Estimation of Hourly Land Surface Heat Fluxes over the Tibetan Plateau by the Combined Use of Geostationary and Polar Orbiting Satellites

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Abstract. The estimation of land surface heat fluxes has significant meaning for energy and water cycle studies, especially for the Tibetan Plateau (TP), which has unique topography and strong land-atmosphere interactions. The land surface heating status also directly influences the movement of atmospheric circulation. However, for a long time, plateau-scale land surface heat flux information with high temporal resolution has been lacking, which greatly limits understanding of diurnal variations in land-atmosphere interactions. Based on geostationary and polar orbiting satellite data, a surface energy balance system (SEBS) was used in this paper to derive hourly land surface heat fluxes with a spatial resolution of 10 km. Six stations scattered through the TP and equipped for flux tower measurements were used to correct the energy imbalance problem existing in the measurements and to perform cross-validation. The results showed good agreement between derived fluxes and in situ measurements through 3738 validation samples. The RMSEs for net radiation flux, sensible heat flux, latent heat flux and soil heat flux were 76.63 Wm⁻², 60.29 Wm⁻², 64.65 Wm⁻² and 37.5 Wm⁻², respectively. The derived results were also found to be superior to GLDAS flux products (RMSEs for the surface energy balance components were 114.32 Wm⁻², 67.77 Wm⁻², 75.6 Wm⁻² and 40.05 Wm⁻², respectively). The diurnal and seasonal cycles of land surface energy balance components were clearly identified. Their spatial distribution was found to be consistent with the heterogeneous land surface status and general hydrometeorological conditions of the TP.
1. Introduction

Mass and energy exchanges are constantly carried out between the land surface and the atmosphere above. At the same time, the weather, climate and environmental changes at multiple spatiotemporal scales are greatly influenced by such land-atmosphere exchanges. Land-atmosphere interaction is a popular topic not only in the field of atmospheric research but also in hydrology, geography, ecology and environmental sciences (Ye and Fu 1994). The impacts of land-atmosphere interactions on weather and climate change have been assessed through surface sensible heat flux, latent heat flux and momentum flux (Seneviratne et al, 2008; Ma et al, 2017). How to accurately derive the surface heat fluxes has always been a main research question and a focus of atmospheric science.

The Tibetan Plateau (TP), with an average elevation of more than 4000 m, is also called ‘the Third Pole’ and ‘the World Roof’. The thermal and dynamic effects caused by the TP’s high elevation and relief have profound impacts on atmospheric circulation, the Asian monsoon and global climate change (Ye and Gao 1979; Ma et al, 2006; Ma et al, 2008; Zhong et al, 2011; Zou et al, 2017; Zou et al, 2018). The interactions between TP multisphere, such as the atmosphere, hydrosphere, lithosphere, biosphere, and cryosphere, are the drivers of all these changes. The TP is also one of the most sensitive regions in response to global climate change (Liu et al, 2000). In recent years, some studies have argued that the major factor impacting the South Asian monsoon is the insulating effect of the southern mountain edges of the Tibetan Plateau, rather than the elevated heating by the Tibetan Plateau (Boos and Kuang 2010; Boos and Kuang 2013). However, some other studies have proven that the thermal effects of the TP are the main driving force of the South Asian summer monsoon (Wu et al, 2012; Wu et al, 2015). Obviously, opinions differ in understanding the thermal forcing by the TP. One of the most important reasons is that high spatial and temporal resolution data on land-atmosphere interactions, which can be used in different climate models, are still lacking. To study the characteristics of land-atmosphere interactions in the TP, it is necessary to estimate the surface energy heat fluxes with fine spatial and temporal resolution over the TP.

