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Evapotranspiration and water balance of high-elevation grassland on the Tibetan Plateau

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SUMMARY

High-elevation grasslands of the Cyperaceae *Kobresia pygmaea* cover nearly half a million km^2 on the Tibetan Plateau. As a consequence of climate change, precipitation patterns in this monsoon-influenced region may change with possible consequences for grassland productivity. Yet, not much is known about the water cycle in this second largest alpine ecosystem of the world. We measured the evapotranspiration of a high-elevation *Kobresia* pasture system at 4400 m a.s.l. in the south-eastern part of the plateau in two summers using three different approaches, weighable micro-lysimeters, eddy covariance measurements, and water balance modeling with the soil–plant–atmosphere transfer model SEWAB. In good agreement among the three approaches, we found ET rates of 4–6 mm d^{-1} in moist summer periods (June–August) and ~2 mm d^{-1} in dry periods, despite the high elevation and a leaf area index of only ~1. Measured ET rates were comparable to rates reported from alpine grasslands at 1500–2500 m a.s.l. in temperate mountains, and also matched ET rates of managed lowland grasslands in the temperate zone. At the study site with 430 mm annual precipitation, low summer rainfall reduced ET significantly and infiltration into the subsoil occurred only in moist periods. Our results show that the evapotranspiration of high-elevation grasslands at 4400 m can be as high as in lowland grasslands despite large elevational changes in abiotic and biotic drivers of ET, and periodic water shortage is likely to influence large parts of the Tibetan *Kobresia* pastures.

1. Introduction

The vast mountain grasslands and steppes of the Tibetan Plateau represent the largest alpine ecosystem of the world. Pastures built predominantly by the Cyperaceae *Kobresia pygmaea* cover an area of about 450.000 km^2 in the south-east of the plateau, where a dense grazing lawn of only ~2 cm height exists (Miehe et al., 2011). Intensive grazing by yak and other livestock has partly shaped the physiognomy and species composition of this ecosystem at elevations of 3500–5000 m a.s.l., and grazing has resulted in the degradation of the sward at many places leading eventually to the exposure of bare soil (Wang et al., 2000). The Tibetan Plateau is characterized by a precipitation gradient from the humid south-east to the arid north-west with large parts of the *Kobresia* ecosystem receiving less than 500 mm of rainfall and snow per year. At many places, growing season length seems to depend on water availability and the timing of monsoon-related precipitation (Miehe et al., 2011). The onset of *Kobresia* growth in summer may be delayed in years with late arrival of the summer monsoon which brings moist air masses from the south. Thus, water limitation seems to be an important factor for plant growth in large parts of the Tibetan Plateau, despite its high elevation and low mean temperature. While quite a number of studies have examined potential evapotranspiration or pan evaporation on the plateau

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(e.g. Shenbin et al., 2006; Zhang et al., 2007; Xie et al., 2010), only few authors have investigated the hydrology and water turnover in these extended alpine grasslands (e.g. Gu et al., 2008; Hu et al., 2008). A better understanding of the carbon and water cycles of the *Kobresia* pastures is urgently needed in the light of climate change which already has increased temperature and the atmospheric vapor saturation deficit on the Tibetan Plateau (Zhang et al., 2007; Xie et al., 2010; Yang et al., 2011, 2014) and may result in a drying tendency in future (May, 2004). From the elevation-driven trends in the governing in the meteorological, hydrological and biological factors, one would expect that the evapotranspiration (ET) of mountain grasslands decreases with elevation, mainly due to the temperature-dependent decrease of atmospheric vapor saturation deficit (VPD), but also reductions in leaf area index (LAI) and the length of the growing season (Wieser et al., 2008; van den Bergh et al., 2013). If transferred to the high-alpine *Kobresia* pastures in Tibet with annual mean temperatures below zero, one would expect low ET rates and thus a positive water balance even at the prevailing low precipitation rates. However, simple extrapolation from measurements in temperate alpine ecosystems at 2000–2500 m a.s.l. to the grasslands of the Tibetan Plateau at 4000–5000 m a.s.l. may not be feasible due to several reasons. First, it is unclear whether elevational trends in ET derived from observations in the first two or three km will remain constant up to 5 km elevation. Second, high-elevation climates on the Tibetan Plateau are generally more arid than in the European Alps or the North American Rocky Mountains where most measurements have been conducted so far; this would suggest generally lower actual ET rates in Tibet. Third, the Tibetan Plateau is subject to a much greater Massenerhebung effect on the climatic drivers of ET than any other mountain region on earth. This indicates that certain thresholds of temperature and VPD should be reached at higher elevation in Tibet than in smaller massifs elsewhere. This could result in higher ET rates at high elevations than in smaller mountain ranges under otherwise equal conditions. Complex interactions between the main determinants of ET, i.e. available energy, VPD, atmospheric turbulence, plant surface area (LAI) and leaf conductance, and their dependence on elevation, make any prediction of the water consumption of Tibetan high-elevation grasslands difficult. However, a better understanding of the hydrology of the Tibetan Plateau is of high importance given that mountain water resources play a paramount role for humanity (Viviroli et al., 2007, 2011) and the rivers originating from this vast mountain region are feeding a large part of South Asia's agricultural land.

