An intercomparison of three remote sensing-based energy balance models using Large Aperture Scintillometer measurements over a wheat–corn production region

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1. Introduction

The accurate partitioning of surface available energy into sensible and latent heat fluxes over various scales has been recognized as being critical in understanding the impact of soil–vegetation–atmosphere interactions on local and regional weather and climate (Idso et al., 1975). Within the last 20 years a great deal of work has demonstrated with varying degrees of success the usefulness of radiometric surface temperature to estimate regional turbulent heat fluxes from remotely sensed data. Recently, Glenn et al. (2007), Kalma et al. (2008) and Li et al. (2009) have provided comprehensive overviews on the advantages, limitations and uncertainties of a wide variety of methods for evapotranspiration (ET) estimation using remotely sensed surface temperature data, in many cases in combination with ground-based near surface observations. Primary approaches for estimating ET using remotely sensed data span a range in model complexity and input requirements, and can be roughly grouped into one-source energy balance models incorporating hydrologic extremes or wet/dry end members defined by ET at potential rate (wet end member) and no ET (dry end member) (e.g., SEBS, Su, 2002; SEBL, Menenti & Choudhury, 1993; SEBAL, Bastiaanssen et al., 1998; S-SEBI, Roerink et al., 2000; METRIC, Allen et al., 2007), two-source energy balance models (among others, N95, Norman et al., 1995; ALEXI, Anderson et al., 1997) considering soil and vegetation contributions to the composite radiometric surface temperature and surface energy fluxes, and models based on distributions in surface temperature–vegetation index triangle/trapezoid space (Gillies et al., 1997; Moran et al., 1994; Price, 1990). All three types of models rely on the surface energy
balance, expressed as follows (neglecting canopy heat storage, photosynthetic uptake and horizontal advection),

\[ R_n = G + H + LE \]  

(1)

where \( R_n \) is the surface net radiation, \( G \) is the soil heat flux, \( H \) and \( LE \) are the sensible and latent heat fluxes, respectively (all in units of W/m²).

The Surface Energy Balance System (SEBS), developed by Su (2002), is one of the representative derivatives of a one-source bulk transfer equation for estimating turbulent sensible and latent heat fluxes at regional scale. The core of the SEBS model lies in 1) the determination of roughness length for heat transfer based on a quadratic weighting from \( k_B^{-1} \) calculated over full canopy cover and bare soil surface and 2) a new formulation of evaporative fraction on the basis of energy balance at limiting cases. Uncertainty in the estimated turbulent heat fluxes in the SEBS from the input variables is minimized by consideration of the energy balance at the limiting cases. However, the significant number of required parameters, observables, and relatively complex solution of the turbulent heat fluxes has made it difficult to apply SEBS operationally over large heterogeneous surfaces.

Estimation of excess resistance to account for the distinction between momentum and heat transfer mechanisms and omission of angular effects on remotely sensed surface temperature are two sources of uncertainty encountered in the estimation of sensible heat flux for models that treat the soil–vegetation system as a single source. Different parameterizations of excess resistance (\( f_e \)), expressed in terms of \( \ln(z_{min}/z_{se}) \) (\( z_{min} \) and \( z_{se} \) are the surface roughness length for momentum and heat transfer, respectively) or the so-called \( k_B^{-1} \) parameter (Garratt & Hicks, 1973), have been proposed with varying degree of complexities in the bulk formulation of land–atmosphere energy transfer (Allen et al., 1989; Lhomme et al., 2000; Su, 2002). Over homogeneous, dense and well-watered vegetation surfaces, angular effects seem to be less important whereas for partially vegetated surfaces, Hall et al. (1992) and Li et al. (2001, 2004) have reported differences as large as 5 K between remotely sensed surface temperature (\( T_s \)) measured at nadir and at 60° off nadir. No universal optimal view angle has been identified for obtaining remotely sensed surface temperature or surface-air temperature difference to derive regional components of surface energy balance (Anderson et al., 1997).

In order to incorporate effects of view geometry and avoid empirical corrections for the excess resistance, a Two-Source Energy Balance (TSEB) model was proposed by Norman et al. (1995) to accommodate the difference between radiometric and aerodynamic surface temperatures and to partition surface energy balance of soil and vegetation components using surface temperature data either from a single view angle or from multiple view angles. The TSEB does not require a priori calibration, in contrast to one-source models that attempt to address the differences between aerodynamic and radiometric temperatures and associated excess resistance empirically (Kustas & Anderson, 2009). Anderson et al. (2005) reported that consideration of vegetation clumping in the TSEB improves the estimates of turbulent heat fluxes at both local and watershed scales, in areas of partial vegetation cover. Compared with other types of remotely sensed ET formulations, two-source energy balance models have been shown to be robust for a wide range of landscape and hydrometeorological conditions (Kustas & Norman, 1997).

While both one- and two-source energy balance models require similar inputs related to land cover and vegetation properties, the TTV approach uses the surface temperature–vegetation index (T–VI) triangle/trapezoid space to define model variables and hence relies on remotely sensed data alone. Jiang and Islam (1999) extended the utility of the Priestley–Taylor equation by linearly interpolating the Priestley–Taylor coefficient between the dry and wet edges in the T–VI triangle space. Evaporative fraction (EF, defined as the ratio of latent heat flux to surface available energy) in the T–VI triangle method can be derived independently from the estimation of surface net radiation and soil heat flux, which is a marked distinction from one- and two- source energy balance models. Jiang et al. (2004) concluded from a theoretical perspective that similar or better results could be achieved for the estimation of latent heat flux over large areas using the T–VI triangle method. A significant number of papers have demonstrated the reliability of T–VI triangle (or its variants) method in estimating regional ET from remote sensing systems such as Advanced Very High Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectroradiometer (MODIS) and Meteosat Second Generation (MSG) (Batra et al., 2006; Jiang & Islam, 2001; Stisen et al., 2008; Tang et al., 2010; Venturini et al., 2004). However, poor results found by Choi et al. (2009) to obtain reliable ET from the triangle method indicate that this method requires further testing.

Although each of the models described earlier has successfully been validated using flux observations from a series of field experiments worldwide and from flux networks such as AmeriFlux, few efforts have been made to evaluate and inter-compare the performance of such models (Choi et al., 2009; Timmermans et al., 2007).

The objective of this paper is to evaluate the performance of these three models (T–VI triangle method, SEBS and TSEB models) using a Large Aperture Scintillometer (LAS) observation system operated to measure sensible heat flux (H) regularly at the MODIS pixel resolution at the Yucheng comprehensive experimental station in Northern China. Measurements were conducted from the end of April through September, 2009 for a winter wheat/summer corn crop rotation. This work differs from prior comparison studies in at least two aspects: 1) an inter-comparison of three models is performed using LAS measurements at moderate resolution scale, which differs from most prior studies that focused on the high (<100 m) resolution remote sensing data (i.e., Landsat TM/ETM+ or aircraft imagery), and 2) data collected at the validation site cover a broad range in vegetation growth stages under pasture conditions from early May through late September, 2009. In Section 2, a brief description of the key formulations used by the three remote sensing-based energy balance models is provided. In Section 3, the near-surface meteorological and ground vegetation measurements and relevant TERRA/MODIS data at the Yucheng station acquired during the wheat and corn growth period are described. In Section 4, the results of ground measurements of surface fluxes are compared to the model estimates and a sensitivity analysis of the model inputs of MODIS data is presented. Summary and conclusion are provided in Section 5.

2. Model descriptions

2.1. T–VI triangle method (TTV)

For the past 20 years, the relationship between remotely sensed surface temperature versus vegetation index or cover has been proposed as a means to estimate regional surface resistance to ET (Nemani & Running, 1989), surface moisture availability (Carlson et al., 1995; Nemani et al., 1993), air temperature (Priebkdo & Goward, 1997), and to monitor land use/land cover change (Lambin & Ehrlich, 1996) and drought (Wan et al., 2004). Jiang and Islam (1999, 2001) adapted the Priestley–Taylor equation for use with the triangular shape obtained by plotting remotely sensed surface temperature against vegetation index,

\[ LE = \phi \left( (R_n - G) \frac{\Delta}{\Delta + \gamma} \right) \]  

(2)
where φ is a combined parameter that accounts implicitly for the effects of aerodynamic and canopy resistances (dimensionless), Δ is the slope of saturated vapor pressure versus air temperature (kPa/°C), γ is the psychrometric constant (kPa/°C). Unlike the parameter α in the Priestley–Taylor equation (\(LE_{PT} = \alpha(R_n - G)/\Delta(\Delta + \gamma)\)), which is generally applicable with a value of 1.26 under wet surface conditions, the parameter φ in Eq. (2) can take a wider range of values extending from 0 (no evaporation) to ~1.26 (potential evaporation). From Eq. (2), EF can be easily derived as,

\[
EF = \frac{\Delta}{\Delta + \gamma} \phi
\]

(3)

A scatterplot of surface temperature (\(T_s\)) versus vegetation index (VI) is characterized by the physics-based dry edge (an oblique line representing minimum ET and maximum surface temperature for different vegetation indices) and wet edge (a nearly horizontal line representing potential ET and minimum surface temperature for different vegetation indices). For a theoretical interpretation of the conceptual \(T_s\)-VI triangle in the estimation of latent heat flux, the reader is referred to the work of Jiang et al. (2004), Stisen et al. (2008), and Tang et al. (2010).

