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Surface energy exchanges above two grassland ecosystems on the Qinghai-Tibetan Plateau

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Abstract

This paper explores the seasonal and inter-annual variations in surface energy exchanges at an alpine shrub-meadow ecosystem (AM) and an alpine meadow-steppe (AS) on the Qinghai-Tibetan Plateau using the 4–5-year continuous flux measurements by the eddy covariance technique. Although ground solar radiation (K_d) was lower at AM than at AS, net radiation (R_n) was higher at AM than at AS due to the lower surface reflectivity for short-wave radiation (albedo) and the lower ratio of upward long-wave radiation to downward long-wave radiation (L_u/L_d) at AM. The ratio of R_n/K_d was lower (about 0.4) at AS than at AM (about 0.6). In the annual scale, annual precipitation was the most important factor controlling energy partitioning at AS, while temperature, especially during the spring, controlled the inter-annual variations in energy partitioning at AM characterized by low temperature. Vegetation growth played an important role in controlling energy partitioning at seasonal scale at both sites. However, soil water content was also one of major factors affecting Bowen ratio (β) due to the lower soil water-holding capacity at AS as compared with AM. Under non-drought conditions, the influence of vapor pressure deficit (VPD) on energy partitioning at half-hourly scale was stronger at AM than at AS due to higher vegetation cover thereof.

1 Introduction

The energy exchange between land surface and the atmosphere is an important process affecting water vapor exchange and carbon sequestration of ecosystems (Ryu et al., 2008), and is critical in driving climate change from the local to even global scales (Raupach, 1998; Cai et al., 2003). The Qinghai-Tibetan Plateau is the highest plateau in the world with a mean altitude of greater than 4000 m above sea level. It is regarded as a sensitive region to global climate change because of their vastness in area and unique geophysical locations. For example, meteorological records for the Qinghai-Tibetan Plateau show that the annual mean temperature increased by

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0.16°C per decade and winter temperature increased by 0.32°C per decade from 1955 to 1996, which are higher than the increase in annual mean temperature of the northern hemisphere and at the same latitude due to global climate change (Zheng and Yao, 2006). Climate change has the potential to affect energy, water vapor and carbon dioxide exchanges of the alpine grassland ecosystem on the Qinghai-Tibetan Plateau.

Recently, a large number of studies on energy and water vapor exchanges have been undertaken in many grassland ecosystems. However, most of these studies have been done in savanna areas, temperate grassland in North America and the steppe on the Mongolian Plateau (Baldocchi et al., 2004; Dugas et al., 1999; Wever et al., 2002; Li et al., 2006a; Hao et al., 2007), and only very few studies have focused on the Qinghai-Tibetan Plateau (Gu et al., 2005; Yao et al., 2008), where alpine grassland occupied more than 60% of the area (Zheng, 2000). It is reported that soil water content is a major factor affecting the energy partitioning in the alpine meadow ecosystem based on 1-year measurement (Gu et al., 2005). However, plant functional-type, weather, and soil physical properties have a profound effect on water and energy fluxes (Baldocchi et al., 2004), and the shift in vegetation types induced by climate may feed back to regional climate (Eugster et al., 2000; Beringer et al., 2005). A model study has suggested that enhanced warming would cause northward shift of the alpine meadow and a reduction in shrub-dominated alpine steppe on the Qinghai-Tibetan Plateau (Song et al., 2005). Therefore, the study on a variety of vegetation communities with continuous flux measurements will advance our understanding of the energy balance on the Qinghai-Tibetan Plateau which has a complicated landscape.

In this paper, we used 4–5 years continuous flux data measured with the eddy covariance technique, from the ChinaFLUX program (Yu et al., 2006), to explore energy exchanges in an alpine shrub-meadow ecosystem and an alpine meadow-steppe on the Qinghai-Tibetan Plateau. There were big differences in vegetation type and dynamics of soil moisture between these two grassland ecosystems due to the differences in climate and soil properties, which affected the radiation balance and surface exchanges of energy and water vapor. The main objective of this paper was to study

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the mechanisms controlling the surface energy exchanges and answer the following two questions:

1. What results in the differences in radiation balance over these two ecosystems?
2. What are the main variables affecting surface energy partitioning over these two ecosystems?

2 Materials and methods

2.1 Site description

The research was conducted at two ecosystems representing the most dominant grassland types on the Qinghai-Tibetan Plateau including an alpine shrub-meadow ecosystem at Gancaitan (referred to as AM) and an alpine meadow-steppe ecosystem at Dangxiong (referred to as AS), respectively. The two sites are both located in the western part of China Grassland Transect (CGT) with a humid and semi-humid continental climate. At the AM, the soil type is silty clay loam and the bulk density is 0.98 g cm^{-3} for the surface horizon (top 30 cm). At AS, the soil type is sandy loam, and there are scattered stones in the surface soil profile and the vegetation growth is limited with nutrients. Table 1 presents more detailed descriptions about climate and vegetation at the sites. Further details can be found in Shi et al. (2006) and Hu et al. (2008).

2.2 Field measurements

The eddy covariance technique was used to measure the fluxes of carbon dioxide, water vapor, and energy at above-mentioned two grassland ecosystems (Yu et al., 2006). Uniform measurement systems and sensor arrangements were used by the program of Chinese Terrestrial Ecosystem Flux Research Network (ChinaFLUX). It

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included a three-dimensional sonic anemometer (Model CSAT-3, Campbell Scientific, Logan, Utah, USA) and an open-path CO₂/H₂O gas analyzer (model LI-7500, Licor Inc., Lincoln, Nebraska). A data logger (Model CSAT-3, Campbell Scientific, Logan, Utah, USA) was used to record the eddy covariance signals with frequency of 10 Hz.

5 All 30 min fluxes were calculated online. We also measured meteorological variables such as air temperature (T_a), relative humidity, precipitation and volumetric soil water content (SWC). Four components of surface radiation balance (up and down long- and short-wave radiation) at each site were measured with the net radiometer (Model CNR-1, Kipp & Zonen, NY, USA). Soil heat fluxes at the depth of 5 cm were measured by
10 two soil heat plates (HFP01, Hukseflux Inc., Delft, The Netherlands). For details see Yu et al. (2006).

NDVI has been widely used to estimate green biomass and leaf area index (LAI). In this study, NDVI during the growing season (May–September) was used to examine the growth of vegetation (10-day maximum-value composite (MVC) with 1 km resolution,
15 <http://free.vgt.vito.be/index.php>) due to the lack of LAI measurements in some years.