Traditional surface energy flux measurements are not only expensive but also limited at the point scale. It is impossible to meet the need for a larger spatial scale with the complex terrain and landscapes of the TP. Remote sensing provides the possibility of deriving surface heat fluxes at a regional scale (Ma et al, 2002; Zhong et al, 2014). The methods of estimating surface energy flux by remote sensing can be roughly divided into two categories: the empirical (semiempirical) model and the theoretical model. The
empirical (semiempirical) model is mainly based on an empirical formula between surface energy fluxes and surface characteristic parameters. The method itself is simple, but its applicability is limited. The basis of the theoretical model is the surface energy balance equation. The physical model mainly includes a single source model and a double source model. The single source model does not distinguish vegetation transpiration and soil evaporation but tends to consider them as a whole (Su et al., 2002; Jia et al., 2003; Roerink et al., 2000; Bastaanssen et al., 1998; Allen et al., 2007). The double source model separates the vegetation canopy from the soil and calculates the soil temperature and canopy temperature. Then, the sensible heat flux and latent heat flux are also calculated (Norman et al., 1995; Sánchez et al., 2008).

Some studies have been carried out to estimate surface energy fluxes over the TP based on polar orbiting satellite data. Ma et al. (2003) estimated the surface energy flux of the CAMP (CEOP Asia–Australia monsoon project)/Tibet area using NOAA-14/AVHRR data. The results show that the estimated surface energy flux is in good agreement with the in situ measurements. Oku et al. (2007) used land surface temperature derived from Geostationary Meteorological Satellite (GMS)-5 and other essential parameters from NOAA-AVHRR, ERA-40 to estimate land surface heat fluxes for regions above 4000 m over the TP. However, the coarse resolution of EAR-40 (25 km) and large error of LST (more than 10 K) brought large uncertainties in final results. Ma et al. (2009) estimated the surface characteristic parameters and surface energy flux of the northern Tibetan Plateau in summer, winter and spring using a parameterized scheme for ASTER satellite data. Chen et al. (2013a) used observations from 4 sites in the TP to evaluate the results of the SEBS model and optimize the thermodynamic roughness parameterization scheme for underlying surface of bare soil. Based on Landsat TM/ETM+ data, Chen et al. (2013b) derived the surface energy flux of the Mount Everest area by using the enhanced SEBS model (TESEBS), which takes the influence of terrain factors on the solar radiation into account, and the SEBS model. The results show that the estimated results from the TESEBS model are superior to those from the SEBS model.

At present, the estimation of the surface energy flux of the TP is mainly based on polar orbit satellite data. Because of the low temporal resolution of the polar orbit satellites, time series of land-atmosphere energy and water exchange data with high temporal resolution in the TP have not been retrieved to date, and the effective basic parameters for the climate model cannot yet be provided. In addition, one of the basic characteristics of the atmospheric boundary layer is its diurnal variation, and information on daily
variations in surface energy flux is also lacking over the TP. Furthermore, in previous studies of surface energy flux estimation, the accuracy of the model estimation is usually validated directly by the in situ measurements. The "energy closure" problem existing in the surface flux observation data has not received much attention, and the validation results have some uncertainties. Many previous studies have shown that there is a widespread "energy unclosed" problem in surface flux observations (Twine et al, 2000; Lee et al, 2002; Mauder et al, 2007; Yang et al, 2008). Pan et al. (2017) noted that the latent heat flux can be significantly underestimated by the eddy correlation method, while the Bowen ratio correlation method, which is based on the surface energy balance equation and the gradient diffusion theory of the surface layer, can effectively improve the underestimation of the latent heat flux.

This paper mainly focused on how to acquire time series of energy flux data with high temporal resolution using a combination of geostationary and polar orbiting satellite data. First, based on the surface flux measurements in the TP, the problem of "energy closure" in the observational data was improved by using the Bowen ratio calibration method. Then, the surface energy fluxes over the TP were estimated using the SEBS model with inputs from high temporal resolution land surface temperature from FY-2C data and other land surface characteristic parameters from polar orbiting satellite data. The derived land surface heat fluxes were validated by flux tower measurements and were also compared with GLDAS flux products. The study area and datasets used in this study are introduced in section 2. The model description is given in section 3, followed by the results and discussion in section 4. The main conclusions are drawn in section 5.

2. Study Area and Data

The TP, located in southwest China, has an area of approximately 2.5×10^6 km^2 (Fig. 1). It is the largest plateau in China. With an average elevation of approximately 4000 m, it is also the highest plateau in the world, and the high elevation can directly influence the middle and upper layers of the atmosphere.

