.82 and SD was 0.12. At AR site, surface available energy measured at MODIS/Aqua overpass time was found to be generally less than that at MODIS/Terra overpass time, while at KG site, opposite results were observed. The lack of closure can be possibly attributed to a number of factors, including measurement errors in R\text{n} and G, inconsistent source areas between eddy covariance sensible and latent heat fluxes and surface available energy, length of sampling intervals, sensor separation, and dispersive fluxes that are not sampled by eddy covariance system.

4.2. Comparison of Surface Net Radiation and Surface Available Energy

[25] Surface net radiation (R\text{n}) estimated from Tang’s algorithm at Terra overpass time has been compared with in situ R\text{n} in Table 2 and Figure 4a. The algorithm of R\text{n} estimation works better at KG site than that at AR site. At AR site, Tang’s algorithm overestimates R\text{n} in most cases with a BIAS of 61.5 W/m\textsuperscript{2} and RMSE of 84.1 W/m\textsuperscript{2}, while at KG site, the BIAS and RMSD are 17.7 W/m\textsuperscript{2} and 56.7 W/m\textsuperscript{2}, respectively (Table 2). Likewise, coefficient of determination (R\textsuperscript{2}) could be observed to increase from 0.338 at AR site to 0.504 at KG site. Moreover, agreement between the estimated and measured R\text{n} can be obtained if the measured R\text{n} is less than about 550 W/m\textsuperscript{2} (Figure 4a) at both the sites. However, if the surface net radiation is larger, then the discrepancy between the estimated and measured R\text{n} will be larger. This may result from different spatial scales representative of remotely sensed data and in situ data. Regardless of the topographic effects and other instrumental uncertainties, Tang’s algorithm seems to likely overestimate R\text{n} even if R\text{n} measured at both the sites is reliable and pixel-scale representative (lack of relevant knowledge and information makes further investigation of sources of errors and uncertainties extremely difficult, if not impossible).

[26] From Figure 4b, one can observe that the surface available energy (R\text{n} − G) retrieved from MODIS/Terra data using equations (5), (6), and (7) is on the whole underestimated when compared with in situ R\text{n} − G measurements by about −107.1 and −53.0 W/m\textsuperscript{2}, on an average, and RMSD = 114.9 and 68.2 W/m\textsuperscript{2} at AR and KG sites, respectively. Calibration of R\text{n} and G estimations at the two sites may improve the model performance. However, the objective of this paper is not to tune the model to agree with in situ measurements at those two specific sites, but instead to test the generality of the model. Some authors [Lloyd et al., 1997; Baldocchi, 2003; Anderson et al., 2007] have questioned the spatial representativeness of point-scale G measurements to the source area of net radiometer mounted on the tower, especially over heterogeneous surfaces. Large discrepancies between the estimated and measured R\text{n} − G at both the sites may result from the overestimation of R\text{n} and distinct spatial scale of averaged G over a remote-sensing pixel with heat flux plate measurements. In addition, turbulent sensible and latent heat fluxes measured in situ by the

Table 2. Statistical Measures\textsuperscript{a}

<table>
<thead>
<tr>
<th>Site</th>
<th>Variable</th>
<th>BIAS (W/m\textsuperscript{2})</th>
<th>RMSD (W/m\textsuperscript{2})</th>
<th>MAD (W/m\textsuperscript{2})</th>
<th>R\textsuperscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR</td>
<td>R\text{n}</td>
<td>61.5</td>
<td>84.2</td>
<td>64.8</td>
<td>0.338</td>
</tr>
<tr>
<td>AR</td>
<td>R\text{n} − G</td>
<td>−107.1</td>
<td>114.9</td>
<td>107.2</td>
<td>0.185</td>
</tr>
<tr>
<td>KG</td>
<td>R\text{n}</td>
<td>17.7</td>
<td>56.7</td>
<td>45.7</td>
<td>0.504</td>
</tr>
<tr>
<td>KG</td>
<td>R\text{n} − G</td>
<td>−53.0</td>
<td>68.2</td>
<td>56.5</td>
<td>0.293</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Estimated instantaneous surface net radiation (R\text{n}) and available energy (R\text{n} − G) (P, in equation (8)) from MODIS/Terra data with eddy covariance measured data (Q, in equation (8)) at Audubon Research Ranch (AR) and Kendall Grassland (KG) sites; R\textsuperscript{2} is coefficient of determination; BIAS, RMSD, and MAD are defined in equation (8).
eddy covariance system mainly come from upwind area, which may be different from the footprint of both \( R_n \) and \( G \) measurements. The inconsistent source area (footprint) among the in situ measurements of surface energy components may complicate the energy closure analysis and evaluation of model performance.