2.3 Data processing

Three-dimensional rotation was applied to align the coordinate system with the mean wind (Wilczak et al., 2001), and the correction for density effect due to heat and water vapor transfer was made according to Webb et al. (1980) during processing the
20 raw 30-min flux data. When filling missing and spurious data, linear interpolation (for <2 h gap) and the mean diurnal variation (MDV) methods were used (Fu et al., 2006). The closure of energy balance is often calculated to assess the performance of the eddy covariance system. There were two studies about the closure of energy balance for sites of ChinaFLUX (Li et al., 2005; Yu et al., 2006), and the energy balance ratio
25 (EBR) of grassland ecosystems ranged between 0.83 and 0.91 (Yu et al., 2006). The imbalance of energy budget may affect the evaluation of sensible heat (H) and latent heat (LE), but it was prevalent in FLUXNET (Wilson et al., 2002).

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2.4 Calculations

Decoupling coefficient (Ω) and canopy surface conductance (g_s) were calculated to assess the effect of physiological and environmental factors on water vapor exchange. The half-hourly g_s was derived from the Penman-Monteith equation (Monteith and Unsworth, 1990):

$$\frac{1}{g_s} = \frac{\rho C_p \text{VPD}}{\gamma LE} + \frac{\frac{\Delta(R_n - G - LE)}{\gamma LE} - 1}{g_a}, \quad (1)$$

where ρ , C_p and VPD are the air density (kg m^{-3}), the specific heat of air ($\text{J kg}^{-1} \text{K}^{-1}$) and the atmospheric saturation vapor pressure deficit (kPa), respectively. And γ is the psychrometric constant (kPa K^{-1}), Δ is the slope of saturation vapor pressure as a function of air temperature (kPa K^{-1}), and g_a is the aerodynamic conductance (m s^{-1}) which is computed with the method described by Lloyd (1995). R_n and LE is net radiation and latent heat flux (W m^{-2}), respectively, and G is soil heat flux (W m^{-2}).

The dimensionless Ω was computed by:

$$\Omega = \frac{\Delta + \gamma}{\Delta + \gamma \left(1 + \frac{g_a}{g_s}\right)}, \quad (2)$$

In calculation of g_s and Ω , only midday values (09:00 to 16:00) were used and those obtained during the time periods with recorded precipitation, inadequate turbulence ($u^* < 0.1 \text{ m s}^{-1}$) and low PAR ($\text{PAR} < 25 \mu\text{mol}^{-2} \text{s}^{-1}$) were excluded (Wever et al., 2002).

In addition, the daily mean reflectivity of short-wave radiation at the surface (albedo) is the average when downward short-wave radiation $> 200 \text{ W m}^{-2}$ to minimize the effect of low solar angles (Li et al., 2006a).

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3 Results and discussion

3.1 Climate conditions and vegetation development

The seasonal and inter-annual variations in T_a , VPD, wind speed at 2.2 m (u), SWC and precipitation are shown in Fig. 1. The seasonal variation of T_a at two ecosystems showed similar pattern, while T_a was usually higher at AS than at AM. Both VPD and u in the growing season were larger at AS than at AM. The mean annual precipitation during the study periods was 507 ± 33 mm at AM and 418 ± 130 mm at AS, respectively. SWC was lower at AS due to the lower soil water-holding capacity. Inter-annual comparison of T_a and precipitation in the growing season at AM and AS are shown in Table 2. The precipitation in the growing season of 2006 (only 207 mm) was significantly lower than the average (480 mm) at AS.

Seasonal and inter-annual variations in NDVI are shown in Fig. 2. The NDVI was generally lower and its inter-annual and intra-seasonal variations were higher at AS than at AM. The mean NDVI in the growing season was 0.27 in 2004 and 2005, higher than in 2006 and 2007. This pattern roughly agrees well with the variation of precipitation at AS (Table 2). The average NDVI in May of 2007 was higher than those of other four years at AM. This is likely due to higher temperature observed in May of 2007 that enhanced plant growth. The average temperature in May of 2007 was 5.33°C , while it ranged from -0.22°C to 3.05°C during the previous four years. Yang and Piao (2006) suggested that the largest NDVI increase during the growing season occurred in the spring is due to the advanced growing season and accelerated vegetation activity for the grasslands on the Tibetan Plateau.

3.2 Seasonal and inter-annual variations in energy fluxes and albedo

For the homogenous grassland ecosystems, net radiation (R_n) at the canopy surface can be derived from the radiation balance equation:

$$R_n = K_n - L_n = K_d - K_u + L_d - L_u, \quad (3)$$

where K and L represent the short-wave radiation and long-wave radiation, respectively. And subscript n, d and u represent net, downward, and upward directions, respectively. Figure 3 shows the seasonal and inter-annual courses of K_d and R_n . Their seasonal pattern was similar at both sites. K_d was higher at AS than at AM and the total K_d in the growing season (May–September) was $3331.9 \pm 90.5 \text{ MJ m}^{-2}$ at AS, and $3023.6 \pm 31.6 \text{ MJ m}^{-2}$ at AM, respectively. However, R_n of AM ($1824.9 \pm 36.2 \text{ MJ m}^{-2}$) was generatively higher than that of AS ($1462.8 \pm 89.5 \text{ MJ m}^{-2}$) in the growing season. The ratio of R_n/K_d was about 0.4 at AS, but 0.6 at AM. The mean albedo ($=K_u/K_d$) and L_u/L_d ratio at AM in the growing season were 0.12 ± 0.01 and 1.23 ± 0.02 , respectively, both being lower than those of AS (0.17 ± 0.01 for K_u/K_d and 1.33 ± 0.04 for L_u/L_d). The ratio of net long-wave radiation to net short-wave radiation was 31.1% at AS and 46.6% at AM, respectively. The lower albedo and lower L_u/L_d were responsible for higher R_n at AM relative to the AS.

Seasonal variations in the daily albedo during the growing season are shown in Fig. 4. Daily albedo varied from 0.08 to 0.15 at AM, and relatively very high (very low) albedo was observed after heavy snowfall (after strong rainfall) (Fig. 4). The albedo at AM was close to that of European sub-alpine wet grassland ecosystems (0.11 in August and September) (Rosset et al., 2001). The daily albedo was usually higher at AS than at AM, ranging from 0.12 to 0.23, which was close to those of an European grassland ecosystems (0.17–0.19) at the same latitude (Rosset et al., 1997), and a central Mongolian steppe (0.13–0.26) (Li et al., 2006a). The variation of albedo was closely associated with the variation of SWC and the vegetation status (Li et al., 2006a). For example, a significant linear relationship at AS was found between albedo and SWC at the 20 cm depth (SWC in %) (albedo = $-0.003 \text{ SWC} + (0.208 \pm 0.002)$, $n=591$, adjusted $R^2 = 0.504$, $F = 602.27$, $P < 0.0001$). Gu et al. (2005) suggested that the high summer-time albedo may favor alpine plants to avoid the high radiation stress on the plateau. By contrast, albedo was lower at AM compared with another meadow ecosystem nearby (0.16–0.26) ($37^\circ 36' \text{ N}$, $101^\circ 18' \text{ E}$) (Gu et al., 2005). This may be due to higher SWC and higher vegetation cover at AM.