For a long time, due to the harsh climate conditions and complex topography of the TP, meteorological stations in this area have been not only sparse but also uneven. A total of 6 meteorological stations have been used to compare with model estimates. Although these 6 sites are not scattered throughout the entire TP, they include several major land cover types (Zhong et al, 2010), and their elevation varies from 3000 m to 5000 m (Table 1). These stations are the only stations currently available, and each station is equipped to make four-component radiation measurements, soil moisture and temperature measurements,
eddy-covariance measurements and conventional observation items such as wind speed ($u$), air temperature ($T_a$), specific humidity (SH) and air pressure ($P_s$).

Both the geostationary satellite Feng Yun 2C (FY-2C) and the polar orbiting satellite SPOT are used to retrieve the essential land surface characteristic parameters. The stretched visible and infrared spin scan radiometer (SVISSR) onboard FY-2C is used to derive the hourly land surface temperature (LST) with a spatial resolution of 5 km following the algorithms developed by our group (Hu et al, 2018). We should point out here is that SVISSR has no infrared channel, which would be needed to derive NDVI, albedo and emissivity. Suppose that these parameters (NDVI, albedo and emissivity) have little variation during a day; then, the product of the orbiting satellite SPOT is used instead. The spatial resolution for NDVI, albedo and emissivity is 1 km with a daily temporal resolution.

A forcing dataset developed by the Institute of Tibetan Plateau Research, Chinese Academy of Sciences (ITPCAS), is used as model input in this study. The dataset has merged the observations from 740 operational stations of the CMA with the corresponding Princeton global meteorological forcing dataset (He, 2010; Yang et al, 2010). The parameters used in this study are downward shortwave radiation ($R_{swd}$), downward longwave radiation ($R_{lw}$), wind speed, air temperature, specific humidity and air pressure. All these parameters have a spatial resolution of 10 km and a temporal resolution of 3 hours (Table 2).

Since 6 stations in Table 1 were not used in ITPCAS forcing data, they can be used as independent data to validate the accuracy of forcing meteorological data. The RMSE (root mean square error), MB (mean bias), MAE (mean absolute error) and R (correlation coefficient) are used to make a comparison between ITPCAS forcing data and in situ meteorological data.

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{N} (x_i - obs_i)^2}{N}} \tag{1}
\]

\[
MB = \frac{\sum_{i=1}^{N} (x_i - obs_i)}{N} \tag{2}
\]

\[
MAE = \frac{\sum_{i=1}^{N} |x_i - obs_i|}{N} \tag{3}
\]

\[
R = \frac{\sum_{i=1}^{N} (x_i - \bar{x})(obs_i - \bar{obs})}{\sqrt{\sum_{i=1}^{N} (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^{N} (obs_i - \bar{obs})^2}} \tag{4}
\]

where $x_i$ and $obs_i$ are estimation and measurement, respectively. $\bar{x}$ and $\bar{obs}$ are the average values of estimation and measurement, respectively. As seen from Table 3, all six parameters show reasonable accuracy with in situ measurements, which means these forcing parameters can be used as model inputs.
All of the above satellite data and forcing meteorological data have been processed with the spatiotemporal matching technique (Zou et al, 2018).

3. Model Description

Fig. 2 shows the general steps to derive the land surface heat fluxes in this paper. The SEBS model is used in this study. Because the surface energy balance has the four components of radiation \((R_n)\), sensible heat flux \((H_s)\), latent heat flux \((LE)\) and soil heat flux \((G_0)\), the energy balance equation can be written as

\[ R_n = H_s + LE + G_0 \]  

where \(R_n\) can be determined by the surface radiation equation as

\[ R_n = R_{swd}(1 - \alpha) + \varepsilon_a \sigma T_a^4 - \varepsilon_s \sigma T_s^4 \]  

where \(R_{swd}\) is the downwelling solar radiation at the land surface. Because there are no infrared channels on board FY-2C, the NDVI, \(\alpha\) and \(\varepsilon_s\) are derived from SPOT/VGT data. \(\alpha\) is the broadband albedo, which can be derived from the narrowband reflectance of VGT \(\alpha_1, \alpha_2, \alpha_3\) and \(\alpha_4\) (Zou et al, 2018). \(\alpha_1, \alpha_2, \alpha_3\) and \(\alpha_4\) refer to reflectance of blue band, red band, near infrared band and short wave infrared band, respectively.