Here, we present the results of a measuring campaign that employed three independent hydrological and micrometeorological approaches for quantifying ET and soil infiltration in a typical *Kobresia* pasture on the Tibetan Plateau at 4410 m elevation. For the first time, ET measurements with weighable micro-lysimeters could be compared with synchronous data from two eddy covariance towers operated in the same alpine pasture. In an attempt to overcome possible error sources of micro-lysimeters (Ben-Gal and Shani, 2002), we operated these instruments with an improved drainage. The measured results were additionally checked against the results of a model of the latent and sensible heat fluxes using the soil–vegetation–atmosphere scheme SEWAB (Mengelkamp et al., 1999, 2001) evaluated with eddy-covariance measurements. The aim of this study was to obtain reliable estimates of grassland ET at very high elevation for this by area most important alpine ecosystem and to examine the dependence of ET on soil moisture or rainfall in a climate with less than 500 mm y^{-1} of precipitation. With consideration of the large Massenerhebung effect, we formulated the hypotheses that (i) daily ET in summer can be as high as in lowland grasslands when soil moisture is high, and (ii) soil moisture and precipitation are main determinants of ET in this high-elevation environment.

2. Material and methods

2.1. Study site

The study was conducted in the summers of 2010 and 2012 in an alpine *Kobresia pygmaea* pasture near the "*Kobresia pygmaea* Research Station Kema" (31°16′N, 92°06′E) at 4410 m a.s.l. on the Tibetan Plateau (established in 2007 by the Marburg University and the Tibet University Lhasa; operated since 2011 by the Institute of Tibetan Plateau Research, Chinese Academy of Sciences, as the "Naqu Ecological and Environmental Observation and Research Station"). The site is located about 30 km from the town of Nagqu around 300 km NNE of Lhasa in slightly undulating terrain in the south-eastern part of the plateau. The countryside consists of extended pastures that are predominantly used for yak grazing. The local climate is dominated by the Indian monsoon with a mean annual air temperature of −1.2 °C, a mean July temperature of 9.0 °C and mean annual precipitation of 430 mm (Chinese Weather Service, station Naqu; recording period 1971–2000, http://www.weather.com.cn). Eighty percent of the precipitation falls in the monsoon period from June to October. The growing season with daytime temperatures >10 °C lasts from June until September (Miehe et al., 2011). The *Kobresia* plants usually start growth around mid of June after the onset of the monsoon-related precipitation. In 2010, the monsoon started unusually late at the end of July, while summer 2012 was more typical.

The vegetation of the study site consists of a golf course-like dense *Kobresia pygmaea* mat as it is characteristic for vast areas of the Tibetan Plateau (Miehe et al., 2011). Other accompanying monocotyledons are *Carex ivanoviae* and other *Carex* species, *Festuca* and *Poa* species, *Kobresia pusilla*, *Stipa purpurea* and a few perennial herbs (Seeber et al., 2015). The *Kobresia* mat is at places degraded and crusts formed by Cyanophyceae and lichens have establish instead of the Cyperaceae; further degradation results in the exposure of bare soil (Babel et al., 2014). This stage lacks the dense *Kobresia* root turf and thus has a by 10–15 cm lower surface. Causes and mechanisms of this degradation are not fully understood, but initial damage of the root mat by yak grazing, freezing events, or ground-dwelling small mammals such as the abundant pika (*Ochotona curzoniae*) are likely. A survey in summer 2012 in direct vicinity of the research plots found patches of open soil to be present on 19% of the area (Babel et al., 2014).

The soil of the measuring site is a Humic Cambisol (FAO classification) with a 10–15 cm thick organic layer and a 15–30 cm thick sandy–loamy *B* horizon; the C_v horizon consists of coarse gravel and begins at a depth of about 30–40 cm. A dominant pedological characteristic of the *Kobresia* pasture is the very firm root mat which was described as a felty turf horizon (A_{fe}) by Kaiser et al. (2008). Pedogenesis and age of this root mat are still under discussion (Kaiser et al., 2007) but it is likely that the formation of this layer takes decades to centuries, given the slow growth of *Kobresia* in this harsh environment.

2.2. Plot design

The experimental site is situated in slightly sloping terrain with an extension of about 500 m × 500 m; slope inclination is ∼10° with a north-eastern aspect allowing for a sufficiently large fetch for the eddy covariance measurements (Biermann et al., 2011). In this area, a grazing exclusion experiment was established in September 2009 with two adjacent plots of 100 m × 250 m, of which the southern one was fenced against yaks. Inside each plot, eight subplots of 15 m × 15 m were demarcated of which four were enclosed by fences of 30 cm high fine-mesh wire dug 20 cm deep into the soil to keep the ground-dwelling pikas out. This