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Validation of the SEBS-derived sensible heat for FY3A/VIRR and TERRA/MODIS over an alpine grass region using LAS measurements

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ABSTRACT

In this study, sensible heat (H) calculation using remote sensing data over an alpine grass landscape is conducted from May to September 2010, and the calculation is validated using LAS (large aperture scintillometers) measurements. Data from two remote sensing sensors (FY3A-VIRR and TERRA-MODIS) are analysed. Remote sensing data, combined with the ground meteorological observations (pressure, temperature, wind speed, humidity) are fed into the SEBS (Surface Energy Balance System) model. Then the VIRR-derived sensible heat (VIRR_SEBS_H) and MODIS-derived sensible heat (MODIS_SEBS_H) are compared with the LAS-estimated *H*, which are obtained at the respective satellite overpass time. Furthermore, the similarities and differences between the VIRR_SEBS_H and MODIS_SEBS_H values are investigated. The results indicate that VIRR data quality is as good as MODIS data for the purpose of *H* estimation. The root mean square errors (*rmse*) of the VIRR_SEBS_H and MODIS_SEBS_H values are 45.1098 W/m^2 (n = 64) and 58.4654 W/m^2 (n = 71), respectively. The monthly means of the MODIS_SEBS_H are marginally higher than those of VIRR_SEBS_H because the satellite overpass time of the TERRA satellite lags by 25 min to that of the FT3A satellite. Relative evaporation (EFr), which is more time-independent, shows a higher agreement between MODIS and VIRR. Many common features are shared by the VIRR_SEBS_H and the MODIS_SEBS_H, which can be attributed to the SEBS model performance. In May–June, *H* is over-estimated with more fluctuations and larger *rmse*, whereas in July–September, *H* is under-estimated with fewer fluctuations and smaller *rmse*. Sensitivity analysis shows that potential temperature gradient (delta_*T*) plays a dominant role in determining the magnitude and fluctuation of *H*. The largest *rmse* and over-estimation in *H* occur in June, which could most likely be attributed to high delta_*T*, high wind speed, and the complicated thermodynamic state during the transitional period when bare land transforms to dense vegetation cover.

1. Introduction

Sensible heat (H) and latent heat (LE) flux are the key components in the energy and mass exchange budget among the atmosphere, hydrosphere, and biosphere (Su, 2002). Accurate quantification of *H* and LE, and their spatio-temporal pattern has been a topic of discussion in many disciplines (van der Kwast et al., 2009). Remote sensing is by far the only technique that is able to provide *H* and LE information at a regional scale with various spatio-temporal resolutions. Many methods have been developed in the past using remote sensing data to estimate *H* and LE, such as the SEBS (Surface Energy Balance System, Su, 2002), SEBI (Surface Energy Balance Index, Roerink et al., 2000), SEBAL (Surface Energy Balance Algorithms for Land, Bastiaanssen, 2000), TSEB (Two Source Energy Balance, Norman et al., 1995) model, METRIC (Mapping EvapoTranspiration at high Resolution with Internal Calibration, Allen et al., 2007) model, and TVT (Temperature and Vegetation Index Triangle, Moran et al., 1994). These models and methods vary greatly in the principles (process-based or not, single source or dual source), inputs, assumptions, and the degree of dependency on ground-based auxiliary measurements (Courault et al., 2005; Li et al., 2009). Comparison of the different models for *H* and LE estimation at the local or global scale has demonstrated a variable degree of success for the different models (Timmermans et al., 2005; Vinukollu et al., 2011; Tang et al., 2011).

The most important step, subsequent to the estimation of *H* and LE by remote sensing models, is to validate the results, which is not an easy task due to the lack of accurate and frequent ground observations that is in sync with the spatial resolution of the space-borne remote sensing data (Jia et al., 2003). The recently developed LAS (large aperture scintillometers) can measure *H* averaged over

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Table 1
VIRR specifications on-board FY3A.

Band	Bandwidth (μm)	Required noise equivalent reflectivity (temperature) difference
1	0.58–0.68	0.1
2	0.84–0.89	0.1
3	3.55–3.93	0.3*k*
4	10.3–11.3	0.2*k*
5	11.5–12.5	0.2*k*
6	1.55–1.64	0.15
7	0.43–0.48	0.05
8	0.48–0.53	0.05
9	0.53–0.58	0.05
10	1.325–1.395	0.19

horizontal distances comparable to a pixel size of about 1–5 km; thus, it provides a promising solution for the difficulty encountered during validation of the satellite-derived *H* (Hoedjes et al., 2002).

There has been extensive research on the use of LAS measurements for regional flux validation. Jia et al. (2003) evaluated the SEBS model using ATSR data by comparing *H* estimates from three different landscapes to those obtained from the LAS instruments. They found that the total *rmse* (root mean square error) of *H* was approximately 25.5 W/m^2. Irrigation areas with fruit trees showed the highest error. Tang et al. (2011) compared three models (SEBS, TSEB, TVT) using LAS measurements and MODIS data over a wheat-corn production region, and reasonable agreements (*rmse* < 50 W/m^2) were observed between the SEBS and TSEB models. They also found the SEBS model to be more sensitive to errors, in the MODIS LST and LAI products, than the TSEB model. Marx et al. (2008) used the SEBAL method and NOAA images to calculate *H* over the savannah region in West Africa. They found that the satellite-derived *H* was lower than the LAS measurements and that the uncertainties in the instantaneous LE were smaller than the uncertainties in *H*.