4.3. Validation of the \( T_s-F_r \)-Derived Surface Turbulent Heat Fluxes and EF

[27] The \( T_s-F_r \)-derived EF is evaluated with the in situ EF corrected by the BR and RE correction methods shown in Figures 5 and 6 for both AR and KG sites. At MODIS/Terra overpass time, agreement between the \( T_s-F_r \)-derived EF and in situ EF corrected by the BR correction method was found with a BIAS of 0.065 and RMSD of 0.120 for AR site, and BIAS = 0.039 and RMSD = 0.100 for KG site. At MODIS/Aqua overpass time, similar performance was obtained with BIAS = 0.067, RMSD = 0.125 at AR site and BIAS = 0.058, RMSD = 0.103 at KG site, when in situ EF measurements from eddy covariance system were corrected for energy closure using the BR correction method. With the in situ EF corrected by the RE correction method, the differences were relatively larger than those with in situ EF corrected by the BR correction method. For each site, the \( T_s-F_r \)-derived EF against the in situ EF corrected by the BR correction method gave the highest \( R^2 \) (with an exception for MODIS/Aqua at AR site) and the lowest BIAS (with an exception for MODIS/Aqua at AR site) and RMSD. Enforcing energy closure with the RE correction method seemed to deteriorate statistics of RMSD and BIAS (with an exception for MODIS/Aqua at AR site). The \( T_s-F_r \) triangle method performed slightly better in the estimation of EF at KG site than it did at AR site.

[28] One can see from Figure 7a that the \( T_s-F_r \)-derived EF from MODIS/Terra products agrees well with that derived from MODIS/Aqua products with a BIAS (EF at MODIS/Aqua time as predicted variable (P), EF at MODIS/Terra time as measured variable (O)) of \(-0.016\) and RMSD of about 0.087 at AR site and BIAS = -0.014 and RMSD = 0.088 at KG site. Furthermore, it can be observed that \( R^2 \) at AR and KG sites is 0.485 and 0.642, respectively. These statistics have demonstrated the reliability and robustness of our edges determination in the \( T_s-F_r \)-triangle space to derive regional EF with MODIS data alone. Furthermore, inter-comparison of the in situ EF measured at MODIS/Terra and MODIS/Aqua overpass times shown in Figure 7b yields agreement with high \( R^2 \), low intercept, and slope approaching unity of the linear regression at both the sites.
implying, to some extent, the constant EF found in a number of studies at daylight time during a clear-sky day. Comparisons between the satellite-derived and in situ–measured H and LE corrected using the BR and RE correction methods at MODIS/Terra overpass time for AR and KG sites are shown in Figures 8, 9a, and 9b, respectively. At both the sites, it can be noted that there is a tendency to seriously underestimate the in situ H corrected by the BR correction method with a BIAS of $-113.9 \text{ W/m}^2$ and RMSD of 127.1 W/m$^2$ at AR site, and a BIAS of $-60.5 \text{ W/m}^2$ and RMSD of 79.8 W/m$^2$ at KG site, as a result of the underestimation of surface available energy and overestimation of EF. Furthermore, comparison of the estimated H from the $T_s$-$F_r$ triangle method with the in situ H corrected by the RE correction method showed RMSD of about 57 W/m$^2$ and absolute BIAS of less than 20 W/m$^2$ at both AR and KG sites. Comparisons between estimated LE from the $T_s$-$F_r$ triangle method and in situ LE using the BR correction method showed a BIAS of 6.8 W/m$^2$ and RMSD of 45.4 W/m$^2$ at AR site, and BIAS of 7.5 W/m$^2$ and RMSD of 36.8 W/m$^2$ at KG site. For the comparison of in situ LE using the RE correction method, BIAS was $-100.9 \text{ W/m}^2$ and RMSD was 112.0 W/m$^2$ at AR site, while BIAS was $-72.2 \text{ W/m}^2$ and RMSD was 88.1 W/m$^2$ at KG site.