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Figure 5 shows the seasonal variations of sensible heat (H), LE and G . The highest H values were often observed from mid April to mid June at both sites. With the increase of rainfall and growth of vegetation, LE increased gradually while H decreased. The H increased again after the peak growth. H was generally higher at AM than at AS (Fig. 5). LE was higher in May at AM than at AS due to the higher SWC at AM than at AS. The seasonal pattern of G was similar at both sites. G was usually negative from early November to early February, indicating that the ground was energy source for the atmosphere. G was generally higher at AS than at AM from late February to late March, which was consistent with the seasonal variation of K_d (Fig. 3). During the study periods, average value of G/R_n in the growing season at both sites kept almost constant of about 0.04.

3.3 Comparison of inter-annual variations in the Bowen ratio between two ecosystems

The Bowen ratio ($\beta = H/LE$) is widely used for comparing the energy partitioning among different ecosystems (Wilson et al., 2002). The inter-annual variations in β were low at AM, ranging between 0.55 and 0.68. Similarly, T_a , NDVI and canopy surface conductance (g_s) varied little inter-annually at AM (Table 2). The average β in the growing season of 2007 was lowest, which may stem from the abnormal high temperature in May as mentioned above (Sect. 3.1). The AM ecosystem is characterized by low temperature (Table 1). More water vapor was evapotranspired with the advanced vegetation growth under the conditions of warm spring in 2007 at AM. The amount of ET was 95 mm in May of 2007, higher than previous four years (varied from 54 to 60 mm). By contrast, at AS, β varied from 0.37 (2004) to 0.66 (2006), being consistent with the wide variation in precipitation, indicating that water availability controls the energy partitioning at inter-annual scale.

Wilson et al. (2002) suggested that the large variability of β (0.34–1.91) between sites and years at grassland can be explained by two reasons: at first, the grassland ecosystem is highly sensitive to human disturbance (e.g. grazing); and secondly it is

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more sensitive to soil moisture than shrubs and forests due to the difference in the ability of roots to access deep soil water. In this study, the difference of β at two sites can be explained by climate, soil type and vegetation. On the one hand, Indian monsoon has a greater influence on precipitation in the south of the Qinghai-Tibetan Plateau (Tian et al., 2001). During the study periods, the coefficient of variation of the annual precipitation was 31.1% at AS, higher than that at AM (6.5%). On the other hand, soil water-holding capacity was lower at AS than at AM. In addition, root mass was mainly distributed in the soil layer of 0–10 cm at AS, while it was in 0–40 cm depth at AM (Li et al., 2006b), resulting in further intensification of water limitation at AS.

The vegetation distribution may change due to the climate change on the Qinghai-Tibetan Plateau (Song et al., 2005). However, more attention should be given to the effect of grazing. On the Qinghai-Tibetan Plateau, a large area of grassland has been degraded in the past few decades because of overgrazing (Cui et al., 2007), e.g. the AS site in this study. Bremer et al. (2001) suggested that grazing decreased ET, and thus the β increased. The increase in β indicates a higher fraction of available energy ($R_n - G$) is partitioned into H which will cause a positive feedback to atmospheric temperature. Eugster et al. (2000) suggested that the vegetation change from tundra to shrub or shrub to forest in arctic would cause a negative feedback because forests had a lower ET rate, which reduced the water vapor flux to the atmosphere as a strong greenhouse gas. There was little information about effect of vegetation change on ET on the Qinghai-Tibetan Plateau. From our study, we learned that a conversion from AM to AS or vice versa would alter surface energy balance and the partitioning of the available energy though the change of surface albedo, giving rise to a change in local or even regional climate. However, there was still some uncertainty about climate change and the feedback from vegetation change on the Qinghai-Tibetan Plateau. This deserves further study in the future.

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3.4 Comparison of seasonal variations in the Bowen ratio between two ecosystems

The seasonal variation of daily β during the growing season at AM and AS is shown in Fig. 6a, exhibiting a reverse trend with plant growth. However, the range of variations in daily β was larger and the values of β often increased markedly when the SWC was low at AS versus at AM, which was consistent with the seasonal variation of daily surface conductance (g_s) during the growing season (Fig. 6b). At both sites, the g_s was relatively high when NDVI was high and soil was moist. The maximum daily average g_s could reach about 20 mm s^{-1} at both sites, close to that of an annual grassland ecosystem in California (Ryu et al., 2008), and higher than that of temperate grassland in Canada ($\sim 9 \text{ mm s}^{-1}$, lower in droughty year) (Wever et al., 2002).

Figure 7 illustrates the relationship between the monthly average β and NDVI, surface conductance (g_s) at AM and AS. With the increase of g_s and NDVI, indicative of the growth status of vegetation, β decreased, indicating that more water vapor was evapotranspired into the atmosphere. The seasonal pattern of β suggests that the phenology of the vegetation was the major factor affecting the energy partitioning at both sites at intra-seasonal scale. This is consistent with previous studies in that vegetation characteristics strongly influence the energy partitioning (e.g. Li et al., 2006a; Hammerle et al., 2008).

The growth of vegetation not only affects the energy partitioning, but also has great influence on partitioning of evapotranspiration into its components (plant transpiration and soil evaporation). Hu et al. (2009) suggested that the variations in LAI could cause stronger effects on the ratio of evaporation (E) to evapotranspiration (ET) in the sparse-canopy ecosystems than in the dense-canopy ecosystems. It was found that E/ET in the growing season was above 58% at AS, and only about 42% at AM, respectively (Hu et al., 2009).

Figure 8 shows the relationship between the daily average β and SWC at AM and AS. β decreased with the increase of SWC at AS. However, there was no significant

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correlation at AM because water availability was not the limiting factor of energy partitioning.

5 Previous studies have shown that soil moisture is an important factor affecting energy partitioning, particularly in arid and semi-arid areas. For example, β decrease with the increase of SWC after the precipitation events over the semi-arid grassland ecosystems on the Mongolian plateau (Hao et al., 2007; Li et al., 2006a). Gu et al. (2005) also suggested that soil moisture was an important factor affecting the energy partitioning in another alpine meadow ecosystem dominated by *Kobresia humilis* close to AM. However, soil water was not the limiting factor of evapotranspiration at AM. It can be explained by the big differences in soil type (Mat-Cryic Cambisol at Gu et al. 10 (2005), Mol-Cryic Cambisols at AM) and vegetation type between these two ecosystems resulted from the different direction and gradient of slope.

