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Comparison of the surface energy budget between regions of seasonally frozen ground and permafrost on the Tibetan Plateau

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ABSTRACT

Surface energy budgets were calculated using turbulent flux observation data and meteorological gradient data collected in 2008 from two sites: BJ, located in a seasonally frozen ground region, and Tanggula, located in a permafrost region. In 2008, the energy closure ratios for the BJ and Tanggula sites were 0.74 and 0.73, respectively, using 30-min instantaneous energy flux data but 0.87 and 0.99, respectively, using daily average energy flux data. Therefore, the energy closure status is related to the time scale that is used for the study. The variation in the surface energy budget at the two sites was similar: The sensible heat flux (*Hs*) was relatively high in spring and reduced in summer but gradually increased in autumn. The latent heat flux (*LE*) was higher in summer and autumn but lower in winter and spring. Comparably, the starting time for the significant increase in *LE* occurred earlier at the Tanggula site than that at the BJ site, because the freezing and thawing progress of the active layer of permafrost at Tanggula site significantly affected the *Hs* and *LE* distributions, but the freezing and thawing processes of the soil at BJ site did not significantly affect the *Hs* and *LE* distributions. The monsoon significantly affected the variation in *Hs* and *LE* at both the BJ and Tanggula sites. Regarding the diurnal variation of the energy budget at the two sites, the daily maximum of net radiation (*Rn*) occurred at approximately 14:00 Beijing Time, and the daily maximum of ground heat flux (G_0) was earlier than those of *Hs* and *LE*. The albedo and Bowen ratio for the two sites were both low in summer but high in winter. The albedo increased significantly but the Bowen ratio became lower or even negative when the surface was covered with deep snow.

1. Introduction

The Tibetan Plateau plays an important role in providing thermodynamic power within the Asian monsoon system. The energy and water cycles of the Tibetan Plateau are important for the formation and development of the Asian monsoon system, and components of the Asian and global energy and water cycles (Ye and Gao, 1979; Ye, 1981; Yanai et al., 1992; Ye and Wu, 1998; Shi et al., 2001; Hsu and Liu, 2003; Sato and Kimura, 2007; Xu et al., 2008; Ma et al., 2008; Cui and Graf, 2009; Duan et al., 2012; Yang et al., 2011, 2014). Permafrost occupies nearly 54.3% of the area of the Tibetan Plateau (Cheng, 2005), where it is an important component of the natural ecosystem of the plateau and a sensitive indicator of climate change (Pavlov, 1994). Seasonally frozen ground covers 1100 × 10^3 km^2 of the Tibetan Plateau (Zhou et al., 2000) and plays an important role on the plateau because most of the important ecological, hydrological, pedological, and biological activities occur within it (Zhao et al., 2004).

The differences exist between the seasonally frozen ground and the permafrost because of the effects of different regions,

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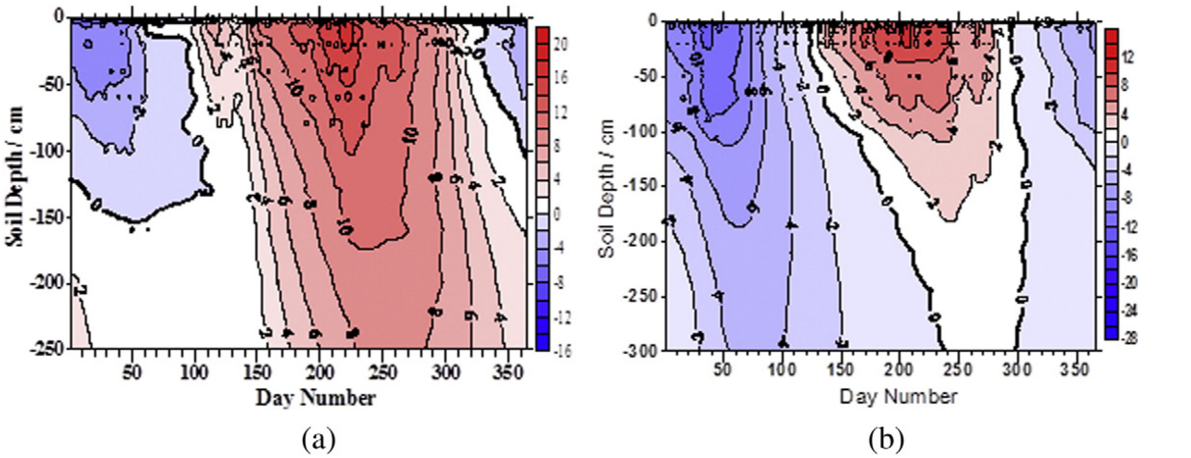

