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Energy exchange of an alpine grassland on the eastern Qinghai-Tibetan Plateau

Lunyu Shang · Yu Zhang · Shihua Lü · Shaoying Wang

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Abstract The seasonal variability in the surface energy exchange of an alpine grassland on the eastern Qinghai-Tibetan Plateau was investigated using eddy covariance measurements. Based on the change of air temperature and the seasonal distribution of precipitation, a winter season and wet season were identified, which were separated by transitional periods. The annual mean net radiation (R_n) was about 39 % of the annual mean solar radiation (R_s). R_n was relatively low during the winter season (21 % of R_s) compared with the wet season (54 % of R_s), which can be explained by the difference in surface albedo and moisture condition between the two seasons. Annually, the main consumer of net radiation was latent heat flux (*LE*). During the winter season, sensible heat flux (*H*) was dominant because of the frozen soil condition and lack of precipitation. During the wet season, *LE* expended 66 % of R_n due to relatively high temperature and sufficient rainfall coupled with vegetation growth. Leaf area index (LAI) had important influence on energy partitioning during wet season. The high LAI due to high soil water content (θ_v) contributed to high surface conductance (g_c) and *LE*, and thus low Bowen ratio (β). *LE* was strongly controlled by R_n from June to August when g_c and θ_v were high. During the transitional periods, *H* and *LE* were nearly equally partitioned in the energy balance. The results also suggested that the freeze–thaw condition of soil and the seasonal distribution of precipitation had important impacts on the energy exchange in this alpine grassland.

L. Shang (✉) · Y. Zhang · S. Lü · S. Wang
Key Laboratory of Land Surface Process and Climate Change in Cold and Arid Regions, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China
e-mail: sly@lzb.ac.cn

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1 Introduction

The energy exchanges between the Earth's surface and the atmosphere drive the Earth's climate system on local, regional, and global scales [1, 2]. The partitioning of net radiation into sensible, latent, ground, and surface storage heat fluxes is controlled by factors such as climate, land cover characteristics, various processes at the land surface, and plant functional type [3–6]. The Qinghai-Tibetan Plateau is the largest and highest plateau in the world, with an area of about 2.5 million km^2 and an average altitude of more than 4,000 m [7–9]. With its unique topographical and landscape features, the Qinghai-Tibetan Plateau has profound dynamical and thermal influences on the atmospheric circulation [10]. The land surface heterogeneity of the Plateau leads to different aerodynamic and thermodynamic parameters [11]. Because of the significant zonal variability in altitude, land surface features, vegetation, and meteorological characteristics, significant differences exist in heating properties between the western and eastern regions of the Plateau [9, 12–14].

Different viewpoints regarding the heating properties of the Qinghai-Tibetan Plateau have been presented in various studies. For example, the Qinghai-Tibetan Plateau was deemed to be an elevated sensible heat source [15], and latent heat, rather than sensible heat, was the main heat flux from the surface to the atmosphere over the eastern Plateau [13]. Some researchers calculated the average heat source intensity over the Plateau for each month of the year and found that sensible heat flux was greater than latent heat flux every month over the entire Plateau [9]. Other researchers estimated the heat budgets for the western and eastern Plateau during the early summer and found that sensible heat flux dominated the heat budget of the Plateau, especially in western regions during the early summer [16]. A recent study indicated that sensible heat flux was dominant during winter while latent heat flux dominated in summer and autumn over the central Plateau [7]. Moreover, surface energy flux partitioning was related to the phase of the Asian summer monsoon over the eastern Plateau [17].