3.5 Comparison of biophysical control on energy partitioning at half-hourly scale between two ecosystems

15 Energy partitioning is principally associated with the complicated interaction between biotic and abiotic variables such as green leaf area index, plant functional type, net radiation, soil moisture availability and vapor pressure deficit (VPD) (Gu et al., 2006; Li et al., 2006a). However, effects of these factors on β are different at different time scales, e.g. LAI and SWC varied little at a 30-min resolution while R_n and VPD varied more at a 30-min than at a daily scale. To further understand the mechanisms controlling the surface energy exchanges at two ecosystems, the effects of R_n and VPD on energy partitioning were analyzed at half-hourly time step. 20

3.5.1 Effect of net radiation

25 The Bowen ratio slightly increased with R_n at both sites (Fig. 9), but drought increased the range of variation at AS (Fig. 9a) which was similar to that at a temperate forest ecosystem (Gu et al., 2006). It is well known that both H and LE increase with R_n ;

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however, their increases are not in proportion because LE is limited by the amount of water available in the soil and stomatal openness (Gu et al., 2006). Therefore, β tends to increase with the increase of R_n at AS and AM, and the trend was stronger under the conditions of drought at AS (Fig. 9a).

5 Gu et al. (2006) suggested that the difference in the Bowen ratio between drought and non-drought conditions increased with R_n and VPD because more available energy was partitioned into LE with the increase of R_n , and this trend was intensified at higher levels of VPD. However, in this study, there was no significant difference in effects of R_n on β at two levels of VPD (<1 kPa and >1 kPa) no matter what soil moisture
10 conditions at AS and AM (data not shown), which means that the effect of R_n on β did not depend sensitively on VPD. This may be related to the low values of VPD at both sites (generally below 1.5 kPa).

3.5.2 Effect of vapor pressure deficit

Figure 10 shows the effect of VPD on energy partitioning at two levels of SWC (non-drought and drought) at AS. Under non-drought conditions, there was no distinct effect of VPD on β at AS (Figures 10a), but β increased with increased VPD under drought
15 conditions (Fig. 10b). In addition, the effect of VPD on β with different levels of R_n can be ignored under all levels of soil moisture (data not shown). The effects of VPD on energy partitioning at two levels of R_n ($<250 \text{ Wm}^{-2}$ and $>500 \text{ Wm}^{-2}$) at AM was shown
20 in Fig. 11. Overall, β decreased with the increased VPD at AM, but the decrease was sharper at high levels of R_n ($>500 \text{ Wm}^{-2}$) (Fig. 11b). And the effect of R_n between 250 Wm^{-2} and 500 Wm^{-2} was medium (data not shown) at AM.

The influence of VPD on energy partitioning was stronger at AM than at AS under non-drought conditions (Figs. 10a and 11), and it was nonlinear at AM (Fig. 11). What
25 caused the difference in effect of VPD on β at AS and AM? Studies showed that the nonlinear effect of VPD on β stems from two simultaneous but opposing effects of VPD on LE : on the one hand, LE increased with the increased VPD driving more water vapor out of the stomatal pore; on the other hand, high VPD reduced the stomatal

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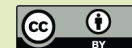
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conductance limiting the LE (Ball et al., 1987). The positive effect of increased VPD outweighs its negative effect on LE when VPD is low (Gu et al., 2006), which explained why β decreased with the increased VPD at AM. Soil evaporation dominated the evapotranspiration at AS as mentioned above due to low LAI (Hu et al., 2009). Therefore, the effect of VPD on stomatal conductance was weaker at AS versus at AM. Further, there was a high correlation between high VPD and severe drought resulting in more available energy was partitioned into H , and thus increased β at AS (like Fig. 10b). Therefore, the difference in effect of VPD on β resulted from the difference in vegetation cover between two sites.

The decoupling coefficient (Ω) is often used to separate the effect of VPD on LE from R_n (Gu et al., 2005; Hao et al., 2007). Ω varies from 0 to 1. A low Ω indicates a relatively high influence of VPD on ET, and a high Ω suggests that R_n exerts the dominant influence on ET (Jarvis and McNaughton, 1986). The values of Ω were often over 0.7 during the peak growth stage at both sites (not shown in this paper), implying that evapotranspiration process at two sites is coupled to the radiation forcing. However, Ω was low during the dry period at AS (e.g. in August 2006 and May–June in 2007), which indicates that the control of VPD on LE was strengthened.

Surface conductance (g_s) and aerodynamic conductance (g_a) are two parameters determining Ω directly. Here, the effects of g_s and g_a on Ω were discussed with the data of 2004 at half-hourly scale. The dependencies of Ω on g_a and g_s were in opposite directions (Fig. 12). As g_a decreased and g_s increased, thus Ω increased, suggesting that evapotranspiration became more coupled with radiation forcing. The magnitude of g_a depends on the aerodynamic properties (e.g. wind speed and roughness) of the surface. The wind speed was larger, resulting in lower g_a at AS compared with AM. Therefore, the value of Ω was higher in 2004 at AS than AM (Table 2) due to the lower g_a and higher g_s .

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The seasonal and inter-annual variations in surface energy exchanges at two grassland ecosystems on the Qinghai-Tibetan Plateau were explored. Relative to the alpine meadow-steppe (AS), solar radiation (K_d) was lower, but net radiation (R_n) was higher at the alpine shrub-meadow ecosystem (AM). This is because the surface reflectivity for short-wave radiation (albedo) and the ratio of upward long-wave radiation to downward long-wave radiation (L_u/L_d) were lower at AM as compared with AS. During the growing season, daily albedo varied from 0.08 to 0.15 at AM and from 0.12 and 0.23 at AS in response to variations of NDVI and soil moisture. It decreased significantly with the increase of SWC at AS. The mean L_u/L_d ratio in the growing season was 1.23 at AM and 1.33 at AS, respectively.

In the annual scale, annual precipitation was the most important factor controlling energy partitioning at AS, while temperature of May controlled the inter-annual variations in the Bowen ratio (β) at AM which is characterized by low temperature. Vegetation growth played an important role in controlling energy partitioning at seasonal scale at both sites. However, abnormally high β often occurred during the growing season under the drought conditions due to the low soil water-holding capacity at AS as compared with AM. In addition, the influence of VPD on energy partitioning was stronger under non-drought conditions at AM than at AS at half-hourly scale due to high vegetation cover.

Acknowledgements. This research was jointly funded by the “Hundred Talents” Program, the Project (2010CB833501), Knowledge Innovation Project (KZCX2-YW-432) of the Chinese Academy of Sciences and National Natural Science Foundation of China (Grant No. 30590381, 30721140307).