The parameter φ is obtained by a two-step linear interpolation scheme proposed by Jiang and Islam (2001) using the \(T_s\)-VI triangle (see Fig. 1). First, global minimum and maximum φ are set to be \(\phi_{\text{min}} = 0\) at dry bare soil and \(\phi_{\text{max}} = 1.26\) at the wet edge at maximum VI. Second, φ is linearly interpolated between \(\phi_{\text{min}} = 0\) and \(\phi_{\text{max}} = 1.26\) with VI along the dry edge for the lower bound of φ (\(\phi_{\text{min},i}\)) and between \(\phi_{\text{min},i}\) and upper bound of φ (\(\phi_{\text{max},i}\)) with surface temperature for any pixel at each VI interval. Jiang and Islam (1999) demonstrated that the upper bound of φ (\(\phi_{\text{max},i}\)) for each VI (Normalized Difference Vegetation Index) is very close to 1.26. For a given pixel i (\(T_s\), VI), φ is expressed as,

\[
\phi = \frac{T_{\text{max},i} - T_s}{T_{\text{max},i} - T_{\text{min},i}} (\phi_{\text{max},i} - \phi_{\text{min},i}) + \phi_{\text{min},i}
\]

(4)

where \(T_{\text{max},i}\) and \(T_{\text{min},i}\) are the maximum and minimum surface temperatures for given VI corresponding to values at the dry and wet edges, respectively.

While the \(T_s\)-VI triangle method does not require explicit parameterization of aerodynamic resistance, a large enough representative area indicative of limiting conditions of ET and surface soil moisture but with similar atmospheric forcing is essential in determining both the dry and wet edges. Tang et al. (2010) proposed an iterative process to determine both the dry and wet edges of the \(T_s\)-VI triangle in arid and semi-arid areas where potentially evaporating pixels are not readily available over satellite pixel resolutions. In this work, the dry edge will be determined using this iterative process and we will identify the wet edge by using an average remotely sensed in-land water body temperature as proposed by Jiang et al. (2009).

As EF for each pixel over the study area can be derived directly from remotely sensed \(T_s\)-VI triangle space based on Eqs. (3–4), we choose an algorithm making use of remotely sensed parameters alone to estimate surface net radiation (\(R_n\)) for the TVT. The algorithm will be briefly described in Section 3.3. Soil heat flux (\(G\)) is generally estimated as a fraction of \(R_n\) using remote sensing-based methods. The scheme of Su (2002) relating the ratio of \(G\) to \(R_n\) (\(\Gamma\)) to fractional vegetation cover (\(f_c\)) is adopted in the \(T_s\)-VI triangle,

\[
\Gamma = \frac{G}{R_n} = \Gamma_f + (1 - \Gamma_f)(\Gamma_s - \Gamma_f)
\]

(5)

where \(\Gamma_f\) and \(\Gamma_s\) are the fractions for the full vegetation cover and dry bare soil, respectively, and \(\Gamma_f = 0.05, \Gamma_s = 0.22\) according to the in-situ point measurements at the Yucheng station.

2.2. Surface Energy Balance System (SEBS)

In SEBS, a distinction is made between planetary boundary layer (PBL) and atmospheric surface layer (ASL) similarity. Inputs to the SEBS include remotely sensed land cover parameters (leaf area index, vegetation height and structure), ground-based meteorological measurements (wind speed, humidity, air temperature), and land surface temperature. See Su (2002) for details on SEBS model formulations and input requirements.

In the ASL, the relationships between fluxes and the profiles of the mean wind speed and mean temperature are as follows,

\[
u = \frac{u}{k} \left[ \ln \left( \frac{z - d}{z_0m} \right) - \Psi_m \left( \frac{z - d}{L_v} \right) + \Psi_m \left( \frac{z_0m}{L_v} \right) \right]
\]

(6)

\[
\theta_s - \theta_a = \frac{H}{k_u \rho C_p} \left[ \ln \left( \frac{z-d}{z_0m} \right) - \Psi_h \left( \frac{z-d}{L_v} \right) + \Psi_h \left( \frac{z_0m}{L_v} \right) \right]
\]

(7)

In Eqs. (6) and (7), \(z\) is the wind speed and air temperature measurement height (m), \(u\) is the friction velocity (m/s), \(k = 0.4\) is the von Karman’s constant, \(d\) is the zero plane displacement height (m), \(\theta_s\) is the potential temperature at the surface (K), \(\Psi_m\) and \(\Psi_h\) are the stability correction

![Fig. 1. A schematic diagram of the conceptual dry and wet edges and the two-step linear interpolation scheme in the surface temperature versus vegetation index triangular space (see the text for the definitions of symbols).](image-url)
functions for momentum and sensible heat transfer, respectively. H is the sensible heat flux (W/m²), L is the Obukhov length (m) defined as

\[ L = - \frac{\rho C_p u^* h}{\kappa g H} \]  

(8)

where g is the acceleration due to gravity (m/s²) and \( h \) is the potential virtual temperature near the surface (K). If the reference height is greater than ASL height, bulk atmospheric boundary layer similarity stability corrections are adopted; otherwise, Monin–Obukhov similarity is used. The stability function criterion proposed by Brutsaert (1999) is used to determine whether Monin–Obukhov surface layer similarity or bulk atmospheric boundary layer similarity stability corrections should be applied. Sensible heat flux is derived independently of other surface energy balance terms by iteratively solving Eqs. (6)–(8). The roughness length for heat transfer (\( z_{0h} \)) is estimated from

\[ z_{0h} = \frac{z_{0m}}{\exp(kB_{1}^{-1})} \]  

(9a)

\[ z_{0m} = \frac{1}{8h} \]  

(9b)

\[ kB_{1}^{-1} = \frac{kC_d}{4C_t u_w (1-e^{-n_{e2}/2})} f_t^c + 2f_c k_{\text{act}} \frac{z_{0m}}{C_t^c} + kB_{2}^{-1} f_s^2 \]  

(10)

where h is the vegetation height (m), \( f_t \) is the fractional canopy coverage and \( f_c \) equals 1–\( f_t \). \( C_t \) and \( C_{1}^{c} \) are the heat transfer coefficient of the leaf and the soil, respectively. \( u(h) \) is the horizontal wind speed at the canopy top (m/s), \( n_{e2} \) is the within–canopy wind speed profile extinction coefficient. The first term in the right-hand side of Eq. (10) comes from the work of Choudhary and Monteith (1988) for full uniform canopy cover, the third term (\( kB_{2}^{-1} \)) is from that of Brutsaert (1982) for a bare soil surface, and the second term describes the interaction between the vegetation and bare soil.

Within the same scene, the two hydrologic extremes or wet and dry end members are defined in the SEBS model. At the dry end, ET is assumed to be zero due to the limitation of soil moisture and H reaches its maximum value (i.e., \( ET_{\text{dry}} = 0 \), \( H_{\text{dry}} = R_n - G \)), while at the wet end, ET occurs at the potential rate (\( ET_{\text{wet}} \)), which can be calculated with a combination equation similar to the Penman–Monteith equation (Monteith, 1965) assuming that the bulk internal resistance is zero, and H reaches its minimum value \( H_{\text{wet}} \). The sensible heat flux at dry and wet limits can be expressed as

\[ H_{\text{dry}} = R_n - G \]  

(11)

\[ H_{\text{wet}} = \left( R_n - G - \frac{\rho C_p e_s - e}{\tau_{\text{rew}}} \right) / \left( 1 + \frac{\Delta}{\gamma} \right) \]  

(12)

where \( \rho \) is the density of air (kg/m³), \( C_p \) is the specific heat capacity at constant pressure (J/(m·K)), \( \tau_{\text{rew}} \) is the external resistance at wet limit (s/m), \( e_s \) and \( e \) are the saturated and actual vapor pressure (kPa), respectively. Surface energy balance at limiting cases is used to estimate the evaporative fraction. The relative evaporative fraction (\( EF_{r} \)) is defined as

\[ EF_{r} = \frac{ET}{ET_{\text{wet}}} = 1 - \frac{ET_{\text{dry}} - ET}{ET_{\text{wet}}} \]  

(13a)

By a series of substitutions into Eq. (13a) with surface energy components at the dry and wet ends, \( EF_{r} \) can be expressed as

\[ EF_{r} = 1 - \frac{H - H_{\text{wet}}}{H_{\text{dry}} - H_{\text{wet}}} \]  

(13b)

and evaporative fraction (EF) is given as

\[ EF = \frac{EF_{r} - 1}{F_{\text{wet}}} \]  

(14)

We will apply the same formulations of surface net radiation and soil heat flux for SEBS as that for the TTV model. SEBS has been successfully used to estimate daily, monthly and annual evaporation in a semiarid environment. Su (2002) demonstrated that SEBS could be used for both local and regional scale ET estimation under all atmospheric stability regimes.

