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Surface water and heat exchange comparison between alpine meadow and bare land in a permafrost region of the Tibetan Plateau

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ABSTRACT

Patch degradation of the alpine meadow on the Tibetan Plateau (TP) induced by climate warming and anthropogenic activities affects the pattern of coupled water and heat cycling between the land surface and the atmosphere, which could positively feedback to the regional and global climate warming. However, previous research has mostly focused on the homogeneous underlying surface rather than heterogeneous underlying surface. Thus, this study aims at forming a better understanding of the difference in water and heat exchange over heterogeneous underlying surface in the permafrost region of the TP hinterland. We based our analysis on two years of weather and energy flux measurements that were collected over two contrasting landscapes under the same climate conditions: a natural alpine meadow (AM) and severely degraded alpine meadow, termed bare land (BL). The major surface characteristics affecting the difference between AM and BL energy budgets are also presented and analyzed (such as land surface albedo and temperature, shallow soil temperature and moisture, soil stratification, and phenology). The results show that the thawing of a shallow active soil layer induced a rapid increase in soil moisture, triggering the dramatic change in main energy partitioning from sensible heat flux (H) to latent heat flux (LE) in both AM and BL sites. Surface albedo decreased but surface cooling increased with the reduction in the vegetation coverage, and temperature gradient between surface and 10 cm depth increased with the erosion of root turf that is capable of thermal insulation and high water retention, together could alter the surface energy budget. The annual surface heat source or available energy ($R_n - G$) in AM was approximately equal to that in BL. However, more available energy was consumed by H to warm the low atmosphere in BL as evidenced by the Bowen ratio increasing from 0.49 to 0.84 in summer and from 2.96 to 5.64 over a whole year. The results of this research suggest that the soil moisture, canopy, and root turf were the major factors affecting the energy partitioning in the hinterland of the TP. The decrease in vegetation coverage results in increases of H and heating of the lower atmosphere. Therefore, this could lead to a potential positive feedback to regional climate warming. In addition, given the background of TP warming, *Kobresia* turf can effectively prevent permafrost degradation due to its thermal insulation characteristics.

1. Introduction

The water and heat exchange between the land surface and the atmosphere plays a very important role in ecosystem processes, hydrologic and biogeochemical cycles, weather variations, and climate change (Baldocchi et al., 2001; Pielke, 2005; Running et al., 1999; Sellers et al., 1997; Stenseth et al., 2002). Many land surface process field experiments have been conducted to better quantitatively understand the effect of different terrestrial ecosystems on heat and water fluxes and the impact of land cover change induced alteration in fluxes on local, regional and global climate change (Andre et al., 1986; Andreae et al., 2002; Coughlan and Avissar, 1996; Halldin et al., 1999; Menenti et al., 2001; Ramier et al., 2009; Sellers et al., 1988, 1997; Rouse et al., 2003). Based on observations of soil–vegetation–atmosphere interaction in these experiments during the intensive observation periods (IOP) as well as satellite data, land surface water and heat flux were quantified in different terrestrial ecosystems, and many land surface process models

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were established and parameters were optimized from the point to a general circulation model (GCM) scale, i.e., 10^4 km^2 (Pielke, 2005; Running et al., 1999; Sellers et al., 1997).

The Tibetan Plateau (TP) provides a huge heat source for the middle troposphere in the Northern Hemisphere (Wu et al., 2012; Ye and Wu, 1998). Due to its location in mid-low latitude, high elevation (4500 m above sea level), and huge area (2.50×10^6 km^2), the total mass of the air column over the TP is much less than its surroundings, thus the atmospheric heating is more efficient in this region. The unique thermodynamic process on the TP enhances the Asian Monsoon and further influences global atmospheric water and energy cycles (Karl and Trenberth, 2003; Molnar et al., 1993; Ye, 1981). Four land surface process field experiments, i.e., QXPMEX, GAME/Tibet, TiPEX, and CEOP (CAMP/Tibet), as well as data from the Tibetan observation and research platform (TORP) have advanced our understanding of the land–atmosphere interaction, and the collected observational datasets are important to validate global datasets, e.g., satellite data or reanalysis data (Gu et al., 2005; Guo et al., 2011; Ma et al., 2008, 2009; Tanaka et al., 2003; Xu et al., 2008; Yang et al., 2008a, 2011a). Nevertheless, these experiments have all been conducted in the summer. Long-term and high-accuracy observation data are still absent and the scarcity of *in situ* observations cannot represent the great spatial heterogeneity of the land–atmosphere hydro-thermal interactions across the TP due to the forest, shrub/grass communities, and bare land from the southeast to the northwest of the TP with a decreasing precipitation gradient (Ma et al., 2009). In addition, high uncertainty exists in regional climate models and GCMs when simulating the climate over the TP (Cui and Graf, 2009).