References

Baldocchi, D. D., Xu, L., and Kiang N.: How plant functional-type, weather, seasonal drought, and soil physical properties alter water and energy fluxes of an oak-grass savanna and an

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- annual grassland, *Agr. Forest Meteorol.*, 123, 13–39, 2004.
- Ball, J. T., Woodrow, I. E., and Berry, J. A.: A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions, in: *Progress in Photosynthesis Research*, vol. IV, edited by: Biggins, J., Martinus Nijhof, Zoetermeer, The Netherlands, 221–224, 1987.
- Beringer, J., Chapin III, F. S., Thompson, C. C., and McGuire A. D.: Surface energy exchanges along a tundra-forest transition and feedbacks to climate, *Agr. Forest. Meteorol.*, 131, 143–161, 2005.
- Bremer, D. J. and Ham, J. M.: Effect of spring burning on the surface energy balance in a tall-grass prairie, *Agr. Forest. Meteorol.*, 97, 43–54, 1999.
- Cai, Y., Li, D. L., Tang, M. C., and Bai, C. Y.: Decadal temperature change over Qinghai-Xizang Plateau in recent 50 years. *Plateau Meteorology*, 22, 464–470, 2003 (in Chinese).
- Cui, Q. H., Jiang, Z. G., Liu, J. K., and Su, J. P.: A review of the cause of rangeland degradation on Qinghai-Tibet Plateau, *Pratacult. Sci.*, 24(5), 20–26, 2007 (in Chinese).
- Eugster, W., Rouse, W., Pielke Sr., R. A., McFadden, J. P., Baldocchi, D., Kittel, T., Chapin III, F., Liston, G., Vidale, P., Vaganov, E., and Chambers, S.: Land-atmosphere energy exchange in Arctic tundra and boreal forest: available data and feedbacks to climate, *Glob. Change Biol.*, 6 (Suppl. 1), 84–115, 2000.
- Fu, Y. L., Yu, G. R., Sun, X. M., Li, Y. N., Wen, X. F., Zhang, L. M., Li, Z. Q., Zhao, L., and Hao, Y. B.: Depression of net ecosystem CO₂ exchange in semi-arid *Leymus chinensis* steppe and alpine shrub, *Agr. Forest. Meteorol.*, 137, 234–244, 2006.
- Gu, L., Meyers, T., Pallardy, S. G., Hanson, P. J., Yang, B., Heuer, M., Hosman, K. P., Riggs, J. S., Sluss, D., and Wullschlegel, S. D.: Direct and indirect effects of atmospheric conditions and soil moisture on surface energy partitioning revealed by a prolonged drought at a temperate forest site, *J. Geophys. Res.*, 111, D16102, doi:10.1029/2006JD007161, 2006.
- Gu, S., Tang, Y. H., Cui, X. Y., Kato, T. M., Du, Y., Li, Y. N., and Zhao X. Q.: Energy exchange between the atmosphere and a meadow ecosystem on the Qinghai-Tibetan Plateau, *Agr. Forest. Meteorol.*, 129, 175–185, 2005.
- Hammerle, A., Haslwanter, A., Tappeiner, U., Cernusca, A., and Wohlfahrt, G.: Leaf area controls on energy partitioning of a temperate mountain grassland, *Biogeosciences*, 5, 421–431, 2008, <http://www.biogeosciences.net/5/421/2008/>.
- Hao, Y. B., Wang, Y. F., Huang, X. Z., Cui, X. Y., Zhou, X. Q., Wang, S. P., Niu, H. S., and Jiang, G. M.: Seasonal and interannual variation in water vapor and energy exchange over a typical

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- steppe in Inner Mongolia, China, *Agr. Forest. Meteorol.*, 146, 57–69, 2007.
- Hu, Z. M., Yu, G. R., Fu, Y. L., Sun, X. M., Li, Y. N., Shi, P. L., Wang, Y. F., and Zheng, Z. M.: Effects of vegetation control on ecosystem water use efficiency within and among four grassland ecosystems in China, *Glob. Change Biol.*, 14, 1609–1619, 2008.
- 5 Hu, Z., Yu G. R., Zhou, Y. L., Sun, X. M., Li, Y. N., Shi, P. L., Wang, Y. F., Song, X., Zheng, Z. M., Zhang, L., and Li, S. G.: Partitioning of evapotranspiration and its controls in four grassland ecosystems: Application of a two-source model, *Agr. Forest Meteorol.*, 149, 1410–1420, 2009.
- Li, S. G., Eugster, W., Asanuma, J., Kotani, A., Davaa, G., Oyunbaatar, D., and Sugita, M.: Energy partitioning and its biophysical controls above a grazing steppe in central Mongolia, *Agr. Forest. Meteorol.*, 137, 89–106, 2006a.
- 10 Li, Y. N., Zhao, L., Wang, Q. X., Du, M. Y., Gu, S., Xu, S. X., Zhang, F. W., Zhao, X. Q.: Estimation of biomass and annual turnover quantities of *Potentilla fruticosa* shrub, *Acta Agrestia Sinica*, 14(1), 72–76, 2006b (in Chinese).
- 15 Li, Z. Q., Yu, G. R., Wen, X. F., Zhang, L. M., Ren, C. Y., and Fu, Y. L.: Energy balance closure at ChinaFLUX sites, *Sci.China Ser. D*, 48 (Supp. 1), 51–62, 2005.
- Lloyd, J., Grace, J., Miranda, A. C., Meir, P., Wong, S. C., Miranda, B. S., Wright, I. R., Gash, J. H., and McIntyre, J.: A Simple Calibrated Model of Amazon Rain-Forest Productivity Based on Leaf Biochemical-Properties, *Plant Cell Environ.*, 18(10), 1129–1145, 1995.
- 20 Monteith, J. L. and Unsworth, M. H.: *Principles of Environmental Physics*, 2nd ed., Edward Arnold, London, 291 pp., 1990.
- Raupach, M. R.: Influences of local feedbacks on land–air exchanges of energy and carbon, *Glob. Change Biol.*, 4, 477–494, 1998.
- Rosset, M., Montani, M., Tanner, M., and Fuhrer, J.: Effects of abandonment on the energy balance and evapotranspiration of wet subalpine grassland, *Agr. Ecosyst. Environ.*, 86, 277–286, 2001.
- 25 Rosset, M., Riedo, M., Grub, A., Geissmann, M., and Fuhrer, J.: Seasonal variation in radiation and energy balances of permanent pastures at different altitudes, *Agr. Forest. Meteorol.*, 86, 245–258, 1997.
- 30 Ryu, Y., Baldocchi, D. D., Ma, S., and Hehn T.: Interannual variability of evapotranspiration and energy exchange over an annual grassland in California, *J. Geophys. Res.*, 113, D09104, doi:09110.01029/02007JD009263, 2008.
- Shi, P. L., Sun, X. M., Xu, L. L., Zhang, X. Z., He, Y. T., Zhang, D. Q., and Yu, G. R.: Net