2.3. Two-Source Energy Balance model (TSEB)

To accommodate the difference between radiometric and aerodynamic surface temperatures, Norman et al. (1995) developed a two-source energy balance model (N95), which partitions both energy fluxes and surface temperature into soil and vegetation components and explicitly treats the difference in coupling between these components and the atmosphere, related to the so-called excess resistance. The two-source model also accounts for the view geometry of directional radiometric surface temperature by computing representative soil and canopy temperatures. Kustas and Norman (2000) made several critical modifications to N95 for two-source fluxes predictions under sparse canopy covered conditions. The modified algorithms compute the divergence of net radiation with a more physically based algorithm and consider variability in clumping effects and the Priestley–Taylor coefficient. The Atmosphere–Land Exchange Inverse (ALEXI) uses the TSEB formulations as part of the land surface scheme, which is coupled to a planetary boundary layer growth model driven by measurements of the morning rise of surface temperature acquired at 1.5 and 5.5 h past sunrise from a geostationary satellite. By solving the heat budget of the PBL, an air temperature is computed by the model at the top of the ASL (~50 m above ground level), hence removing the need for the measurements of ASL air temperature. Moreover by using time-differences in land surface temperature, ALEXI output is relatively insensitive to errors in the absolute surface temperature caused by uncertainties in surface emissivity and atmospheric corrections on the remotely sensed surface temperatures. The TSEB and ALEXI modeling systems have been validated over a wide variety of landscapes and environmental conditions (Anderson et al., 1997, 2008, 2005; Chávez et al., 2009; Choi et al., 2009; French et al., 2005; Gonzalez-Dugo et al., 2009; Kustas & Anderson, 2009; Kustas & Norman, 2000; Norman et al., 1995; Timmermans et al., 2007).

In thermal-based two-source energy balance modeling schemes, the ensemble directional radiometric surface temperature (\( T_{\text{RAD}}(\theta) \)) is determined by the respective fraction of soil and vegetation viewed by a radiometer, which is expressed as

\[ T_{\text{RAD}}(\theta) = [f_{\theta}(\theta) T_{c}^{\theta} + (1 - f_{\theta}(\theta)) T_{s}^{\theta}]^{1/n} \]  

(15)

where \( T_{c} \) and \( T_{s} \) are the vegetation canopy and soil component temperatures, respectively, n is usually set to 4 for 8–14 μm and 10–12 μm wavelength bands, \( f(\theta) \) is the fraction of canopy in the field of view of the radiometer and can be computed by combining view zenith angle (\( \theta \)) and fractional vegetation cover (\( f_{c} \)) when assuming a clumped canopy with a spherical leaf angle distribution,

\[ f_{\theta} = 1 - \exp\left( -0.5 \times \Omega(\theta) \times \text{LAI} \right) \]  

(16)

\[ f_{c} = 1 - \exp(-0.5\text{LAI}) \]  

(17)

where \( \Omega(\theta) \) is the clumping factor as a function of view zenith angle and the ratio of vegetation height versus width of clumps (see Kustas...
and Norman (2000) and Anderson et al. (2005) on details of how to estimate $\Omega$. LAI is the leaf area index (m$^2$/m$^2$). Low values of $\Omega$ represent stronger clumping, $\Omega = 1$ indicates a homogeneous canopy with a random distribution of leaf area, and $\Omega > 1$ for more regularized distributions (Anderson et al., 2005).

With the assumption that there is interaction and flux exchange between soil and canopy layers, $H$ in the TSEB model can be distributed between soil and vegetation using the following series resistance formulations,

\begin{equation}
H = H_s + H_c
\end{equation}

\begin{equation}
H_s = \rho c_p \frac{T_s - T_{AC}}{R_s}
\end{equation}

\begin{equation}
H_c = \rho c_p \frac{T_c - T_{AC}}{R_c}
\end{equation}

where $H_s$ and $H_c$ are the sensible heat fluxes arising from canopy and soil, $R_s$ and $R_c$ are the total boundary layer resistance of the complete canopy of leaves and resistance to heat transfer immediately above the soil surface, respectively. The series resistance network in the TSEB model has been found under sparsely-vegetated conditions to be more reliable than parallel resistance network (Kustas & Norman, 2000).

The other energy balance components of the total soil and vegetation canopy system are calculated from the following formulas, Soil and canopy energy budgets,

\begin{equation}
R_{n,s} = H_s + LE_s + G
\end{equation}

\begin{equation}
R_{n,c} = H_c + LE_c
\end{equation}

Latent heat,

\begin{equation}
LE = LE_s + LE_c
\end{equation}

\begin{equation}
LE_c = \alpha_s \frac{\Delta}{\Delta + \gamma} R_{a,c}
\end{equation}

Soil heat conduction flux,

\begin{equation}
G = \Gamma_s R_{n,s}
\end{equation}

where subscripts $s$ and $c$ are respectively indicative of soil and canopy, $\Gamma_s$ is the fraction of the total LAI that is green, $\Gamma_s$ is the fraction of the ratio of soil heat flux to surface net radiation at bare soil surface, $\alpha$ is the Priestley–Taylor coefficient for the potentially transpiring canopy with an initial approximation of 1.3.

A solution for the TSEB begins with Eq. (18g) assuming the canopy is transpiring at potential rate. This allows computation of $H_c$ and solving for soil and canopy temperatures via Eq. (15). If soil evaporation ($LE_s$), calculated as the residual of energy balance equation from Eqs. (15)–(18h), becomes negative under daytime conditions, suggesting condensation onto the soil surface is occurring, this is not considered a physically plausible solution. It suggests that the canopy is not transpiring at the potential rate and requires the Priestley–Taylor coefficient in Eq. (18g) to be reduced, and as a result $LE_c$ is throttled back until $LE_c \geq 0$ and there is a convergence in both the soil-surface and canopy convective energy and radiation balance (see Anderson et al. (1997) for details).

For the TSEB model, a more physically based algorithm considering the transmission of direct and diffuse shortwave radiation and the transmission of longwave radiation through the canopy is employed to estimate the divergence of surface net radiation in the whole system to the radiation components of soil and canopy at the Yucheng station. Besides the reflectance and emissivity for the soil and canopy, inputs of this algorithm include a series of near-surface measurements of global solar radiation, air temperature, and actual vapor pressure. The net shortwave radiation ($S_{n,s}$ and $S_{n,c}$) and the net longwave radiation ($L_{n,s}$ and $L_{n,c}$) balance for the soil and canopy system are estimated following the work of Campbell and Norman (1998) and the adaption of Ross (1975), respectively. Equations related to the divergence of shortwave and longwave radiations are as follows:

\begin{equation}
L_{n,s} = \exp(-k_s LAI) L_s - L_c - L_{sky}
\end{equation}

\begin{equation}
L_{n,c} = (1 - \exp(-k_c LAI))(L_{sky} + L_c - 2L_s)
\end{equation}

\begin{equation}
S_{n,c} = (1/T - 1/\alpha_c) R_{global}
\end{equation}

\begin{equation}
S_{n,s} = T(1 - \alpha_s) R_{global}
\end{equation}

where $k_s$ is the extinction coefficient for longwave radiation, typically on the order of 0.95, $L_s$, $L_c$ and $L_{sky}$ represent the longwave emissions from the canopy, soil and sky, respectively, and can be estimated from the Stefan–Boltzmann equation using canopy temperature, soil temperature and shelter air temperature and vapor pressure, $\tau$ is the transmission coefficient for shortwave radiation, $\alpha_c$ and $\alpha_s$ are the canopy and soil albedos, respectively, $R_{global}$ is the global solar radiation either from the ground-based measurements or from remotely sensed observations. The ground-based measurements of global solar radiation will be used in this specific study. The transmission coefficient, canopy and soil albedos are derived by weighting the direct and diffuse shortwave components in both visible and near-infrared bands. See Campbell and Norman (1998) for details on how these variables are estimated.