\[ \alpha = -0.8141\alpha_1 + 0.4254\alpha_2 + 1.2605\alpha_3 - 0.2902\alpha_4 + 0.1819 \]  

The \(\sigma\) in equation (6) is the Stefan-Boltzmann constant \((5.76 \times 10^{-8} \text{W m}^{-2} \text{K}^{-4})\). \(\varepsilon_a\) and \(\varepsilon_s\) are the emissivities of surface air and the land surface, respectively. \(T_a\) and \(T_s\) are the surface air temperature and land surface temperature, respectively. The hourly \(T_s\) is derived from split window algorithms (Hu et al, 2018) based on two thermal bands of FY-2C.

The soil heat flux is determined by net radiation flux and vegetation coverage.

\[ G_0 = R_n[T_s^c + (1 - f_c)(T_s^b - T_s^c)] \]  

where \(T_s^b\) and \(T_s^c\) are ratios of soil heat flux and net radiation flux for bare soil and full vegetation cover, respectively. \(f_c\) is vegetation coverage and can be derived from NDVI as follows.

\[ f_c = \left( \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \right)^2 \]  

\[ NDVI = \frac{\alpha_3 - \alpha_2}{\alpha_3 + \alpha_2} \]  

By using the wind speed and air temperature at the reference height, the sensible heat flux, together with the friction velocity and Obukhov stability length, can be derived by solving the following nonlinear equations.
equations (11-13). Then, the latent heat flux can be estimated by applying equation (5).

\[ L = -\frac{\rho \cdot c_p \cdot \theta_v \cdot u_*^3}{k \cdot g \cdot H_s} \]  

(11)

\[ u_* = k \cdot u \left[ \ln \left( \frac{Z - d_0}{z_{0m}} \right) - \Psi_m \left( \frac{Z - d_0}{L} \right) + \Psi_m \left( \frac{Z_{0m}}{L} \right) \right]^{-1} \]  

(12)

\[ H_s = k \cdot u_* \cdot \rho \cdot c_p \cdot (\theta_0 - \theta_a) \cdot \left[ \ln \left( \frac{Z - d_0}{z_{0h}} \right) - \Psi_h \left( \frac{Z - d_0}{L} \right) + \Psi_h \left( \frac{Z_{0h}}{L} \right) \right]^{-1} \]  

(13)

where \( L \) is the Obukhov length, \( c_p \) is the specific heat at constant pressure, \( \theta_v \) is the surface potential virtual air temperature, \( u_* \) is the friction velocity, \( k \approx 0.4 \) is the von Karman constant, \( g \) is the acceleration due to gravity, \( H_s \) is the sensible heat flux, \( u \) is the mean wind speed at reference height \( z \), \( d_0 \) is the zero plane displacement height, \( z_{0m} \) is the roughness height for momentum transfer, \( z_{0h} \) is the roughness height for heat transfer, \( \Psi_m \) is the stability correction function for momentum heat transfer, \( \Psi_h \) is the stability correction function for sensible heat transfer and \( \theta_0 \) and \( \theta_a \) are the potential temperatures at the surface and reference height, respectively.

4. Results and Discussion

4.1 Validation Against In Situ Flux Tower Measurements

With the aid of SPOT/VGT and FY-2C/SVISSR data, the surface energy budget components have been estimated using the SEBS model. The accuracy of these estimates needs to be validated before further analyses. A total of 6 stations over the TP equipped with eddy-covariance measurements were selected for validation (Table 1). These validation stations cover a variety of climates, land cover types and elevations. The ‘energy imbalance’ is an important research issue and has been widely reported in former studies (Twine et al., 2000; Wilson et al., 2002; Wolf et al., 2008; Majoji et al., 2017; Pan et al., 2017). If these measurements were not corrected and directly used to compare with estimates, some discrepancies would appear. Therefore, a so-called Bowen ratio correction method (Twine et al., 2000; Wilson et al., 2002; Hu et al., 2018) is used to process the in situ flux measurements. The results show that the energy closure ratio can be improved by approximately 20% for different stations (Hu et al., 2018).