Although these previous studies focused on the energy budget and role of sensible and latent heating over interior regions of the Qinghai-Tibetan Plateau, few studies have addressed the energy exchange near the boundaries of the Plateau where land and atmosphere conditions can be quite different from interior regions. The eastern border of the Qinghai-Tibetan Plateau is the transitional zone between the Qinghai-Tibetan Plateau and the Loess Plateau, and its land surface features, vegetation, and meteorological characteristics are distinctly different from other regions of the Plateau. The amount of precipitation in Qinghai-Tibetan Plateau decreases from southeast to northwest with a range from 800 to 150 mm. Similar to precipitation, the Normalized Difference Vegetation Index (NDVI) value decreases gradually from southeast to northwest [18]. The dominant vegetation types in the eastern border of the Qinghai-Tibetan Plateau are high-cold shrub meadow and montane steppe, which are different from other parts of the Plateau (e.g., high-cold steppe and meadow steppe in the central Plateau) [19]. However, few studies on energy exchange have been carried out in the region. Additional knowledge on the energy exchange in this border region would provide a more comprehensive understanding of the heating properties of the Qinghai-Tibetan Plateau. Thus, in this paper, an analysis of surface energy exchange in alpine grassland on the eastern Qinghai-Tibetan Plateau is presented. The objective of this study is characterizing the pattern of seasonal and diurnal variation of the energy exchange and examining the roles of sensible and latent heat flux with respect to the total energy flux and the influence of driving variables on energy partitioning.

2 Methods

2.1 Site description

The measurement site (latitude 33.89°N, longitude 102.14°E, and altitude 3,423 m) is located in an alpine meadow grassland, Maqu Grassland, in the Gannan Tibetan Autonomous Prefecture, Gansu Province, China. Maqu Grassland is situated in the eastern Qinghai-Tibetan Plateau (Fig. 1), which is the transitional zone between the Qinghai-Tibetan and Loess Plateaus. The grassland is more than 3,300 m above sea level and dominated by Cyperaceae and Gramineae with an average height of about 0.2 m. The maximum grass height in the peak growth period (late July to early August) can reach up to 0.3 m. The grassland is a typical meadow used for grazing. Topography at the study site is flat and homogenous, with the slope less than 3 %. The soil is silt clay loam, which is composed of 29.8 % sand, 66.7 % silt, and 3.5 % clay in the top 40 cm. The climate at the site is generally cold and damp with wet mild summers and dry cold winters. Based on climate data measured at a meteorological station (latitude 34°N, longitude 102.08°E, and altitude 3,471 m) located approximately 14 km north of the study site, the annual mean air temperature from 1981 to 2010 was 1.9 °C, and the annual mean precipitation was 593 mm with most of the precipitation occurring between May and September and little precipitation during winter. Snow occurred between November and next April with no stable snowpack at the site. Monthly mean air temperatures over the past 30 years were −8.7, −6.0, −1.7, 2.5, 6.1, 9.3, 11.4, 10.7, 7.4, 2.4, −3.5, and −7.5 °C from January to December, respectively. Based on the change of air temperature and the seasonal distribution of precipitation, the year was separated into a winter season (November to March), wet season (from May to September), and transitional periods (April and October).

2.2 Field measurement

Sensible heat flux (*H*) and latent heat flux (*LE*) were estimated using an eddy covariance (EC) system. The system consisted of a three-dimensional sonic anemometer (CSAT-3, Campbell Scientific, Inc., Logan, UT, USA) oriented to the prevailing wind direction and an open path fast response infrared gas analyzer (LI-7500, LI-COR Biosciences Inc., Lincoln, NE, USA). The separation distance between the gas analyzer and sonic anemometer sensors was 0.15 m. The gas analyzer was tilted approximately 15° from the vertical to facilitate the draining of water from the lower lens surface. Both sensors were mounted 3.15 m above the soil surface. The dominant prevailing wind directions are east and southeast in wet season and northwest in winter season at the site. The fetch at the site is greater than 1.5 km for all directions. Calculations with a footprint model [20] indicated that the peak for the flux footprint was approximately 58 m upwind of the sonic sensor, with 90 % cumulative flux footprint extending to approximately 168 m upwind (the two values are the average of the entire measurement period). An air temperature and relative humidity sensor (HMP-45C, Vaisala, Helsinki, Finland) was also installed at the same