3. Ground and satellite data

3.1. Ground measurements

In Fig. 2a the spatial distribution of the 1 km resolution MODIS NDVI data on Day Of Year (DOY) 123 over the study area used to construct the T$_n$–VI triangle space is illustrated. The study area ranges from 35.00° N to 38.00° N in latitude and from 114.65° E to 118.50° E in longitude with total area of about 93,000 km$^2$. Surface elevation in most areas is approximately 0–400 m above sea level. The validation site located at the Yucheng Comprehensive Experimental Station (hereafter referred as the Yucheng station, indicated by the black filled triangle in Fig. 2a) is part of the Chinese terrestrial ecosystem flux research network (ChinaFlux) established in 2002 aiming at measuring continuously the long-term exchange of carbon dioxide, water vapor and heat between land and atmosphere across different terrestrial ecosystems in China (http://www.chinaflux.org/). The Yucheng station is geographically located in the southwest of Yucheng County, Shandong Province with winter wheat and summer corn crop rotation in North China. Land cover near the Yucheng station is primarily classified as crop (wheat/corn rotation), bare soil, trees, and water, as shown in the classification map from TM data in Fig. 2b. The soil type of this area is sandy loam and the climate is subhumid and monsoon climate with mean annual temperature and precipitation being 13.1 °C and 528 mm, respectively. Surface temperature over Dongping Lake, marked in circle in Fig. 2a and located in the southwest of the Yucheng station, is used to identify the wet edge of the T$_n$–VI triangle space.

Measurements of meteorological variables including precipitation, air temperature, wind speed, relative humidity and atmospheric pressure have been made routinely at the Yucheng station at two heights above ground level (agl) since the establishment of the station. The measurement heights of the upper level and lower level
instrument sets were elevated from 2.89 m and 1.63 m to 4.24 m and 2.93 m above ground on 31, July 2009. In addition, 4-component radiation (downwelling and upwelling shortwave and longwave radiations) measurements are acquired with a CNR-1 (Kipp & Zonen). [Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA] and soil heat flux is estimated with a single HFP-01 soil heat flux plate (HuksFlux) at 2 cm soil depth and no accounting for heat transfer for the 2 cm storage layer above the plate. Soil water content is measured at depths of 20 cm and 40 cm below surface with CS616 (Campbell Scientific) soil moisture sensors. All the data mentioned above are recorded as 5-min averaged values.

Turbulent sensible and latent heat fluxes are also measured regularly by an Eddy covariance (EC, 36.8291° N/116.5703° E, see Fig. 2b) system consisting of an open-path CO2/H2O gas analyzer (model LI-7500, Licor Inc., Lincoln, Nebraska) and a 3-D sonic anemometer/thermometer (model CSAT3, Campbell Scientific Inc., Logan, Utah). The height of turbulent flux measurements was changed from 2.68 m to 3.35 m agl on 31, July 2009. The EC measurements are collected at 10-Hz frequency by a data logger for archiving and on-line computation of the turbulence statistics and 30-min averaged fluxes are computed. Effects of fluctuations in air density on the fluxes of CO2 and water vapor have been corrected by the online flux computation and post-field data programs. A series of data quality control steps following Aubinet et al. (2000), Foken et al. (2004), and others have been made to the eddy fluxes data over all ChinaFlux sites (Yu et al., 2006).

A Large Aperture Scintillometer (LAS, Kipp & Zonen Inc.) was installed along a northeast–southwest direction in late April in 2009 at the Yucheng Station to provide routine measurements of the turbulent sensible heat flux at the MODIS pixel scale (see Fig. 2b). The receiver (36.8314° N/116.5717° E) and transmitter (36.8212° N/116.5661° E) of LAS were at a fixed height of about 8.8 m, while the path length between the two sensors was 1240 m. The logarithm of the structure parameter of the refractive index of air with 10 as the base (UCn2), the signal strength, and the variance of UCn2 were stored over each ten minute interval in a built-in data logger. Post-processing of the LAS measured signal requires the support of additional meteorological observations of wind speed, atmospheric pressure, air temperature, relative humidity and Bowen ratio, surface roughness and displacement height. Monin–Obukhov similarity theory (MOST) is applied iteratively to derive sensible heat flux from the LAS measurement and other additional data. The Bowen ratio is derived iteratively together with LAS-derived sensible heat flux from the measured net radiation and soil heat flux using the energy balance equation (Eq. 1). Details on how to calculate sensible heat flux over length path distance from the LAS measurements are given by Tang et al. (2010).

All the meteorological measurements together with the EC measurements were located about 200 m from the transmitter along the path length in an experimental area having dimensions of approximately 250 m by 90 m dimension at the Yucheng station. The study period in this paper begins from the time LAS was installed in late April 2009, through late September when corn was mature and harvested. Wheat was harvested in early to mid June across the Yucheng station and corn was seeded at mid June. In addition to the meteorological data listed above, vegetation height and leaf area index (LAI) sampled at 3 sites in the experimental area were measured periodically every 15 and 7–8 days during the winter wheat and summer corn growth period, respectively. LAI was measured in the laboratory from green leaves sampled from the field using a portable leaf area meter (LI-3000).

### 3.2. MODIS data

The MODIS sensor onboard the TERRA satellite has 36 discrete spectral channels with spatial resolution of 250 m at 2 visible bands, 500 m at 5 near-infrared bands and 1000 m for the rest thermal infrared bands. MODIS/TERRA data/products used in this paper include land surface temperature/emissivity (MOD11_L2), surface reflectance (MOD09GA), 8-day LAI (MOD15A2), calibrated radiances (MOD021KM), geolocation (MOD03), and precipitable water (MOD05_L2) products. The Level 2 MOD11_L2 swath product is generated daily at 5-minute increments using the generalized split-window algorithm at 1000-m spatial resolution (Wan & Dozier, 1996). Daytime surface temperature, emissivity at channels 31 and 32 and overpass time were respectively extracted from MOD11_L2 product for estimation of upward longwave radiation. 500-m surface spectral reflectance for bands 1–7 and 1000-m 8-day LAI data were extracted from MOD09GA and MOD15A2 products on a Sinusoidal grid, respectively. Estimated regional NDVI with a nominal spatial resolution of 500 m from surface spectral reflectances at bands 1 (red band) and 2 (near-infrared band) over the study area was re-sampled to spatial resolution of 1000 m by non-weighted average of the four nearest sampled data. MOD021KM consists of calibrated and geocoded radiances and reflectances at top of atmosphere (TOA) for 36
bands. MOD03 product mainly includes datasets of geodetic coordinates (latitude and longitude), solar zenith and azimuth angles, satellite zenith and azimuth angles, and ground elevation for each 1-km sample (pixel). MOD05_L2 contains column water-vapor amounts over clear land areas and above clouds over both land and ocean. All the MODIS/TERRA products, if necessary, were georeferenced and resampled to 1000-m spatial resolution.

Because LAI measurements from ground-based LI-3000 data and from the MODIS/TERRA product (MOD15A2) sample only green leaf area (Myneni et al., 2002; Privette et al., 2002), this study focuses on days in 2009 during the wheat (late April to late May, from DOYs 121 to 163) and corn (early July to late September, from DOYs 166 to 273) growth period and excludes the maturity stage when senescent and dead leaves become dominant. Thirty-three clear MODIS scenes were collected during this period. Fig. 3a–b show seasonal variations in vegetation height, leaf area index (both ground observations and MODIS-derived) and daily precipitation across the wheat and corn growth period. While MODIS LAI has been shown to capture the phenological variability of crops, the ground-based LAI is shown to be systematically larger than MODIS LAI during both the winter wheat and summer corn growth periods. Moreover, one can also see that MODIS-derived LAI is markedly underestimated by using TM data acquired in April 2004 over a winter wheat crop (also in winter wheat growth stage and from DOY 242 for corn growth stage). Yang et al. (2007) concluded from an evaluation of the MODIS LAI product over clear land areas and above clouds over both land and ocean. All MODIS/TERRA products, if necessary, were georeferenced and resampled to 1000-m spatial resolution.