Then, the corrected in situ flux measurements are used to validate the satellite estimates. As shown in Fig. 3, the estimates of surface energy budget components show reasonable agreement with in situ measurements. The RMSEs for the net radiation flux, sensible heat flux, latent heat flux and soil heat flux are 76.63 Wm\(^{-2}\), 60.29 Wm\(^{-2}\), 64.65 Wm\(^{-2}\) and 37.5 Wm\(^{-2}\), respectively. The total validation numbers (N) are more than 3837 to make the results much more representative and convincing. To test the
robustness of our results, the surface energy budgets obtained from the Global Land Data Assimilation System (GLDAS) are selected for comparison with FY-2C estimations. The GLDAS products are produced by combining satellite and ground-based observations using advanced land surface modeling and data assimilation techniques (Zhong et al., 2011). These products have been proved to simulate key variables and fluxes with high accuracy (Rodell et al., 2004). Here, 3-hour land surface heat flux products with a spatial resolution of 25 km are selected for comparison with satellite estimates. The comparison shows that the accuracies of surface energy budgets from satellite estimation are much higher than those of GLDAS products (Table 4). The RMSE of the net radiation flux is reduced from 114.32 Wm$^{-2}$ to 76.63 Wm$^{-2}$, while the values for sensible heat flux, latent heat flux and soil heat flux are reduced from 67.77 Wm$^{-2}$, 75.6 Wm$^{-2}$ and 40.05 Wm$^{-2}$ to 60.29 Wm$^{-2}$, 64.65 Wm$^{-2}$ and 37.5 Wm$^{-2}$, respectively. Therefore, the new energy budget products not only have a finer spatial (10 km) and temporal resolution (hourly) than traditional polar orbiting satellite retrievals but also possess much higher accuracy than data assimilation results from GLDAS. Although SEBS algorithm was used in this study and Oku et al. (2007) (Oku 07 hereinafter), the methods to derive the land surface characteristic parameters, such as land surface temperature and albedo are different (Hu et al., 2018; Oku and Ishikawa 2004; Zou et al., 2018). The higher accuracy and finer spatiotemporal resolution of input forcing data (10km, 3 hour) and land surface characteristic parameters derived from satellites make our results superior than Oku 07. It should also be noted that there is only one station used to do the validation in Oku 07 while six stations with four major land cover types were used in this study to make the results much more robust. Moreover, our results cover the entire TP while Oku 07 only cover the region above 4000 m in the TP.

However, that there are indeed some discrepancies for this new product should be pointed out here, which means some room is still available to improve current products. The error sources may come from multiple aspects, such as the uncertainties of input forcing data, the accuracy of land surface parameters from satellite retrievals and some assumptions and simplification in the SEBS model itself. Furthermore, the mismatch between in situ measurements at the point level and the scales at the pixel level or grid level may also cause some errors. According to Zou et al. (2018), the input variables of land surface temperature, air temperature, wind speed and humidity have the largest influences on the accuracy of land surface heat fluxes. As revealed by Hu et al. (2018), the MB for LST is approximately -0.1 K. However, there are clearly underestimations of the surface air temperature and wind speed of approximately -0.045 K and -1.1 m s$^{-1}$, respectively. Under a combination of land-atmosphere
temperature difference and wind speed, the sensible heat flux is underestimated. The underestimation of net radiation can be explained by the negative deviations (-4.73 W m⁻² and -8.49 W m⁻², respectively) of the downward shortwave flux and longwave radiation flux. A positive deviation in land surface temperature leads to greater upward longwave radiation flux, and a negative deviation in air temperature causes less downward longwave radiation. According to the surface radiation balance equation (Eq. 2), the net radiation flux is underestimated. The overestimation of latent heat flux may be caused by the negative deviation of specific humidity with approximately -0.76 × 10⁻⁴ kg kg⁻¹. This result occurs because less water vapor and higher land surface temperature promote more evapotranspiration.