[30] We noticed that the estimated H from the $T_s$-$F_r$ triangle method agrees better with the in situ H corrected by the RE method, while the comparison of the estimated LE with the in situ LE corrected by the BR method produces better results for both AR and KG sites. This inconsistent statistics is primarily due to the overestimation (underestimation) of in situ EF corrected by the BR (RE) correction method at a Audubon Research Ranch site and (b) Kendall Grassland site.

Figure 6. Comparisons of the $T_s$-$F_r$-derived evaporative fraction (EF) from MODIS data with in situ eddy covariance measurements corrected using the Bowen ratio correction method at (a) Audubon Research Ranch site and (b) Kendall Grassland site.

Figure 7. (a) Intercomparison of the $T_s$-$F_r$-derived EF from MODIS/Terra and MODIS/Aqua daytime products at Audubon Research Ranch and Kendall Grassland sites. (b) Same as Figure 7a but with in situ EF corrected using the Bowen ratio correction method.
method and underestimation of surface available energy in this work. As

\[ LE = EF \times (R_n - G) \]  

\[ H = (1 - EF) \times (R_n - G) \]

an error on EF (\( \Delta EF \)) and \( R_n - G \) (\( \Delta(R_n - G) \)) leads to an error on LE (\( \Delta LE \)) and H (\( \Delta H \)) as

\[ \Delta LE = \Delta EF \times (R_n - G) + EF \times \Delta(R_n - G) \]  

\[ \Delta H = -\Delta EF \times (R_n - G) + (1 - EF) \times \Delta(R_n - G) \]

Therefore, as predicted by equations (10a) and (10b), the effect of underestimation of measured \( R_n - G \) on estimated H and LE is respectively amplified (counteracted) and counteracted (amplified) in different magnitudes by overestimation (underestimation) of in situ EF corrected by the BR (RE) correction method for both AR and KG sites. The negative feedback on the estimated H (LE) generates better comparison results between estimated H (LE) and in situ H (LE) corrected by the RE (BR) correction method. Correspondingly, the positive feedback on the estimated LE (H) will make it deviate more seriously from in situ LE (H) corrected with the RE (BR) correction method. As mentioned earlier, the BR correction method actually produces the best agreement between estimated and measured EF.

4.4. Comparison of H and LE Estimated Using the In Situ–Measured \( R_n - G \)

[31] As the algorithms used in this paper significantly underestimate the surface available energy (\( R_n - G \)) with respect to the in situ–measured \( R_n - G \), evaluation of the model performance of the T_s-F_r triangle space using MODIS/Terra (T) data with in situ eddy covariance data (O_i in equation (8)) at Audubon Research Ranch and Kendall Grassland sites (see Figure 5 for variable definitions).

Figure 8. Statistics of BIAS and RMSD in comparison of instantaneous sensible (H) and latent heat (LE) fluxes (\( P_i \) in equation (8)) estimated from T_s-F_r triangle space using MODIS/Terra (T) data with in situ eddy covariance data (O_i in equation (8)) at Audubon Research Ranch and Kendall Grassland sites (see Figure 5 for variable definitions).