In this study, we validated satellite-derived *H* with the LAS instrument and compared two sensors namely, the FY3A-VIRR and TERRA-MODIS. We estimated *H* with the SEBS model over the Alpine grass region in the Qinghai Province of China. This study differs from the earlier studies in two ways. First, it is a relatively long-term validation (May–September 2010) compared to other studies, which used a limited number of images. Therefore, the sample size for validation is larger, and consequently, the seasonal change in *H* estimation accuracy can be also analysed. Second, a new sensor data (viz., FY3A-VIRR, visible and infrared radiometer) is used in the *H* estimations and is compared with its counterpart (TERRA-MODIS), which is novel and informative for researchers interested in VIRR data application. The FY3A, a new generation of polar-orbiting meteorological satellite, was launched on 27 May 2008. VIRR is one of the 11 uploads on the FY3A satellite (Dong et al., 2009). It has 10 bands with a spectral range of 0.44–12.5 μm (see Table 1). The spatial resolution is 1 km, and the local equatorial crossing time is approximately 10:05 am, which is 25 min earlier than the TERRA satellite.

The main objectives of this study are to evaluate the SEBS model performance for our study region and to check if FY3A-VIRR data is qualified for *H* estimation using the MODIS-derived *H* result as a benchmark. In Section 2, a brief description of the SEBS model is provided. In Section 3, the study site, ground data collection methods and remote sensing data processing steps are described. In Section 4, the accuracy of the satellite-derived *H* is validated with the LAS-estimated *H*. Discussion and conclusions are provided in Sections 5 and 6, respectively.

2. The SEBS model

The SEBS model, proposed by Su (2002), is one of the most important and widely used single-source models for estimating *H* and LE (Rwasoka et al., 2011; Jia et al., 2009). Intensive research has been performed to validate the SEBS results for multiple spatio-temporal scales (McCabe and Wood, 2006). Studies also pay attention to the uncertainties and sensitivities of the model inputs (Gilbson et al., 2010; van der Kwast et al., 2009). Su (2002) examined the SEBS model performance in depth with four datasets. He concluded following: (1) Mean error of the SEBS model estimates is expected to be approximately 20% relative to the mean *H*, if the geometric and physical input variables are reliable. (2) Temperature, wind speed, roughness length for heat transfer, and stability corrections have large impacts on the SEBS results. (3) Currently available stability corrections are inadequate for describing the transition period (from stable night condition to unstable daytime condition). Recently, Gokmen et al. (2012) proposed an updated SEBS model that explicitly included the effect of soil moisture availability and obtained satisfactory results for *H* calculation in water-stressed regions. However, the updated model requires spatial information on soil moisture and tuning for several new parameters, making it difficult to apply the model in real world situations. Therefore, in this study, the original SEBS model has been used.

Inputs to the SEBS model include land cover structural parameters (leaf area index, vegetation height, and fractional vegetation cover), meteorological measurements at a reference height (wind speed, humidity, air temperature, and pressure), height of the planetary boundary layer, and remote sensing products such as land surface temperature (LST), albedo (α), emissivity (ε), and NDVI. The SEBS model has three distinctive features compared to other models. First, it has two methods for the estimation of the stability parameters needed for the *H* calculations. If the reference height is below the top of the atmospheric surface layer (ASL), then the Monin–Obukhov similarity functions are invoked, otherwise the bulk atmospheric similarity model is used (Wang et al., 2008). Second, the non-dimensional parameter KB^{-1} is usually adopted as a constant in other models, whereas in the SEBS, the same parameter is calculated on a per pixel basis with an algorithm that combines an earlier full-cover canopy model (Choudhury and Monteith, 1988), a bare land model (Brutsaert, 1999), and a new equation term describing the vegetation-bare soil interaction (Su et al., 2001; Wang et al., 2008; Jia et al., 2003). Third, the radiation balance, *H* and LE under dry and wet limits, and the EFr (Evaporative fraction) are calculated for every pixel (Su, 2002; Gibson et al., 2011).

Given below is a simple description of the method of *H* estimation in the SEBS model. In the ASL, the similarity relationships for the profiles of the mean wind speed *u*, and mean temperature, $\theta_0 - \theta_a$, are usually written in the integral form as

$$u = \frac{u_*}{k}\left[\ln\left(\frac{z-d_0}{z_{0m}}\right) - \Psi_m\left(\frac{z-d_0}{L}\right) + \Psi_m\left(\frac{z_{0m}}{L}\right)\right] \quad (1)$$

$$\theta_0 - \theta_a = \frac{H}{ku_*\rho C_p}\left[\ln\left(\frac{z-d_0}{z_{0h}}\right) - \Psi_h\left(\frac{z-d_0}{L}\right) + \Psi_h\left(\frac{z_{0h}}{L}\right)\right] \quad (2)$$

In the above equations, $k = 0.41$ is the von Karman's constant; z is the reference height (m); u_* is the friction velocity (m/s); ρ is the density of air (kg/m^3); C_p is the specific heat capacity of air (J/kg K); θ_0 and θ_a are the potential air temperatures (K) at the surface and reference height, respectively; z_{0m} is the roughness height for the momentum transfer (m); z_{0h} is the scalar roughness height for the heat transfer (m), $z_{0h} = z_{0m}/\exp(\mathrm{KB}^{-1})$; d is the zero-plane displacement height (m); and Ψ_m and Ψ_h are the stability correction functions for momentum and sensible heat transfer, respectively,