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Surface energy balance closure at ten sites over the Tibetan plateau☆

Yu-Fei Xin[a], Fei Chen[a,b,*], Ping Zhao[a], Michael Barlage[b], Peter Blanken[c], Yue-Li Chen[a], Bin Chen[a], Ying-Jun Wang[a]

[a] State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Science, Beijing, China
[b] National Center for Atmospheric Research, Boulder, CO 80301, United States
[c] Department of Geography, University of Colorado, Boulder, CO 80301, United States

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ABSTRACT

Observations of the surface heat fluxes can be used to evaluate and improve land-surface models (LSMs). There are significant uncertainties, however, in measured surface-energy budgets, especially for the heterogeneous Tibetan Plateau (TP) region where the observation conditions are harsh. In this study, summer (July-October 2014) surface flux data were obtained using the eddy covariance method from ten sites over the TP during the Third Tibetan Plateau Atmospheric Scientific Experiments. Data analysis was performed to assess the surface-energy balance ratio (SEBR = H + LE/(Rn-G)) and associated uncertainties across various land-cover types and elevation heights. Measured latent heat fluxes were positive during nighttime and exhibit substantially greater uncertainty than the sensible heat fluxes. The ten-site averaged SEBR was 74.2 ± 5.4%, largely on par with reported SEBR for other regions. SEBR values were similar among homogeneous sites, and the averaged SEBR (93.4%) for those sites was better than that (67.3%) for the heterogeneous sites. The soil heat storage term represents the most significant source of uncertainty (8.2%) than the canopy storage term (0.22%) to closing the surface energy budget. The SEBR showed a strong diurnal cycle and the midday (10:00 ~ 15:00 local time) values were higher than those nearest sunrise and sunset times. The late-night SEBR (00:00 ~ 6:00 local time) at sites located at higher elevations were more reliable than those at lower elevation sites, because of the frequent occurrence of neutral conditions (instead of stable or very stable conditions) at high terrains. The relationships between SEBR and surface-layer turbulent parameters (ξ, u*,θ*) and wind direction were investigated. An uncertainty range for measured surface heat fluxes was derived to provide a meaningful guidance for applying these observations in evaluating LSMs.

1. Introduction

The Tibetan Plateau (TP), through its orographic and thermal effects, significantly influences the Asian Monsoon system and even global climate (Boos and Kuang, 2010; Wu et al., 2012; Xu et al., 2008; Zhao et al., 2016a; Zhou et al., 2009).The complex interactions between the TP land surfaces and the atmosphere play an important role in modulating these influences (Duan et al., 2011; Xu et al., 2012; Liu and Zhao, 2015; Zhao et al., 2007; Liu et al., 2014; Gao et al., 2016). Nevertheless, numerous studies revealed significant challenges in simulating TP land-surface processes such as the surface energy balance, soil moisture and temperature, seasonal snow evolution, and seasonal and permanent frozen soil (e.g., Ma et al., 2008; Yang et al., 2013; Gao et al., 2015, 2016; Zhang et al., 2016).Since land surface models (LSM) improvements heavily rely on evaluation data, it is therefore necessary to first assess the uncertainties in observed surface-heat fluxes and explore methods to consider those uncertainties in evaluating LSMs, especially in the complex terrain and data-scarce regions such as the TP.

The eddy-covariance method using ultrasonic anemometer and trace-gas analyzers to measure the mass and energy flux exchange between land and the atmosphere has been considered superior to other gradient-based methods (Foken, 2008). Nevertheless, since the eddy covariance method does not required energy balance closure to calculated turbulent fluxes, the individually-measureed components of the surface energy balance equation may not balance. This is the well-known "energy balance closure" issue that has faced the flux community for decades (Wilson et al., 2002). It is thisclosure problem, typically on the order of 20% of the surface availableenergy, that is the main uncertainties in observed surface-heat flux and makes the evaluation of LSMs more challenging (Chen et al., 2007). This problem is reported in sites around the globe regardless of surface type (Foken and Oncley, 1995; Foken, 2008; Wilson et al., 2002; Franssen et al., 2010;

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* Corresponding author at: NCAR/RAL, PO Box 3000, Boulder, Colorado 80307-3000, United States.
E-mail address: feichen@ucar.edu (F. Chen).