3.3. Net radiation model inputs

Many studies have concentrated on the estimation of surface net radiation using either routine meteorological measurements and remotely sensed surface temperature or using remotely sensed data alone. Recently, Tang et al. (2006) and Tang and Li (2008) proposed a simple scheme to estimate the instantaneous net shortwave and longwave radiations from MODIS products alone. This MODIS scheme for net radiation is used in the T–VI triangle and SEBS model runs presented here, using MODIS/TERRA data collected over the Yucheng station. The TSEB model, on the other hand, includes an internal computation of net radiation, and therefore the MODIS net radiation cannot be reasonably imposed. Therefore the TSEB model uses downwelling radiation measured at the Yucheng station. To test impacts of using MODIS vs. tower-based radiation data, the net radiation from TSEB is also used as input to SEBS and TVT (see Sections 4.2 and 4.3).

Inputs to the MODIS net radiation algorithm are MOD021KM, MOD03, MOD05_L2, and MOD11_L2 products which can be freely downloaded. Instantaneous surface net shortwave (Rnw) and longwave (Rlw) radiations are estimated using the following equations,

\[ R_{sw} = \frac{E_0 \cos \theta}{D^2} (\alpha' - \beta' r) \]  

\[ R_{lw} = \varepsilon_d d - 5.67 \times 10^{-8} \varepsilon_s T_{s}^4 \]  

\[ r = b_0 + \sum_{i=1}^{6} b_i \rho_i \]  

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

\[ \varepsilon_s = 0.273 + 1.778 \varepsilon_{31} - 1.807 \varepsilon_{31} \varepsilon_{32} - 1.037 \varepsilon_{32} + 1.774 \varepsilon_{32}^2 \]

where \( E_0 \) is the solar irradiance at TOA, \( \theta \) is the solar zenith angle extracted from MOD03, \( D \) is the earth–sun distance in astronomical unit, \( \alpha', \beta' \) are the parameters dependent on solar zenith angle, and atmospheric precipitable water extracted from MOD05_L2 over land surface. \( b_0-b_2 \) are the coefficients depending on the view zenith angle and the solar zenith angle both retrieved from MOD03, \( c_i \) is the TOA narrowband reflectance measured by MODIS band \( i \) retrieved from MOD021KM, \( T_s \) is the MODIS surface temperature (K), \( \varepsilon_{31} \) and \( \varepsilon_{32} \) are respectively the surface emissivity in MODIS channels 31 and 32 retrieved with \( T_s \) from MOD11_L2, \( c_i \) (i = 0–6) are the coefficients depending on view zenith angle and surface altitude both extracted from MOD03, \( M \) is the TOA radiance measured by the MODIS thermal infrared channel extracted from MOD021KM, and the number in the subscript indicates the thermal channel of MODIS sensor. It is noted that because there are many stripes in MODIS/AQUA band 6 in all of MYD021KM data (AQUA data) due to the large number of dead detectors in band 6 of MODIS/AQUA instrument, only MODIS products from TERRA satellite were used in this study for estimating \( R_{sw} \).

3.4. Comparison of EC and LAS flux measurements

Prior to conducting any analysis and comparison with surface flux measurements, the flux footprint \( f(x, y) \) of EC and LAS was evaluated for the 33 MODIS overpass times in this study. The footprint \( f(x, y) \) is computed using a crosswind-integrated footprint model \( f_i \).
multiplied by a Gaussian crosswind concentration distribution function $D_s(x, y)$, following the work of Hsieh et al. (2000),

$$f_y = f(x, z_m) = \frac{1}{k^2 \pi^2} D_s(x, y)^{1-p} \exp\left(-\frac{1}{k^2 \pi^2} D_s(x, y)^{1-p}\right)$$  \hspace{1cm} (25)

and the crosswind distribution function is expressed as

$$D_s(x, y) = \frac{e^{-y^2/(2 \delta^2)}}{\delta \sqrt{2\pi}}$$  \hspace{1cm} (26)

where $z_m$ is the measurement height (m), $x$ is the wind streamwise distance (m), $D_t$ and $P$ are the similarity constants grouped under three atmospheric stability conditions, $z_a$ is a length scale (m), $y$ is crosswind distance (m), $\delta_y$ is the lateral dispersion dependent on the crosswind standard deviation.

For the LAS observation, the footprint ($f_{LAS}(x, y)$) is obtained by integrating the point footprint with the bell-shaped weighting function ($W(x_L)$) over the length path (McAneney et al., 1995; Wang et al., 1978),

$$f_{LAS}(x, y) = f(x, y) * W(x_L)$$  \hspace{1cm} (27)

with

$$W(x_L) = 4\pi^2 k^4 \int_0^\infty t \cdot \Phi(t) \cdot \sin^2\left(\frac{t x_L (L_{LAS} - x)}{2k t_{LAS}}\right) \left[\frac{2 J_1(0.5 t d Cn_{t_{LAS}})}{0.5 t d Cn_{t_{LAS}}} \left(1 - \frac{1}{4 t^2_{LAS}}\right)\right]^2 dt$$  \hspace{1cm} (28)

where the operator $*$ represents a convolution between the functions, $x_L$ is the propagation distance along the LAS path (m), $K$ is the optical wave number, $t_{LAS}$ is the path length (m), $t$ is the spatial wave number, $D_t$ is the aperture diameter (m), $\Phi(t)$ is the three-dimensional spectrum of refractive index fluctuations (0.033 $\pi^{-1/3} Cn^2$), $J_1$ is the Bessel function of the first kind of order one.

The path weighting function $W(x_L)$ along the LAS length path as well as the wind speed and direction for the 33 MODIS overpass times involved in this study are shown in Figs. 4 and 5, respectively. $W(x_L)$ takes on a bell shape with the maximum weight occurring at the middle of the path and minimum weight at the transmitter and receiver sites. The maximum $W(x_L)$ varies from $1.87 \times 10^{-7}$ to $4.66 \times 10^{-6}$ at the MODIS overpass times. In most cases, wind at the near surface height came from the southwest direction (see Fig. 5). Depending on the different atmospheric conditions and surface vegetation property, the source area of LAS-measured $H$ varied primarily within the $1.24 \text{ km} \times 0.4 \text{ km}$, extending from $50 \text{ m}$ to $400 \text{ m}$ along the crosspath direction while for the EC tower the source area was generally less than $0.05 \text{ km} \times 0.03 \text{ km}$ in this study (90% flux fetch). Two schematic diagrams with relatively larger source areas for both EC (within $0.1 \text{ km} \times 0.05 \text{ km}$) and LAS (within $1.24 \text{ km} \times 0.6 \text{ km}$) representing the wind approximately parallel (DOY 123 with wind direction 211°) and perpendicular (DOY 204 with wind direction 115°) to the LAS path length over the wheat and corn crops, respectively, are shown in Fig. 6. Large differences have been observed in the extent and location of the footprint (source area) between LAS and EC. The source area of EC measurements (on the order of $10^{-10}$ m$^2$) is generally much smaller than that of LAS, which is capable of measuring sensible heat flux over distances of few kilometers. With MODIS pixel resolution on the order $10^5 \text{ km}^2$ and given the reliability of ancillary data used in deriving the sensible heat flux, the LAS flux-footprint would provide more representative values of the heat fluxes to compare with model output. By having flux observations at a scale commensurate with the resolution of model output, it has been shown to reduce scatter due to non-compatibility in model-measurement spatial resolution (Anderson et al., 2004).

A number of papers (Anderson et al., 2008; Li et al., 2008; Norman et al., 2003; Sánchez et al., 2008; Twine et al., 2000) have reported the energy imbalance in surface energy budget measured by the EC technique (the sum of turbulent sensible and latent heat fluxes is generally less than the surface available energy). In Fig. 7a, the closure of surface energy budget from EC measurements for daytime conditions (6:00 AM to 18:00 PM) during the study period at the Yucheng station is shown. The linear least square fit of the sum of sensible and latent heat fluxes to surface available energy shows a slope of 0.80, an intercept of 7 W/m$^2$, and a coefficient of determination of 0.27. The mean value of the closure ratio, defined as $(H + LE)/(R_{n} - G)$, is about 0.78 with an average energy balance residual $(R_{n} - G - H - LE)$ of approximately 40 W/m$^2$. This magnitude in the closure ratio and the residual closure in W/m$^2$ are similar to other studies and can be attributed to several factors, including measurement errors in $R_{n}$, inadequate sampling and measurement of $G$ (a single plate measurement with no storage layer computation), inconsistent source areas represented by EC measurement of sensible

![Fig. 4. The path weighting function of the Large Aperture Scintillometer for the 33 MODIS overpass times involved in this study at the Yucheng station.](image-url)

![Fig. 5. Wind speed and direction (asterisk) at 33 MODIS overpass times involved in this study at the Yucheng station in the polar coordinate system with the LAS length path indicated (solid blue line).](image-url)
and latent heat fluxes and surface available energy observations \((R_n - G)\).