Figure 9. Comparisons of surface turbulent heat fluxes estimated from MODIS/Terra data with the in situ measurements corrected for inclosure using the Bowen ratio correction method at Audubon Research Ranch and Kendall Grassland sites (a) for sensible heat flux (H) and (b) for latent heat flux (LE).
and RMSD = 40.2 W/m², R² = 0.669 at KG site. At MODIS/Aqua overpass time, comparison of the estimated H and LE from in situ–measured Rn − G with in situ H and LE corrected by the BR correction method at AR site showed a BIAS of −27.0 W/m² for in situ H and 27.0 W/m² for in situ LE with RMSD = 51.2 W/m², while at KG site, BIAS was −24.7 W/m² for in situ H and 24.7 W/m² for in situ LE with RMSD = 44.1 W/m². The model performed better at KG site with R² = 0.702 and 0.593 for H and LE comparisons, respectively, than at AR site with corresponding R² = 0.384 and 0.446.

It is evident that both the estimated H and LE yield the best agreement with eddy covariance measurements corrected using the BR correction method at MODIS/Terra and MODIS/Aqua overpass times, which is in accordance with the findings from comparison between the estimated and measured EF. Statistical measure of sensible and latent heat fluxes corrected using the BR correction method, shown in Figures 10 and 11, is found to greatly improve when compared with that given in Figures 8 and 9, owing to the more reliable surface available energy that originated from measurements at AR and KG sites. It can be noticed that at both the AR and KG sites, the statistics of RMSD and MAD in comparison with the in situ H corrected by the RE and BR methods are respectively the same as those in comparison with the in situ LE corrected by the RE and BR methods. Furthermore, it can be observed that the BIAS is at the same value, but with opposite (plus and minus) signs. This may be explained by the application of surface available energy from the same source (in situ–measured Rn − G) to estimate turbulent heat fluxes of H and LE.

Several aspects make Tₐ-VI triangle method advantageous to the single- and two-source surface energy balance residual methods (e.g., SEBS [Su, 2002] and N95 [Norman et al., 1995]) in the estimation of regional ET over large heterogeneous areas. First, complex parameterization of aerodynamic resistance and extensive ground-based measurements can be avoidable in Tₐ-VI triangle method. Second, the accurate atmospheric correction and absolute accuracy in Tₐ are not indispensable. Third, EF can be derived directly from Tₐ-VI triangle without resorting to estimating surface energy budget. Finally, estimation of instantaneous EF is independent of that of surface available energy, which can help evaluate the performance of Tₐ-VI triangle from the validation of EF. When compared with the simplified empirical equation [Jackson et al., 1977], Tₐ-VI triangle does not require site-specific tuning of model parameters. With regard to the comparison results shown earlier, several notes have been taken here. A prerequisite for the Tₐ-VI triangle method to estimate regional ET and EF is that similar atmospheric forcing over the study area should be ensured [Jiang and Islam, 2001]. However, this is contradictory to the requirement of large number of pixels over flat surfaces for the utilization of Tₐ-VI triangle method. The iterative process developed by Tang et al. [2010] with Tₐ-Fᵢ triangle can filter out the spurious dry points and guarantee the closer approaching of the observed dry edge to the true dry edge with surface soil moisture equal to zero and no water stress conditions in the root zone soil water content. Another advantage of the iterative process is that wet edge in the Tₐ-Fᵢ triangle can be determined from the intersection of dry edge with Fᵢ = 1, assuming no differences in the surface temperatures under potentially evaporating (transpiring) conditions for different vegetation covers. This advantage is especially useful for the application of Tₐ-VI triangle method to estimate ET in arid and...
5. Conclusions