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- ecosystem CO₂ exchange and controlling factors in a steppe-Kobresia meadow on the Tibetan Plateau, *Sci. China Ser. D*, 49, 207–218, 2006.
- Song, M. H., Zhou, C. P., and Ouyang, H.: Simulated distribution of vegetation types in response to climate change on the Tibetan Plateau, *J. Veg. Sci.*, 16, 341–350, 2005.
- 5 Tian, L., Yao, T. D., Numaguti, A., and Sun, W. Z.: Stable Isotope Variations in Monsoon Precipitation on the Tibetan Plateau, *J. Meteorol. Soc. Jpn.*, 79(5), 959–966, 2001.
- Webb, E. K., Pearman, G. I., and Leuning, R.: Correction of flux measurements for density effects due to heat and water vapour transfer, *Q. J. Roy. Meteor. Soc.*, 106, 85–100, 1980.
- 10 Wever, L. A., Flanagan, L. B., and Carlson, P. J.: Seasonal and interannual variation in evapotranspiration, energy balance and surface conductance in a northern temperate grassland, *Agr. Forest. Meteorol.*, 112, 31–49, 2002.
- Wilczak, J. M., Oncley, S. P., and Stage, S. A.: Sonic anemometer tilt correction algorithms, *Bound.-Lay. Meteorol.*, 99, 127–150, 2001.
- 15 Wilson, K. B., Baldocchi, D. D., Aubinet, M., Berbigier, P., Bernhofer, C., Dolman, H., Falge, E., Field, C., Goldstein, A., Granier, A., Grelle, A., Halldor, T., Hollinger, D., Katul, G., Law, B. E., Lindroth, A., Meyers, T., Moncrieff, J., Monson, R., Oechel, W., Tenhunen, J., Valentini, R., Verma, S., Vesala, T., and Wofsy, S.: Energy partitioning between latent and sensible heat flux during the warm season at FLUXNET sites, *Water Resour. Res.*, 38(12), 1294, doi:10.1029/2001WR000989, 2002.
- 20 Yang, Y. H. and Piao, S. L.: Variations in grassland vegetation cover in relation to climatic factors on the Tibetan Plateau, *Acta Phytoecol. Sin.*, 30(1), 1–8, 2006 (in Chinese).
- Yao, J. M., Zhao, L. Ding, Y. J., Gu, L. L., Jiao, K. Q., Qiao, Y. P., and Wang, Y. X.: The surface energy budget and evapotranspiration in the Tanggula region on the Tibetan Plateau, *Cold Reg. Sci. Technol.*, 52, 326–340, 2008.
- 25 Yu, G. R., Wen, X. F., Sun, X. M., Tanner, B. D., Lee, X. H., and Chen, J. Y.: Overview of ChinaFLUX and evaluation of its eddy covariance measurement, *Agr. Forest. Meteorol.*, 137, 125–137, 2006.
- Zheng, D. and Yao, T. D.: Uplifting of Tibetan Plateau with its environmental effects, *Advances in Earth Science*, 21(5), 451–458, 2006 (in Chinese).
- 30 Zheng, D., Zhang, Q., and Wu, S.: *Mountain Geoecology and Sustainable Development of the Tibetan Plateau*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 303 pp., 2000.

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Table 1. Site information at the alpine shrub-meadow (AM) and the alpine meadow-steppe (AS) during the measurement periods (January 2003–December 2007 at AM and January 2004–December 2007 at AS).

Site	AM	AS
Location	37°40′ N, 101°20′ E	30°51′ N, 91°05′ E
Elevation (m)	3293	4333
Mean precipitation (mm)	580	480
Mean temperature (°C)	−2	1.3
Canopy height (cm)	55	10
Dominant species	<i>Potentilla fruticosa</i> , <i>Kobresia capillifolia</i> , <i>Kobresia humilis</i>	<i>Stipa capillacea</i> , <i>Carex montis</i> , <i>Kobresia pygmaea</i>
Grazing	Grazed in winter	Grazed in winter

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Table 2. Inter-annual comparison of air temperature at 2.2 m (T_a), precipitation, NDVI, the Bowen ratio (β), canopy surface conductance (g_s), and the decoupling factor (Ω) in the growing season at AM and AS.

Site	Year	T_a (°C)	Precipitation (mm)	NDVI	β	g_s (mm s ⁻¹)	Ω
AM	2003	6.44	445.70	0.57	0.64	8.60	0.55
	2004	6.18	418.70	0.57	0.68	8.50	0.52
	2005	6.38	454.40	0.59	0.66	8.70	0.55
	2006	7.05	455.10	0.58	0.64	9.90	0.59
	2007	7.10	394.10	0.60	0.55	10.40	0.59
AS	2004	8.99	512.30	0.27	0.37	9.90	0.66
	2005	9.02	426.90	0.27	0.51	6.80	0.60
	2006	9.63	207.00	0.20	0.66	4.70	0.54
	2007	9.91	409.50	0.21	0.60	6.10	0.54

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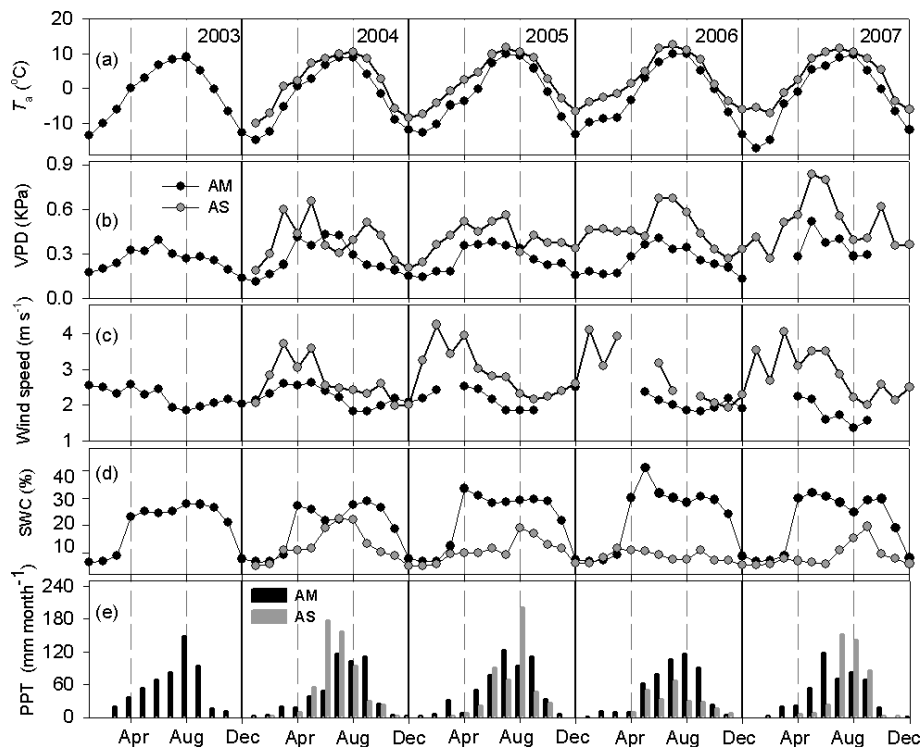


Fig. 1. Variation of (a) monthly average of daily air temperature (T_a), (b) monthly average of daily VPD, (c) monthly average of daily wind speed, (d) monthly average of daily volumetric soil water content at 20-cm depth (SWC), and (e) monthly sum of precipitation (PPT) at the shrub-meadow ecosystem (AM) and the alpine meadow-steppe ecosystem (AS).