The uncertainty of LAS-measured sensible heat flux from the perturbations of the ancillary measurements over the length path was evaluated based on Gaussian Error Propagation principle following the work of Marx et al. (2008) and Tang et al. (2010). The uncertainty \((\sigma)\) for sensible heat flux \(H\) with \(n\) independent variables \(x_i (i = 1 \text{ to } n)\), expressed in first order accuracy as standard deviation, can be estimated as:

\[
\sigma^2 = \sum_{i=1}^{n} \left( \frac{\partial H}{\partial x_i} \right)^2 \sigma_{x_i}^2
\]

where \(\sigma_{x_i}\) is the uncertainty in \(x_i\).

Perturbations for the ten variables in this study and the induced uncertainty for each variable in the 33 LAS-measured \(H\) are given in Table 1. The uncertainty resulting from the path length was implicitly included in the \(C_n^2\) variable. \(R_n\) and \(G\) measurements contribute to the uncertainty in the Bowen ratio estimation. Assuming these ten variables were independent, the overall uncertainty of LAS-derived sensible heat flux from the entire ancillary measurements was estimated to be about 8 W/m² (~12%). This magnitude of uncertainty is comparable to the results shown in the work of Tang et al. (2010) (9 W/m²) and Solignac et al. (2009) (11–12%), but greater than the value obtained by Marx et al. (2008) (7–8%). The differences

Figure 6. The LAS and EC footprint on DOYs 123 (a) for wheat and 204 (b) for corn superimposed on the land cover classification map from TM data.

Figure 7. (a) Closure of surface energy budget from EC measurements at daytime (6:00 AM to 18:00 PM) on every day during the study period, (b) comparison of 30-min averaged sensible heat flux measured by EC and LAS at MODIS overpass times for the 33 clear sky days.

Table 1

<table>
<thead>
<tr>
<th>Quantity (x)</th>
<th>Unit</th>
<th>Assumed uncertainty</th>
<th>Induced uncertainty of H (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>°C</td>
<td>±0.5</td>
<td>0.17</td>
</tr>
<tr>
<td>Wind speed</td>
<td>m/s</td>
<td>±10%</td>
<td>4.4</td>
</tr>
<tr>
<td>Atmospheric pressure</td>
<td>hPa</td>
<td>±10%</td>
<td>0.21</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>–</td>
<td>±10%</td>
<td>0.07</td>
</tr>
<tr>
<td>Roughness length</td>
<td>m</td>
<td>±10%</td>
<td>1.69</td>
</tr>
<tr>
<td>Height of wind speed measurements</td>
<td>m</td>
<td>±0.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Path height</td>
<td>m</td>
<td>±0.5</td>
<td>3.48</td>
</tr>
<tr>
<td>The structure parameter of the refractive index of air ((C_n^2)^a)</td>
<td>(K^2)</td>
<td>±10%</td>
<td>5.4</td>
</tr>
<tr>
<td>Surface net radiation ((R_n)^a)</td>
<td>W/m²</td>
<td>±5%</td>
<td>1.25</td>
</tr>
<tr>
<td>Soil heat flux ((G)^a)</td>
<td>W/m²</td>
<td>±20%</td>
<td>0.5</td>
</tr>
</tbody>
</table>

\(a\) The uncertainty resulting from the path length is implicitly included in the \(C_n^2\) variable. \(R_n\) and \(G\) measurements contribute to the uncertainty in the Bowen ratio estimation.
between these results can be explained in part by the different magnitudes in the perturbations assumed for these variables.

In order to evaluate the reliability and consistency between the LAS and EC measurements, a comparison of 30-min averaged sensible heat flux measured by both systems at the MODIS/TERRA overpass times on clear sky days from late April to the end of September in 2009 is shown in Fig. 7b. Because the soil heat flux estimates associated with the EC tower site are not reliable for assessing closure errors, the EC data in Fig. 7b have not been corrected for closure. Moreover, a series of studies focusing on the comparisons of LAS- and EC-measured H do not in general invoke an energy balance closure correction (Hoedjes et al., 2007; Von Randow et al., 2008; Zeweldi et al., 2009). Since the LAS technique cannot determine the stability of the atmosphere and thus the direction of the heat flux, the gradient calculated from the near-surface two-level air temperature measurements at the Yucheng station was used as an indicator. Overall, sensible heat flux measured by EC (H_EC) tended to have systematically higher values compared with that by LAS (H_LAS). The mean bias (H_EC - H_LAS) and RMSD between H_EC and H_LAS are approximately 10 W/m² and 20 W/m², respectively. This bias is a little larger than the uncertainty of LAS-measured H listed in Table 1 (~8 W/m²). Given the typical differences in contributing source-areas between the EC and LAS systems illustrated in Fig. 6, this is likely to be the primary factor contributing to the bias and RMSD.

4. Results and discussion

As no comprehensive information on the clumping factor (Ω) in the total leaf area index was collected at the Yucheng station during our study period, comparison and discussion among the three energy balance models will be made in this section assuming Ω = 1. To evaluate the model performance at the MODIS pixel resolution, LAS measurements at the Yucheng station are compared with the sensible heat fluxes estimated from the three remote sensing based energy balance models. Surface net radiation and soil heat flux in the SEBS and TVT are estimated from the work of Tang et al. (2006) and Tang and Li (2008) (thereafter referred to Tang’s algorithm) and Su (2002) using the equations given in Sections 3.3 and 2.1, which do not need ancillary near surface information and are different from the Rn and G estimations as shown in Section 2.3 for the TSEB model.

4.1. Correction of leaf area index and surface temperature measurements

As mentioned earlier, the MODIS LAI product significantly underestimated LAI at the measurement site, and this is likely to influence the model performance in producing surface energy components. Fig. 8a shows a scatterplot of leaf area index (LAI) measured in situ versus estimates from the MODIS product. The in situ measurements are systematically larger than MODIS LAI, especially for LAI > 1 m²/m². For wheat, a good linear relationship is found between in situ and MODIS LAI, with a coefficient of determination (R²) of 0.95 while there is considerable scatter for corn with R² of 0.57. A linear least squares fitting of ground LAI to MODIS LAI produced slopes of 5.8 and 1.1 and intercepts of -3.8 and 0.4 for wheat and corn, respectively. These two linear equations are used to correct the MODIS LAI data, to give reliable LAI estimates at MODIS pixel scale over the Yucheng station.

Although the MODIS LST product has been widely validated with accuracy better than 1 K under a range of conditions (Coll et al., 2009; Hulley & Hook, 2009; Wan & Li, 2008), cirrus clouds and oblique viewing angles can result in the underestimation of surface temperature from satellite measurements under some circumstances. MODIS LST over 33 clear sky days during wheat and corn growth period was compared with LST derived by using tower measurements of upwelling longwave radiation and estimated reflected downwelling longwave radiation to see if there was any significant bias (Fig. 8b). In most cases, MODIS LST was in good agreement with LST estimated from the ground-based longwave radiation measurements. The bias (ground-based–MODIS-based LST) and RMSD value were 0.4 K and 2.3 K; however, a significant underestimation as large as 8 K of MODIS LST product occurred on DOY 147. The 8 K departure is likely caused by the effect of a cirrus cloud for that particular overpass. Air temperature from the nearby weather station was greater than the MODIS LST for several days which suggests stable conditions. However, this is in contradiction with the near-surface air temperature gradient from the nearby weather station suggesting unstable atmospheric conditions. Based on these observations, it was decided that on days where the ground-MODIS LST difference > 1 K, the LST from the ground-based longwave radiation measurements would replace LST from MODIS. Both corrected and uncorrected MODIS LST and LAI products were used by the three models in order to assess model performance and sensitivity due to uncertainty in these key remotely-sensed inputs.

4.2. Modeled versus measured surface fluxes using corrected MODIS LST and LAI products

Corrected LAI and MODIS surface temperature from local measurements were used as the most accurate inputs to investigate the model performance by comparing with ground surface energy flux measurements. A comparison of instantaneous surface net radiation (Rn) estimated from the TSEB, TVT and SEBS models using corrected MODIS surface temperature and LAI with ground measurements at
the Yucheng station, respectively, is illustrated in Fig. 9. It appears that Tang's algorithm requiring fully MODIS products as inputs used in the SEBS and TVT models overestimated Rn, with a positive bias (modeled-measured) and a larger RMSD compared to the TSEB model which underestimated Rn but with a smaller bias and RMSD-value. The largest deviations from Rn measurements using Tang's algorithm occurred on DOYs 132, 239 and 256, which were caused by the intermittent cloud cover. This was verified using the ground surface radiation measurements showing moderate fluctuations in incoming solar radiation values. The passing clouds likely caused oscillations in 5-min averaged surface net radiation measurements surrounding satellite overpass time. The closer agreement with the measurements using the TSEB model is due in large part to having local ground-based solar radiation measurements used as input. Due to the lack of multiple measurements of soil heat flux (G) to obtain a representative spatial sample and no accounting for heat storage above the plate, a comparison with modeled G was not conducted.