During recent decades, the TP has been experiencing significant climate changes. Meteorological data show that the ground surface temperature increases at a decadal rate of 0.36 K in the past 50 years (Wang et al., 2008), which is more than twice of the rate of the global average (0.12 K/decade) (IPCC, 2013). Due to the warming climate, land evaporation increased and led to increase in water vapor levels and deep cloud cover (Yang et al., 2011b). This subsequently caused decrease in solar radiation (Yang et al., 2012). Yet, potential evaporation decreased due to lowered wind speed and solar dimming (Zhang et al., 2009). Sensible heat flux has been weakening as a result of complementary effects between the weakening of wind speed and the increasing difference between ground and air temperature (Guo et al., 2011; Yang et al., 2011a). Warming of TP has already resulted in extensive and profound environmental change, like mountain glaciers retreat (Yao et al., 2007) and permafrost thaws (Cheng and Wu, 2007; Guo et al., 2012; Wu and Zhang, 2008). Significant increases in the net primary production (NPP) and normalized difference vegetation index (NDVI) of alpine grasslands on the TP were found with increasing ground surface temperature and elevating atmospheric CO_2 concentration (Piao et al., 2006; Tan et al., 2010), which could contribute to the development and expansion of alpine grassland (Gao et al., 2014). However, studies in the northern TP and source regions of the Yangtze and Yellow Rivers on the TP show that alpine grasslands have experienced significant degradation (Wang et al., 2007a; Xue et al., 2009; Yi et al., 2011). Alpine meadows (AM) cover an area of about 7×10^5 km^2, accounting for about 50% of the total usable grassland on the TP. AM represents the main pasture area in China and the most widespread grassland type in the permafrost regions of the TP which are the water source areas of several large rivers (Yangtze, Yellow, and Lancang–Mekong rivers). According to a study by Holzner and Kriechbaum (2000), about 30% of the AM on the TP is in optimal condition; about 30% is overgrazed where restoration can be achieved by grassland management and about 40% is in recent or ancient complete degradation. Complete degradation is a condition in which the entire *Kobresia* turf is eroded and underlying mineral soil layer is visible, which is reclassified as bare land (BL) (Wang et al., 2009a; Cui and Graf, 2009; Harris, 2010).

Degradation of AM not only loses fine soil particles, reduces soil organic matter, and deteriorates water sorption and thermal conductivity (Wang et al., 2009a, 2012b), but also affects the regional climate through the surface water and heat budgets (Chen et al., 2009; Pielke, 2005), the regional ecology, and water security of downstream regions (Wang et al., 2007a; Yao et al., 2007). The heterogenous land surface due to the interwoven distribution of the degraded patches and the intact grassland makes it more difficult to predict the water and heat exchange between the land surface and the atmosphere. However, there is a lack of detailed information characterizing the land surface water and heat exchange between the natural AM and secondary BL.

In order to enrich the land surface process field observations and better understand the impacts of grassland degradation on land surface water and heat exchange on the TP, we examined the differences in the water and heat flux between AM and BL. In this paper, an aerodynamic method (or profile method) is used to calculate sensible heat flux (H) and latent heat flux (LE). This method is a useful supplement for turbulent flux calculation due to the remoteness, vastness, and the harsh climatic conditions on the TP, even though the eddy covariance technique (EC) and large aperture scintillometer (LAS) have become the basic tools in the FLUXNET because they can directly measure the turbulent flux (Baldocchi et al., 2001; Stoy et al., 2013; Wilson et al., 2002). Since the diurnal and seasonal variations of the four components of the radiation budget, ground heat flux, H, and LE have been quantified, the land surface heating source strength and energy balance closure on the TP are clear (Gu et al., 2005; Ma et al., 2009; Tanaka et al., 2003; Yang et al., 2011a). Thus, our objectives were limited to (1) quantifying water and heat flux between the land surface and the atmosphere at AM and BL sites, (2) comparing the differences in the surface water and heat flux between AM and BL, (3) examining the effect of underlying surface characteristics on the partitioning of energy fluxes, and (4) performing a preliminary analysis of the AM degradation effect on the permafrost degradation and its feedback to the future climate change on the TP.

2. Materials and methods

2.1. Study site

An *in situ* experiment was conducted in a natural alpine meadow (AM) and adjacent bare land (BL), which represent the most common landscapes in the hinterland of the TP with the geographical coordinates of 34.82° N, 92.92° E (Fig. 1a). The main geomorphologic types in the study area are vast high plains and open valley plains with an average height of 4600–4800 m above sea level (a.s.l.) and relatively small variations in elevation (200 m) (Wang et al., 2007a). The study area belongs to the subfrigid semiarid climate. According to the continuous records for the last 30 years (1981–2010) of the Wudaoliang National Meteorological Station which is situated 46 km north of the study site (4612 m above sea level), the mean annual air temperature is −5.1 °C and the mean annual maximum and minimum air temperatures, derived from the average of the daily maximum and minimum air temperature, is 4.6 °C and −10.8 °C, respectively. The mean annual precipitation is 302 mm, of which 93% falls in the growing season from May to September. Meteorological data also show that 10% of annual precipitation falls as snow. Because of small snowfall amounts and strong solar radiation, there is no steady snow cover on the ground at the study site (data were provided by the Meteorological Information Center of the China Meteorological Administration). The study site is located in the area where permafrost in the TP mainly