4.2 Multitemporal and spatial distribution of surface energy budget components

One-year observation data and satellite estimations at BJ station were selected for comparison. As shown in Fig. 4, the satellite results can reproduce both the diurnal and seasonal surface flux variations very well. At the daily temporal scale, all the surface heat fluxes increase with sunrise and reach their maximum at mid-day before decreasing again with sunset. A unique characteristic of the atmospheric boundary layer is its well-known diurnal variations. The diurnal pattern of surface heat fluxes is in agreement with the diurnal evolution of the surface atmospheric boundary layer because the surface energy budgets provide a driving force for the surface atmospheric boundary layer. Fig. 4 also shows that the flux values are usually positive during the day while they become negative in the night. This feature means that the dynamic and thermal contrasts of land and atmosphere are totally different between day and night. The daytime surface heat fluxes are much larger than the values at night. At the seasonal scale, the net radiation flux usually increases from January to its maximum in July. Then, it decreases again from July to December. The variation trends for sensible heat flux and latent heat flux are quite opposite. Because the TP is greatly influenced by the Asian monsoon system and the vegetation intensity usually increases from May to September (Zhong et al., 2010), the sensible heat flux usually decreases while the latent heat flux usually increases from the premonsoon season to the monsoon season. However, from the monsoon season to the postmonsoon season, the sensible heat flux increases while the latent heat flux decreases.

A clear diurnal variation in hourly sensible heat flux and latent heat flux maps over the entire TP is shown in Fig. 5. Similar to the diurnal variations of net radiation flux, the amplitude of the sensible heat flux is relatively small before sunrise. Then, the sensible heat flux increases quickly until it reaches its
maximum at approximately 14:00 (local standard time). After this time, it decreases gradually and tends to be smooth at night. The spatial distribution of sensible heat flux is somewhat complicated. In general, because of the sparse vegetation coverage and limited soil moisture in the western TP, the sensible heat flux is much lower than those in other parts of the TP. The latent heat flux tends to be zero before sunrise. With more solar energy after sunrise and much more evaporation from the soil and transpiration of vegetation, the latent heat flux rises gradually and reaches its maximum at 14:00. The spatial distribution of latent heat flux is in good agreement with land surface status. In the southeastern part of the TP, the climate conditions are warm and wet. Thus, the vegetation density is much higher than that in the northwestern part. From southeast to northwest, the vegetation changes from forest, meadow, grassland to sands and gravels, and the latent heat flux decreases accordingly.

5. Conclusions and remarks

A typical characteristic of the atmospheric boundary layer is diurnal variation. For a long time, little knowledge has been acquired to understand plateau-scale land-atmosphere interactions, especially their energy and water transfers, because of the limitation of point-scale observation and the low temporal resolution of polar orbiting satellites. In this study, polar orbiting satellite data were used to retrieve land surface characteristic parameters such as NDVI, vegetation coverage, albedo and emissivity. These parameters can be considered to have relatively very small diurnal variation but large seasonal variation. For other parameters with more typical diurnal variations, such as land surface temperature, the geostationary satellite FY-2C was used to retrieve plateau-scale land-surface temperatures. Other parameters with typical diurnal characteristics, such as downward longwave and shortwave radiation, air temperature, specific humidity, wind speed and air pressure, were derived from ITPCAS data. Based on the SEBS model and the above inputs, a time series of hourly land-atmosphere heat flux data over the TP was derived using a combination of geostationary and polar orbiting satellite data. The new dataset has a fine spatial resolution of 10 km. According to the validation with 6 field stations (more than 3800 samples), the high correlation coefficients and low RMSEs indicate that the estimated land surface heat fluxes are in good agreement with ground truth. Furthermore, the estimates were also compared with GLDAS flux data, which were thought to have high accuracy. The results showed that most derived variables were superior to GLDAS data. Based on this new dataset, the diurnal cycle of land surface heat fluxes was clearly identified. Moreover, the seasonal variations were found to be influenced by the Asian...
monsoon system. This new dataset can help to understand and quantify the diurnal variations in the land surface heating field, which are very important for atmospheric circulation and weather changes in the TP, especially in winter and spring when the main heating source is from the land surface. This dataset can also help to evaluate the results of numerical models. The uncertainties of input forcing data, the accuracy of land surface parameters from satellite retrievals, the mismatch between different scales and some assumptions and simplification in the SEBS model itself lead to some discrepancies between estimation and observation. For the next step, it is worthwhile to examine subpixel surface heat fluxes using techniques such as the temperature-sharpening method. Additionally, the FY-4 satellite with much high spatial, temporal and spectral resolution will provide the opportunity to monitor land-atmosphere interactions in much more detail.