Since the LAS measurement of sensible heat flux is over a path-length distance of ~1 km and G measured at the tower is unreliable, model estimated sensible heat flux (H) will be compared with the LAS measurements and model estimated latent heat flux (LE) will be compared to residual LE derived by using H from LAS and surface available energy (Rn − G) from an average of the remotely sensed TSEB and SEBS/TVT model estimates. This means that the residual LE (hereafter referred as LAS-estimated LE) is used as the ground truth/validation data, which is at a similar spatial resolution as the model output.

In Fig. 10, H and LE estimated from the three remote sensing-based ET models using corrected MODIS LST and LAI inputs are compared with LAS-estimated H and LE at the Yucheng station. Good performance was obtained for both TSEB and SEBS derived H values (Fig. 10a) with relatively small negative bias (underestimate of measured H) and a RMSD<45 W/m². The TVT model, on the other hand performed poorly with a significant bias (overestimate) compared to LAS-measured H of nearly 80 W/m² and a large RMSD-value (Fig. 10a). The LAS-measured H is systematically underestimated by both TSEB and SEBS models when LAS-measured H is greater than 100 W/m² whereas LAS-measured H was overall overestimated when the values are lower than 100 W/m². Underestimation of H occurred when the field was in corn, while during the period the field was in wheat, there are no major differences in the LAS-measured H. For LE, output from the TSEB model agreed more closely with the LAS-estimated values than SEBS (Fig. 10b). The SEBS model tended to overestimate LAS-estimated LE with a larger RMSD of ~55 W/m² compared to ~40 W/m² for the TSEB model. The TVT model output resulted in a significant bias (underestimate) resulting in a RMSD-value >110 W/m². Both TSEB and SEBS models systematically overestimate LAS-derived LE when the flux is less than 500 W/m², which occurred primarily during the corn growing season. The TSEB model typically underestimates LAS-derived LE when the flux is greater than 500 W/m² which occurred primarily during the wheat growing season.

It is noted that the superior performance of the TSEB model over the SEBS model in reproducing LAS-estimated LE is attributable in large part to the use of ground-based solar radiation measurements as one of the key inputs for estimating surface net radiation in the TSEB model. Use of different surface net radiation sources in the TSEB and TVT/SEBS models complicates direct comparison of model performance in computing the turbulent heat fluxes, H and LE. Tang's algorithm does not require downward shortwave solar radiation as input, nor can the downward shortwave solar radiation be deduced for the use in the TSEB model. Therefore, another test was performed using the Rn estimated from the TSEB model to drive the TVT and SEBS models. Because H is estimated independently from Rn in the SEBS, there was no effect on SEBS-estimated H by using Rn from the TSEB. LE from the SEBS in this experiment had a similar performance to the TSEB model in reproducing LAS-estimated LE with the RMSD decreasing to ~40 W/m² and bias decreasing from 35 W/m² to 20 W/m². For the TVT model, H and LE are derived from the independent estimates of Rn − G and EF and therefore varying Rn will not influence the Tn–VI derived EF but will affect the magnitudes
of H and LE. Little improvement is obtained with RMSD \(>110 \text{ W/m}^2\) for both H and LE using \(R_n\) estimated from the TSEB model.

### 4.3. Model versus measured surface fluxes using uncorrected MODIS LST and LAI products

In Fig. 11a-c, a comparison of the estimated \(R_n\), H and LE from three models is illustrated using the original (uncorrected) MODIS LST and LAI products with surface radiation measurement and LAS-measured H and LE. The TSEB model output is in better agreement with measured \(R_n\) (see Fig. 11a), having a smaller bias and RMSD-value (Fig. 11a). The TSEB model yields the closest agreement with LAS-measured H and LE resulting in a RMSD of \(\sim 65 \text{ W/m}^2\) and \(55 \text{ W/m}^2\), respectively (see Fig. 11b–c). Both the TSEB and SEBS models consistently underestimate LAS-measured H and as a result overestimate LAS-estimated LE. In contrast, the TVT model overestimates LAS-measured H and underestimates LAS-estimated LE. The SEBS model output of H agrees slightly better with LAS-measured H than the TVT model output (Fig. 11b). However, for LE, the RMSD-value with the SEBS model (\(\sim 95 \text{ W/m}^2\)) is significantly greater than RMSD from the TVT model (RMSD = \(75 \text{ W/m}^2\), if \(R_n\) from the TSEB model replaces Tang’s algorithm in the SEBS and TVT models, the RMSD-value decreases to \(\sim 80 \text{ W/m}^2\) for LE using the SEBS model but increases to \(\sim 80 \text{ W/m}^2\) for both H and LE estimated by the TVT model.

From Fig. 11b, H estimated from the SEBS model is negative for several overpass dates even though the local two-level near surface air temperature gradient measurement indicates unstable conditions (LAS-measured H > 0). Unstable conditions are also consistent with the EC measurement of H. The LAS-measured H on these overpass dates varied from \(-25 \text{ W/m}^2\) to \(140 \text{ W/m}^2\), whereas the corresponding estimated H ranged from approximately \(-40 \text{ W/m}^2\) to \(10 \text{ W/m}^2\) using the TSEB model and from \(-145 \text{ W/m}^2\) to \(0 \text{ W/m}^2\) running the SEBS model with the uncorrected MODIS LST product. These large discrepancies caused by inaccurate LST-air temperature differences result in a significant deterioration in the performance of model estimated versus LAS-measured H for both the TSEB and SEBS models. It is noted that with time-differencing techniques used in ALEXI and DTD approaches (Anderson et al., 1997; Norman et al., 2000), such biases in LST can be accommodated and as a result model output is not significantly affected.

#### 4.4. Evaluation of model sensitivity to MODIS product error

Use of ground-corrected MODIS LST and LAI improves the performance of both TSEB and SEBS models in reproducing surface energy fluxes while model estimates of H and LE from TVT model deteriorate slightly. To quantitatively assess the effects on model output of using uncorrected versus corrected MODIS LST and LAI products, an intercomparison of surface energy fluxes using the corrected (MODIS-adjusted) \(R_n\), G, H, and LE versus uncorrected (MODIS-original) \(R_n\), G, and LE) MODIS LST and LAI products was performed. Results are illustrated in Fig. 12 and Table 2 for TSEB, SEBS, and TVT models.

For the TSEB model, no significant difference is observed between MODIS-adjusted versus original MODIS inputs for computing \(R_n\) (see Fig. 12a and Table 2). This is due in part to compensating errors with the underestimation of MODIS LST (causing an increase in \(R_n\)) and an overestimation of fraction of soil (underestimation of LAI), which causes a decrease in \(R_n\) via albedo effects. The estimated G was significantly overestimated due to an underestimation of LAI using the original MODIS LAI product, by an average of \(-35 \text{ W/m}^2\). The estimates of H using MODIS-adjusted inputs were consistently lower on average than using MODIS-original products while for LE differences ranged between \(-60 \text{ W/m}^2\) and \(55 \text{ W/m}^2\) with an overall small mean bias. The differences as quantified by the RMSD between TSEB output using MODIS-adjusted versus original LST and LAI products indicate relatively small errors compared to the SEBS model results (see Table 2). For the TSEB model, estimations of \(R_n\) and G are coupled with the partition of \(G - F_n\) into H and LE. Since LAI is a key factor that determines the partitioning of net radiation between the canopy and soil system, the wind profile inside the canopy layer, and soil and canopy temperatures, a significant bias from the actual LAI by the MODIS-original LAI product in the TSEB model strongly affects the partitioning of the turbulent heat fluxes, H and LE, between soil and canopy components. However, this does not...
appear to affect the total (soil + canopy) estimated fluxes as much as with the SEBS model.