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Oncley et al., 2007; Barr et al., 2006; Twine et al., 2000; Yates et al., 2001). To date, an averaged surface-energy closure ratio range between 0.75 and 0.87 (Barr et al., 2006; Franssen et al., 2010; Li et al., 2005) though near-to-fullclosure ratio has been reported (Wilson et al., 2002; Lindroth et al. 2009). However, due to buoyancy-driven turbulent circulations resulting from landscape heterogeneity (Foken, 2008; Panin and Bernhofer, 2008), surface-energy closure problem has still be found and its reasons has still be debated in micrometeorological and ecosystem communities (Sakai et al., 2001; Finnigan et al., 2003; Stoy et al., 2013; Castelvi and Oliphant, 2017), including the TP region (Li et al., 2015).

Field experiments focusing on land and boundary-layer observations have been conducted over the TP such as the Global Energy and Water Cycle Experiment (GEWEX)Asian Monsoon Experiment (GAME/Tibet, Tanaka et al., 2003),the Coordinated Enhanced Observing Period of Asia-Australia Monsoon Project on the TP(CAMP/Tibet, Ma et al., 2008), and Japan International Cooperation Agency Project on the TP (JICA/Tibet, Xu et al., 2008).A recent effort led by the Chinese Meteorological Administration (CMA) and joined by numerous groups in China built new observational networks, and reorganized existing ones to improve and extend observations across theTP. This new field experiment, the Third Tibetan PlateauAtmospheric Scientific Experiment (TIPEX III, Zhao et al., 2016b), started in July 2014 and is expected to continue for 8–10 years, as a follow-up experiment to the First Tibetan Plateau Atmospheric Scientific experiment (TIPEX I) in 1979 and the Second Tibetan Plateau Atmospheric Scientific Experiment (TIPEX II) in 1998. Data collected from those experiments are valuable to study the surface energy and water cycle, and to evaluateLSMs.

To date, only a few studies have examined the surface-energy balance closure at selectedsites over the TP (Li et al., 2015; Gu et al., 2005; Tanaka et al., 2003).Li et al. (2015) found the surface energy closure ratio varied seasonally at four TP sites with over a 3-year period. Gu et al. (2005) found the surface energy closure ratio at an alpine-meadow site averaged 0.66, and the Tanaka et al. (2003) results were about 0.7 ~ 0.8 over several Tibetan sites during the Intensive Observation Period (IOP) of the GEWEX Asian Monsoon Experiment (GAME) in 1998.

Given the significant lack of energy balance closure, and the lack of such analysis at the TP sites created since these last studies, this study aims to:1) provide an assessment of surface-energy balance closure using data collected at ten sites over different land-cover types from the recent TIPEX-III Experiment;2) investigate the relationship between surface-energy imbalances, various surface-layer stability parameters and environmental conditions, and 3) explore methods of quantifying observation uncertainties to aid in the evaluation of land models. Observation data and analysis methods are introduced in Section 2, the energy balance closure, its relationship with stability parameters, and implication to LSM evaluation are discussed in Section 3, followed by the summary in Section 4.

2. Data and methods

2.1. Study sites

Fig. 1 shows the geographical locations of the ten TIPEX III flux-tower sites used in this study, with details provided in Table 1. Land-surface characteristics are shown in Fig. 2 and Fig. 4. The Ali (AL) site is located in the northwest TP where the observation conditions are challenging due to thin air and low oxygen concentration, while the relatively low-elevation Dali (DL) site is located at the southeastern edge of the TP, an area vital for East Asian monsoon water-vapor transport. Eight of the ten sites are located at elevations higher than 4,000 m, and are dominated by short alpine meadow except for Dali (DL, cropland) and Linzhi (LZ, grassland). Despite the harsh observation environments, TIPEX-III successfully instrumented planetary boundary layer (PBL) towers equipped witheddy-covariance observational systems at those sites as the part of the TIPEX-III mission to investigate land-atmospheric interactions (Zhao et al., 2016b). Fig. 2 provides a snapshot of site environments.