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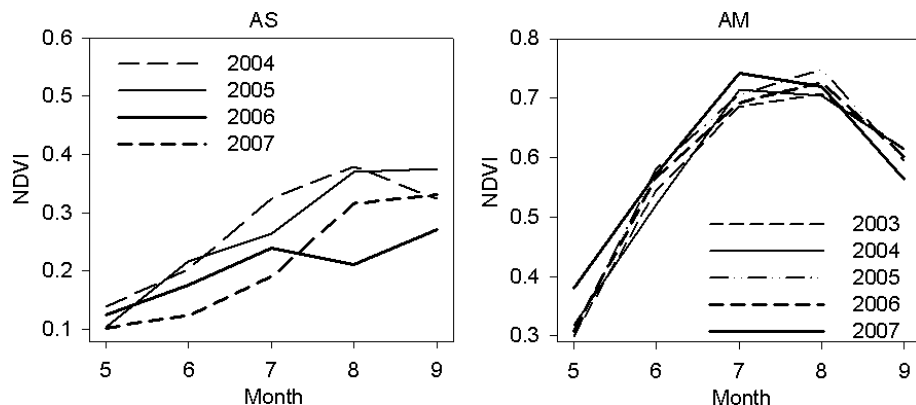


Fig. 2. Seasonal and inter-annual variations in NDVI at the shrub-meadow ecosystem (AM) and the alpine meadow-steppe ecosystem (AS).

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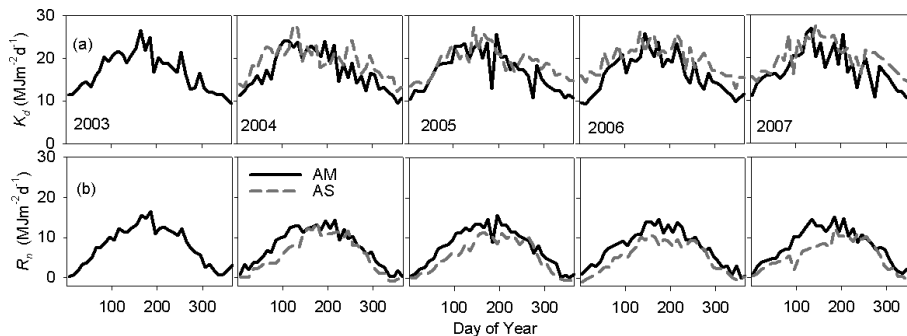


Fig. 3. Seasonal and inter-annual variations in the ground solar radiation (K_d) and net radiation (R_n) at the shrub-meadow ecosystem (AM) and the alpine meadow-steppe ecosystem (AS): **(a)** downward solar radiation (K_d) and **(b)** net all-wave radiation (R_n).

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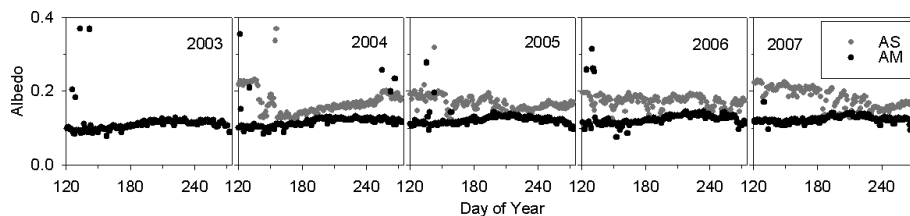


Fig. 4. Seasonal and inter-annual variation in the daily albedo during the growing seasons at AM and AS.

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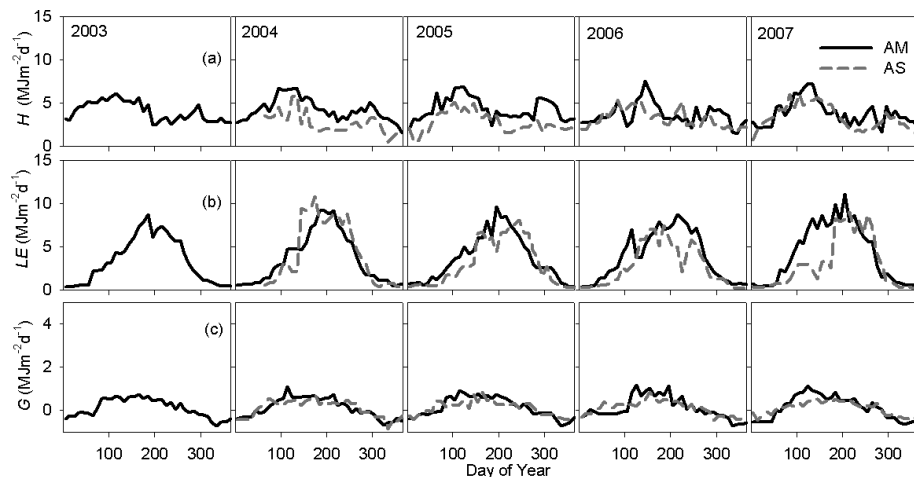


Fig. 5. Seasonal and inter-annual variations in **(a)** sensible heat (H), **(b)** latent heat (LE), and **(c)** soil heat (G) at AM and AS.

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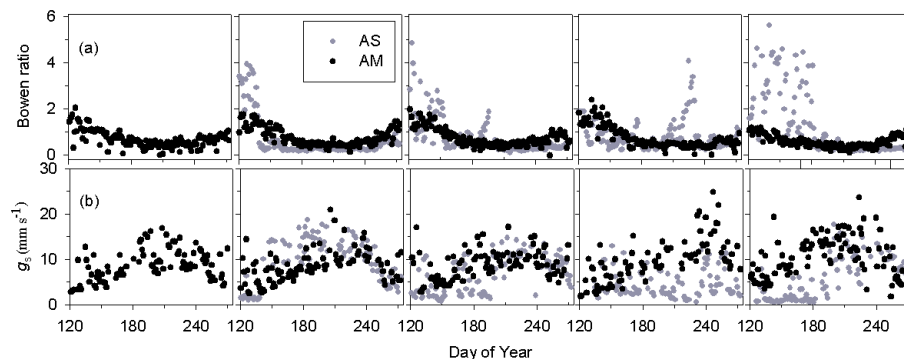


Fig. 6. Seasonal and inter-annual variations in **(a)** the daily Bowen ratio (β) and **(b)** surface conductance (g_s) during the growing season at AM and AS.

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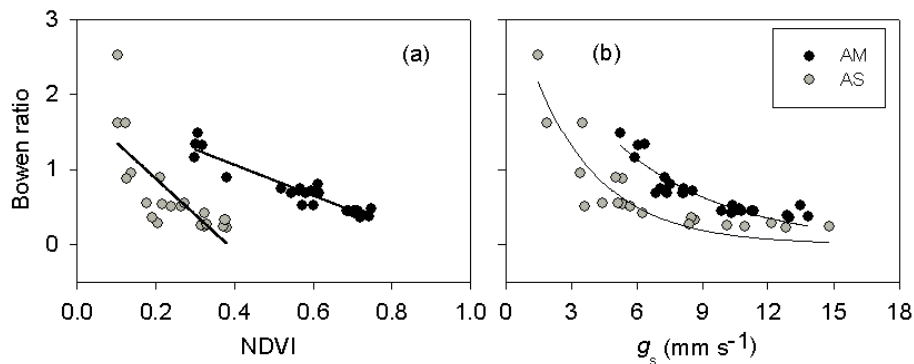


Fig. 7. Relationship between monthly average Bowen ratio (β) and **(a)** NDVI, **(b)** surface conductance (g_s) at AM and AS.