Fig. 1. Comparison of the soil temperatures between BJ site (a) and Tanggula site (b).

geological features, hydrothermal features, and physical processes that play important roles in the regional and global climate systems (Yang et al., 2003). By definition, the seasonally frozen ground only freezes for two weeks to several months each year (Roger and Thian, 2011). The seasonally frozen ground is an important portion of hydrologic and climatic variables because of their effects on water supplies, energy exchanges, and climate–cryosphere interactions in the atmospheric boundary layer (Duguay et al., 2005). Permafrost is ground that remains at or below 0 °C for at least two consecutive years, and the near surface formed an active layer along with the transition of seasons (Woo, 2012). The freezing and thawing processes of the active layer of the permafrost affect the migration and distribution of the unfrozen water in the frozen soil, thereby affecting the hydrothermal conduction properties and heat flux of the soil. Additionally, the permafrost influenced the infiltration of rain and snowmelt and affected surface runoff and evaporation. Such processes are important influences on the surface energy budget (Zhao et al., 2000). The monitoring of the energy flux change in the permafrost region is meaningful for the study of frozen soils, the interactive feedback of matter, and the energy exchange between the cryosphere and other major spheres as well as for sensitivity analyses (Ramos et al., 2007).

The surface energy, mass, and momentum are changing with climatic warming and may have direct and/or indirect feedbacks to the climate. The energy and water budgets for the regions of seasonally frozen ground and permafrost on the Tibetan Plateau are extremely important and strongly coupled with hydrology and climate as well as with other biological and physical processes related to ecosystem structure and function (Gu et al., 2005; Ma et al., 2009; Duan et al., 2012; Yang et al., 2014). The surface of the Tibetan Plateau absorbs a large amount of solar radiation energy and undergoes dramatic seasonal changes in surface heat and water fluxes that greatly influence regional and global climates. Several atmosphere–land interaction experiments have been conducted on the Tibetan Plateau in recent years (Ma et al., 2003, 2009; Tanaka et al., 2001, 2003). Those scientific experiments have resulted in much progress regarding the understanding of the surface energy and water budget, regional evaporative fraction, the seasonal variability of soil moisture distributions, atmospheric chemistry, and climatic change (Ma and Tsukamoto, 2002; Hirose et al., 2002; Tanaka et al., 2001, 2003; Li et al., 2007; Yao et al., 2008, 2011; Yu et al., 2008; Cong et al., 2009; Ma et al., 2009, 2012; Zheng et al., 2010; Xue et al., 2013; Ma et al., 2014). However, those studies have been limited to the investigation of differences in the surface energy budget between the seasonally frozen ground region and the permafrost region of the Tibetan Plateau.

To understand the mechanisms underlying the surface energy budget processes characterizing the seasonally frozen ground and permafrost regions on the Tibetan Plateau, the present study used the eddy covariance method to calculate the turbulent flux at two sites in 2008: one on seasonally frozen ground (BJ site) and one on permafrost (Tanggula site). The Bowen ratio and mean diurnal variation (MDV) methods were used to fill data gaps. The characteristics and differences in the surface energy budgets at the two sites were analyzed with the goal of contributing to the description and the mechanistic understanding of the land–atmosphere interactions occurring on the Tibetan Plateau.

2. Sites and data

This study used two monitoring sites, one located in the Nagqu Valley region (BJ site) and the other located at Tanggula Pass (Tanggula site). The BJ site (91°54′E; 31°22′N; and 4509 m above sea level (a.s.l.)) is located in the alpine steppe of the Nagqu Valley within a plateau subfrigid semi-humid climate zone. The area of the observation site is 8000 m^2, and the ground is flat, with open surrounding terrain. The surface is primarily covered with sandy soil, accompanied by a sparse distribution of fine stones. An uneven growth of alpine steppe, with a height of 10–20 cm, occurs during the summer. According to the soil temperature data for the BJ site, which is shown in Fig. 1(a), this site is located in the region of seasonally frozen ground. The soil was frozen from January to February, and it thawed from the ground surface beginning at the end of March. The soil froze from the ground surface beginning in early November, and the maximum freezing depth of the soil was approximately 1.5 m.

The Tanggula site (91°52′E; 33°04′N; and 5100 m a.s.l.) is adjacent to the Qinghai–Tibet highway and located on a