In the SEBS model (see Fig. 12b and Table 2), $R_n - G$ was slightly overestimated due to the underestimation of MODIS-original LST. It is noted that LAI does not exert any influence on the estimation of $R_n$ from Tang’s algorithm (Eqs. 23 and 24). However, the LAI estimate does have a significant effect on estimated $G$ and $H$. For $G$ use of MODIS-original LAI results in a consistent bias of nearly 30 W/m$^2$ in this study. The estimate of the available energy $R_n - G$ is independent of the accuracy of $H$ but is used to calculate LE as the residual in the surface energy balance equation (Eq. 1). With the bias in $H$ ranging from approximately $-160 \text{ W/m}^2$ to 10 $\text{ W/m}^2$ using MODIS-original LST and LAI, differences in LE between MODIS-original and adjusted LST and LAI vary from nearly $-55 \text{ W/m}^2$ to $-170 \text{ W/m}^2$, but yielding a very small mean bias. However, differences in model output quantified in terms of RMSD using MODIS-original versus adjusted LST and LAI are significantly larger with the SEBS versus TSEB model (cf. Fig. 12a versus Fig. 12b).

For the TVT model (see Fig. 12c and Table 2), both $H$ and LE are computed from the TVT-derived EF and the estimation of the available energy, $R_n - G$. There were several significant discrepancies in both $H$ and LE using MODIS-original versus MODIS-adjusted LST. For $H$ differences varied from nearly $-290 \text{ W/m}^2$ to 15 $\text{ W/m}^2$ and LE differences ranged from $-45 \text{ W/m}^2$ to $-295 \text{ W/m}^2$. As a result, RMSD values for $H$ and LE using the original versus adjusted MODIS LST and LAI products as input to the TVT model are significant (Table 2). Such large variations in $H$ and LE estimation caused by an inaccurate MODIS LST product are attributed to the uncertainty in determination of the dry edge in the $T_n$–VI space.

It needs to be noted that the TVT model is able to provide an estimate of EF independent of the available energy $R_n - G$. However, sources of error in the estimated $H$ and LE for the TVT model originate from the uncertainties in both the estimations of $R_n - G$ and EF. Due to the cloud effects on water body surfaces, LST at the wet edge on DOYs 138, 139, 144, and 204 was calculated from the intersection of the dry edge with $f_i = 1$ as performed in Tang et al. (2010). Both the estimated $R_n - G$ and EF result in moderate to large scatter when compared with surface measurements. Assuming LST of in-land water bodies is representative of the wet edge LE (equivalent to potential evaporation condition), then it is assumed that underestimation of EF is likely the result of an underestimation of LST at the dry edge. In other words, the dry edge estimated in this study is not representative of a non-evaporating surface. The EF values for 21 of the 33 days during wheat–corn growth stage in this study were underestimated (not shown here). This demonstrates the difficulty to identify the limiting dry edge in subhumid regions within a satellite scene. If LE estimated from the TVT model with an adjusted value for the global $\phi_{min} = 0.4$ (instead of $\phi_{min} = 0$) is compared to the residual LE estimated using LAS-measured H and the average $R_n - G$ estimated from the three models (LAS-estimated LE), the bias and RMSD values are significantly reduced to approximately $-10 \text{ W/m}^2$ and 65 $\text{ W/m}^2$, respectively (see Fig. 13).

The study area (308 columns by 303 rows with pixel resolution of 1 km) appears smaller in comparison to the size of areas used in the application of $T_n$–VI triangle method (Stisen et al., 2008; Venturini et al., 2004; Wang et al., 2006). However, similar atmospheric forcing may not be ensured and effects of cloud and topography may become more significant over a much larger heterogeneous region. It is therefore necessary in future work to determine the feasibility of developing an algorithm independent of the dimension of the study area for estimating both the dry and wet edges.

### Table 2

Statistics of comparison of surface energy balance components estimated using corrected versus original (uncorrected) MODIS LST and LAI products for TSEB, SEBS, and TVT models (in W/m$^2$).

<table>
<thead>
<tr>
<th></th>
<th>$R_n$</th>
<th>G</th>
<th>H</th>
<th>LE</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSEB</td>
<td>BIAS</td>
<td>RMSD</td>
<td>BIAS</td>
<td>RMSD</td>
</tr>
<tr>
<td></td>
<td>-2</td>
<td>10</td>
<td>33</td>
<td>37</td>
</tr>
<tr>
<td>SEBS</td>
<td>6</td>
<td>12</td>
<td>28</td>
<td>32</td>
</tr>
<tr>
<td>TVT</td>
<td>-31</td>
<td>64</td>
<td>9</td>
<td>68</td>
</tr>
</tbody>
</table>

**Fig. 12.** Comparison of surface energy balance components estimated using corrected versus original (uncorrected) MODIS LST and LAI products for (a) TSEB model, (b) SEBS model, and (c) TVT model, respectively.
5. Summary and conclusion

Output of surface fluxes from three remote sensing-based energy balance models (TSEB, SEBS, and TVT) was compared to Large Aperture Scintillometer (LAS) measurements using MODIS land surface temperature (LST) and leaf area index (LAI) products over a winter wheat and summer corn rotation region in China. The study period started in late April and lasted to the end of September in 2009, undergoing different growth stages for wheat and corn, but with the maturity stage having senescent vegetation excluded.

The MODIS LAI product underestimated actual ground-based measurements of LAI which has been reported in other studies (Sprintsin et al., 2009; Yang et al., 2007; Tian et al., 2002). Therefore, MODIS LAI was corrected for both wheat and corn crops using ground-based LAI measurements. The MODIS LST product also showed some inconsistencies when compared to LST derived from ground-based longwave radiation measurements at the site. The MODIS LST product was adjusted to match the ground-based value when underestimations were greater than 1 K. Output of the three models was compared using both corrected and uncorrected MODIS LST and LAI products to investigate the model performance and sensitivity due to uncertainties in these key inputs.

Use of the MODIS/TERRA radiance products for the TVT and SEBS model overestimated $R_n$ measurements by 25 W/m² with RMSD $= 45$ W/m² while the TSEB model using local observations of solar radiation produced $R_n$ estimates closer to the measurements ($Bias = -14$ W/m², RMSD $= 25$ W/m²). Comparison of model estimated versus measured $G$ was not conducted due to the lack of multiple measurements of $G$ to obtain a representative spatial sample and the lack of accounting for heat storage above the plate. With corrected MODIS LST and LAI as inputs, the TSEB model reproduced LAS-measured $H$ and estimated $LE$ as a residual (using average $R_n - G$ from the three model estimates) well within the accuracy of the observations (RMSD $= 45$ W/m²). Reasonable agreement with observations of $H$ and $LE$ was also obtained from SEBS model with RMSD $= 55$ W/m². Using the estimate of $R_n$ from the TSEB, the TSEB and SEBS model output of $H$ and $LE$ produced similar RMSD statistics when compared to LAS-estimated $H$ and $LE$. Due to the underestimation of the dry edge temperature from the MODIS scenes over this subhumid region, $H$ and $LE$ estimates from the TVT model were generally poor with RMSD $= 100$ W/m² compared to the LAS-derived values. With corrected MODIS LST and LAI products, the RMSD statistics obtained for $H$ and $LE$ using the TVT, SEBS and TSEB models is similar in magnitude to other intercomparison studies; namely the METRIC versus TSEB model intercomparison of Gonzalez-Dugo et al. (2009) and the TVT, METRIC and TSEB model intercomparison study of Choi et al. (2009).

Model sensitivity to the errors in two key inputs – LST and LAI – was performed by comparing flux output using corrected versus uncorrected MODIS LST and LAI products. The TSEB model was shown to have the least sensitivity of the three models to errors in LST and LAI inputs for this region. The discrepancies of SEBS model output with LAS-estimated $H$ and $LE$ using corrected versus uncorrected MODIS LST and LAI inputs are shown to be nearly double that of the TSEB model results. Variation in TVT model output was more variable due to different magnitudes in the underestimation of the dry edge when using corrected versus uncorrected MODIS products.

The results of this study suggest that for the SEBS model, LAI as a critical input for parameterizing the $K_B^{-1}$ factor significantly affects model output of $H$ which in turn has a strong impact on $LE$ output. Other factors such as sensor viewing angle, vegetation structure and radiometric resistance are not considered in the SEBS formulation and are likely to add error (Kustas & Anderson, 2009). The TSEB model is also sensitive to errors in LAI and LST, but for this study site and conditions, it is more resilient to these errors compared to SEBS. The TVT model generally performed poorly regardless of whether or not the MODIS LST and LAI products were corrected. The poor performance of the TVT model was attributed to the difficulty in defining a reliable dry edge for the satellite scene. In subhumid regions, the wet edge may be easily defined whereas the dry edge may not exist or is ill-defined. It is shown that it would be necessary to develop a technique that can adjust the TVT $\phi_{min}$ parameter for such conditions in order to compute more reasonable fluxes.

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