**Data availability.** The ground-based measurements used in this study were obtained from the Third Pole Environment Database (http://www.tpedatabase.cn/portal/MetaDataInfo.jsp?MetaDataId=43). The SPOT data can be downloaded from https://www.vito-eodata.be/PDF/portal/Application.html. The FY-2C data can be downloaded from http://satellite.nsmc.org.cn/portalsite/Data/DataView.aspx. The forcing data set for this study can be obtained from http://dam.itpcas.ac.cn/chs/rs/?q=data.

**Author contributions.** LZ designed the study and performed the SEBS model with help from YM and ZH. XW, MC and NG collected the analyzed the in-situ flux data and forcing data. YH and LZ retrieved the land surface parameters form FY-2C and SPOT data. LZ wrote the manuscript with help from YM and YF. All commented on the paper.

**Competing interests.** The authors declare that they have no conflict of interest.

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Table 1: Ground measurement sites.

<table>
<thead>
<tr>
<th>Sites</th>
<th>Longitude (°E)</th>
<th>Latitude (°N)</th>
<th>Elevation (m)</th>
<th>Land cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>BJ</td>
<td>91.899</td>
<td>31.369</td>
<td>4509.0</td>
<td>Plateau meadow</td>
</tr>
<tr>
<td>D105</td>
<td>91.943</td>
<td>33.064</td>
<td>5039.0</td>
<td>Plateau grassland</td>
</tr>
<tr>
<td>MS3478</td>
<td>91.716</td>
<td>31.926</td>
<td>4620.0</td>
<td>Plateau meadow</td>
</tr>
<tr>
<td>Linzhi</td>
<td>94.738</td>
<td>29.765</td>
<td>3326.0</td>
<td>Slope grassland</td>
</tr>
<tr>
<td>Nam Co</td>
<td>90.989</td>
<td>30.775</td>
<td>4730.0</td>
<td>Plateau grassland</td>
</tr>
<tr>
<td>QOMS</td>
<td>86.946</td>
<td>28.358</td>
<td>4276.0</td>
<td>Gravels</td>
</tr>
</tbody>
</table>

Table 2: Summary of the input datasets used for calculating land surface heat fluxes.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Data Source</th>
<th>Spatial</th>
<th>Temporal</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_a)</td>
<td>FY-2C/SVISSR</td>
<td>5 km</td>
<td>hourly</td>
</tr>
<tr>
<td>NDVI</td>
<td>SPOT/VGT</td>
<td>1 km</td>
<td>daily</td>
</tr>
<tr>
<td>(R_s)</td>
<td>SPOT/VGT</td>
<td>1 km</td>
<td>daily</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>SPOT/VGT</td>
<td>1 km</td>
<td>daily</td>
</tr>
<tr>
<td>(\epsilon_s)</td>
<td>SPOT/VGT</td>
<td>1 km</td>
<td>daily</td>
</tr>
<tr>
<td>(R_{swd})</td>
<td>ITPCAS</td>
<td>10 km</td>
<td>3-hour</td>
</tr>
<tr>
<td>(R_{lwdd})</td>
<td>ITPCAS</td>
<td>10 km</td>
<td>3-hour</td>
</tr>
<tr>
<td>(u)</td>
<td>ITPCAS</td>
<td>10 km</td>
<td>3-hour</td>
</tr>
<tr>
<td>(T_a)</td>
<td>ITPCAS</td>
<td>10 km</td>
<td>3-hour</td>
</tr>
<tr>
<td>SH</td>
<td>ITPCAS</td>
<td>10 km</td>
<td>3-hour</td>
</tr>
<tr>
<td>(R_s)</td>
<td>ITPCAS</td>
<td>10 km</td>
<td>3-hour</td>
</tr>
</tbody>
</table>
Table 3: The validation of forcing data.