A site categorization is useful for conducting data analysis. After conducting a simple two-dimensional parameterization for the upwind source area contributing to the turbulent flux following the Kljun et al. (2015) model, the turbulent flux footprints only for unstable conditions ((z-d)/L < 0, z is the sensor height, d the zero-plane displacement height, L the Monin-Obukhov length) for ten sites are shown in Fig. 4. Combined with each site terrain information (as shown in Fig. 3), since the Auduo (AD), Naqu (NQ), Bange (BG), sites are located in flat areas (Fig. 3) and flux mainly contributed from the relative simple meadow land cover (Fig. 4), it is reasonable to characterize them as homogeneous meadow sites. On the other hand, the Biru (BR), Jiali (JL), and Nierong (NR) are surrounded by complex terrains (Fig. 3) and tower is circled by many complex land cover (Fig. 4), the three sites are characterized as heterogeneous sites. The AL site is relatively flat (Fig. 3), but there are building structures near the eddy-covariance sensors (Fig. 4). So it is also classified as heterogeneous sites. The DL site is flat and the land cover (Fig. 4) is used for rotating crops of rice (May-October) and horse bean (November-April), and characterized as a cropland site. The LZ site ranges over a grass land but near a sparse forest (Fig. 2 and Fig. 4) and surrounded by complex terrain (Fig. 3), characterized as grassland site. The Namco (NMC) site is flat and mostly bare soil, so it is characterized as a bare-soil site.

2.2. Observation data

Table 2 lists the tower—based instruments used to measure the surface energy balance. The data obtained for this study, for most of sites, spanned the period beginning in July and ending in September 2014 during the typical Monsoon vegetation-growing season. All sites employed similar radiometers, sonic anemometers, and soil flux plates (Table 2), and the accuracy of all sensors was classified as Type A with measuring errors less than 5 ~ 10% (Foken, 2008). The measuring height of most radiometers was1.5 m and sonic anemometers are 2–5 m, consistent with measuring heights for short grassland and bare ground (Foken, 2008). For all sites, the solar radiation and ground heat fluxes underwent (same?) data quality control, and the turbulent fluxes were processed and quality-controlled by the EDDYPRO (version 5.1) software package. The processing steps and flux corrections listed as following: 1) discard flux data missing more than 11%, and use 30-min as the flux averaging interval; 2) use the double axis rotation for the sonic anemometer tilt correction (Tanner and Thurtell, 1969); 3) use the block 30-min average method for turbulent fluctuations; 4) use the WPL (Webb et al., 1980) method for correcting density effects; 5) use high/low frequency spectral corrections to compensate for flux losses (Moncrieff et al., 1997); 6) use the method of Vickers and Mahrt (1997) to assess the statistical quality of the raw time series; and 7) assign quality flag to a specific half-hourly turbulent flux (Foken et al., 2004) and only use quality flag classes 1–2 for the next analysis. Additionally, the footprint analysis for the turbulent fluxes are showed in Table 2 and Fig. 4.

The ground heat flux (G) at the soil surface is an important variable in surface energy balance, which includes two parts: the heat flux observed from ground heat plate and the heat storage in the upper soil-layer. The first part should be corrected when the thermal conductivity of soil is different from that of the sensor (Tanaka et al., 2003; Oncley et al., 2007), and Philip (1961) suggested using the following formula:

$$\frac{G'}{G} = \frac{\omega}{1 + (\omega - 1)(1 - 1.7\eta)} \tag{1}$$

Where $\omega = \lambda_{plate}/\lambda_{soil}$ is the ratio of the thermal conductivity of the heat plate to that of soil, and $\eta = d/A^{1/2}$ is the deformation factor of the heat plate defined by the ratio of the thickness d (4 mm) to the square