This work has made an attempt to further investigate the robustness of the edges determination algorithm in the $T_s$–$F_r$ triangular space proposed by Tang et al. [2010] with the in situ measurements from May to September during the years 2004–2007 at two AmeriFlux sites in Arizona. Totally, 89 and 131 MODIS/Terra and 92 and 129 MODIS/Aqua overpass time observations (corresponding to the clear-sky daytime data) were respectively used at AR and KG sites to validate the $T_s$–$F_r$–derived EF (and $R_n$, $G$, $H$, and LE if possible) using the in situ measurements. Tang’s algorithm was shown to systematically overestimate the surface net radiation ($R_n$) in general. When compared with surface measurements collected in this work, the overestimation can be as large as about 60 W/m². However, agreement between the estimated and in situ–measured $R_n$ can be obtained if the measured $R_n$ is less than about 550 W/m². Large discrepancies between the estimated and measured surface available energy ($R_n - G$) with absolute BIAS greater than 50 W/m² at AR and KG sites might result from the overestimation of $R_n$ and distinct spatial scale of averaged soil heat flux ($G$) over a remote-sensing pixel with in situ heat flux plate measurements.

When compared with the RE correction method, the BR correction method was found to yield better agreement for the comparison of the $T_s$–$F_r$–derived EF with in situ EF ($EF_{\text{in situ}}$) from eddy covariance system, which is in agreement with the findings by Twine et al. [2000]. The $T_s$–$F_r$ triangle method with edges determined by the iterative process proposed by Tang et al. [2010] could reproduce $EF_{\text{in situ}}$ reasonably well with BIAS and RMSD of less than 0.07 and 0.13, respectively. Misleading comparison results between the satellite–derived and in situ–measured sensible and latent heat fluxes ($H$ and $LE$) were observed because of the combined effect of underestimation of $R_n - G$ and overestimation of EF at both AR and KG sites. Therefore, accuracy of satellite–derived surface available energy should be ensured to obtain accurate regional turbulent heat fluxes.

Figure 11. Comparisons of sensible (H) and latent (LE) heat fluxes estimated using in situ–measured surface available energy instead of the estimated one with in situ H and LE corrected by the Bowen ratio correction method (a and b) for Audubon Research Ranch site and (c and d) for Kendall Grassland site.
H and LE, using T$_s$-F$_i$ triangle method. When measurements of surface available energy at both the sites and the T$_s$-F$_i$-derived EF were used to estimate the turbulent heat fluxes, agreement could be obtained with RMSD of less than 54 W/m$^2$ for AR site and 45 W/m$^2$ for KG site if estimated H and LE were compared with in situ eddy covariance measurements corrected by the BR correction method at both MODIS/Terra and MODIS/Aqua overpass times.

[15] This paper, together with the work by Tang et al. [2010], has successfully demonstrated the applicability and robustness of the iterative process proposed in the determination of dry and wet edges in the T$_s$-F$_i$ triangular space in arid and semiarid areas. To make the T$_s$-VI triangle method more general and operational in the estimates of regional ET and EF under different climatic conditions, future work must be focused on the edges determination and exploration of nonlinearity in the T$_s$-VI triangle using a soil-vegetation-atmosphere transfer model.

[19] Acknowledgments. Special thanks are given to the principal investigators, Russell L. Scott and Tilden Meyers, who are responsible for the micrometeorological and surface flux measurements from AmeriFlux sites used in this analysis. We would like also to thank Russell L. Scott who gave his permission to use the data and provided some valuable suggestions on our work. Three anonymous reviewers are acknowledged for their valuable comments that have greatly improved the paper. This work was partly supported by the National Natural Science Foundation of China under grant 40871169, by the State Key Laboratory of Resource and Environment Information System under grant 088RAA005SA and partly supported by the National Science Council, Taiwan, under grant NSC99–M008–009. R. Tang is financially supported by China Scholarship Council for his stay at LSHT, France.

References


K.-S. Chen, Center for Space and Remote Sensing Research, National Central University, Chung-Li, 320, Taiwan.

Z.-L. Li and R. Tang, State Key Laboratory of Resources and Environmental Information System, Institute of Geographic Sciences and Natural Resources Research, Beijing 100101, China. (lizl@igsnrr.ac.cn)