<table>
<thead>
<tr>
<th>Variables</th>
<th>RMSE</th>
<th>MB</th>
<th>MAE</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{swd}$ (W m$^{-2}$)</td>
<td>68.50</td>
<td>-4.73</td>
<td>37.38</td>
<td>0.974</td>
<td>1048</td>
</tr>
<tr>
<td>$R_{ldf}$ (W m$^{-2}$)</td>
<td>20.98</td>
<td>-8.49</td>
<td>16.98</td>
<td>0.954</td>
<td>1048</td>
</tr>
<tr>
<td>$u$ (m s$^{-1}$)</td>
<td>1.71</td>
<td>-1.01</td>
<td>1.28</td>
<td>0.793</td>
<td>1440</td>
</tr>
<tr>
<td>$T_a$ (K)</td>
<td>2.08</td>
<td>-0.045</td>
<td>1.08</td>
<td>0.975</td>
<td>1440</td>
</tr>
<tr>
<td>SH (kg kg$^{-1}$)</td>
<td>0.56$\times$10$^{-3}$</td>
<td>-0.76$\times$10$^{-4}$</td>
<td>0.37$\times$10$^{-3}$</td>
<td>0.981</td>
<td>1438</td>
</tr>
<tr>
<td>$P_s$ (hPa)</td>
<td>8.51</td>
<td>-2.25</td>
<td>6.53</td>
<td>0.865</td>
<td>1440</td>
</tr>
</tbody>
</table>

Table 4: Comparison of derived flux data product and GLDAS against in situ measurements (Units: W m$^{-2}$).

<table>
<thead>
<tr>
<th>Model</th>
<th>Indicators</th>
<th>Rn</th>
<th>H</th>
<th>LE</th>
<th>Gs</th>
<th>SWU</th>
<th>LWU</th>
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</thead>
<tbody>
<tr>
<td>SEBS</td>
<td>RMSE</td>
<td>76.63</td>
<td>60.29</td>
<td>64.65</td>
<td>37.5</td>
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<td>52.99</td>
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<tr>
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<td>MB</td>
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<td>-22.13</td>
<td>6.03</td>
<td>7.81</td>
<td>11.74</td>
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<tr>
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<td>44.39</td>
<td>28.43</td>
<td>26.88</td>
<td>39.31</td>
</tr>
<tr>
<td></td>
<td>R</td>
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<td>0.789</td>
<td>0.792</td>
<td>0.791</td>
<td>0.900</td>
<td>0.798</td>
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<td>4554</td>
<td>3865</td>
<td>3837</td>
<td>4898</td>
<td>4721</td>
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<tr>
<td>GLDAS</td>
<td>RMSE</td>
<td>114.32</td>
<td>67.77</td>
<td>75.60</td>
<td>40.05</td>
<td>56.97</td>
<td>45.18</td>
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<tr>
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<td>27.88</td>
<td>-10.35</td>
<td>-4.00</td>
<td>-15.42</td>
<td>-28.06</td>
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<td></td>
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<tr>
<td></td>
<td>R</td>
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<td>0.660</td>
<td>0.755</td>
<td>0.779</td>
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<tr>
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<td>1633</td>
<td>1580</td>
<td>1341</td>
<td>1329</td>
<td>1633</td>
<td>1633</td>
</tr>
</tbody>
</table>
Figure 1: Location of the Tibetan Plateau. The pentagrams represent the eddy-covariance stations in the Tibetan Plateau.
Figure 2: Flowchart of the flux estimation method.
Figure 3: Validation of surface heat fluxes estimated by the SEBS model with in situ measurements (a. Net radiation flux; b. Sensible heat flux; c. Latent heat flux; d. Soil heat flux).
Figure 4: Time series of diurnal change in surface energy fluxes (units: Wm\(^{-2}\)) observed by in situ measurements (curve) and those estimated by using the SEBS model (circle) at the BJ station in 2008.
Figure 5: The spatial distribution and diurnal cycle of sensible heat flux (top panels) and latent heat flux (bottom panels) over the TP.