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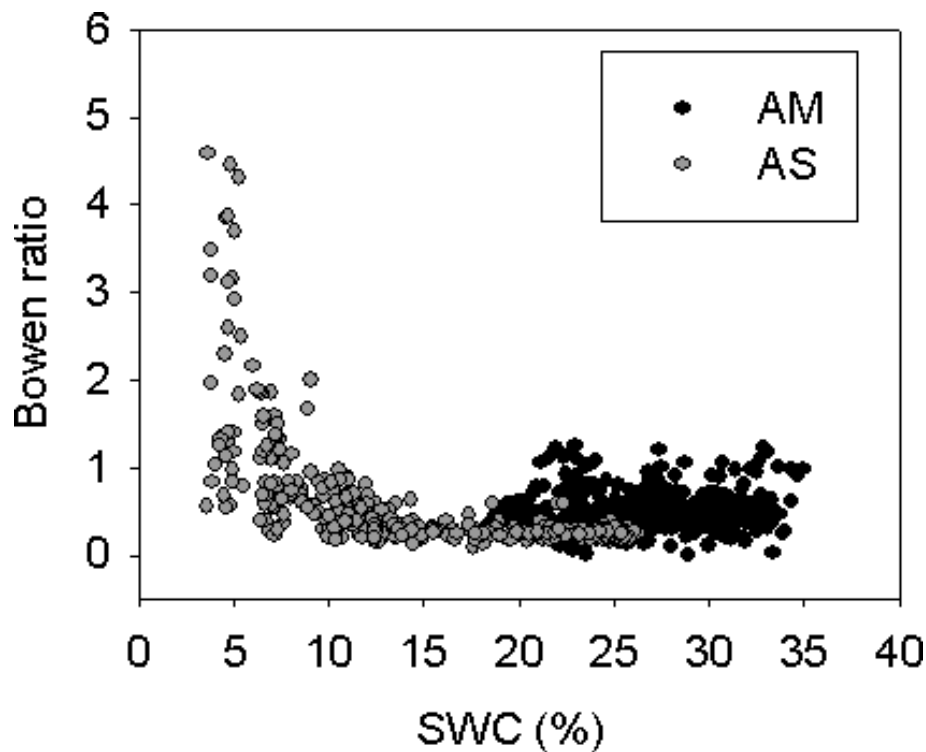


Fig. 8. Relationship between the daily average Bowen ratio (β) and volumetric soil water content (SWC) at AM and AS.

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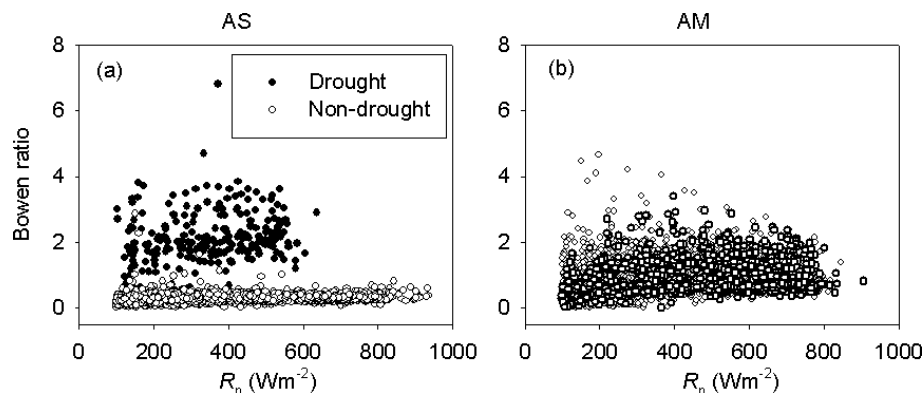


Fig. 9. Effect of net radiation (R_n) on the Bowen ratio (β) at (a) AS and (b) AM. (“non-drought” indicates SWC >15%, and “drought” indicates SWC <8%, the same below).

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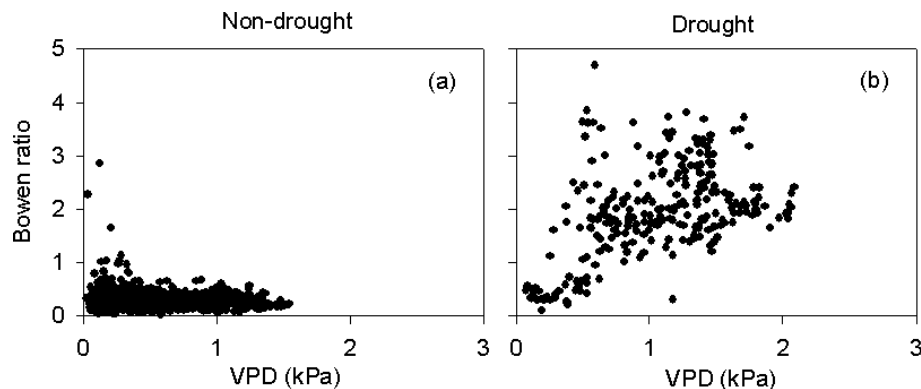


Fig. 10. Effect of VPD on the Bowen ratio (β) under (a) nondrought and (b) drought conditions at AS.

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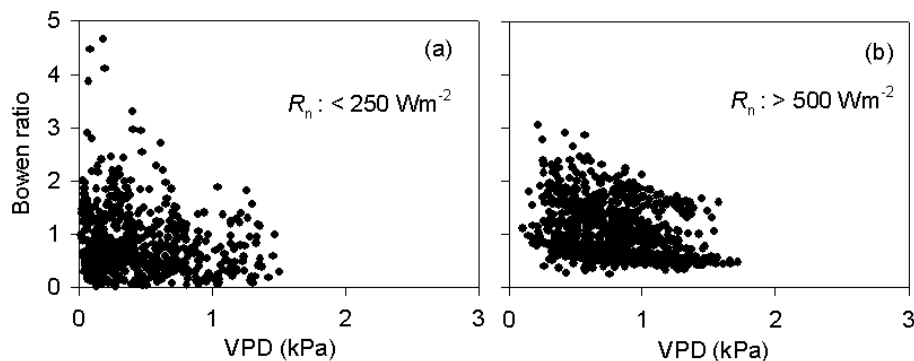


Fig. 11. Effect of VPD on the Bowen ratio (β) at two levels of net radiation (R_n) at AM.

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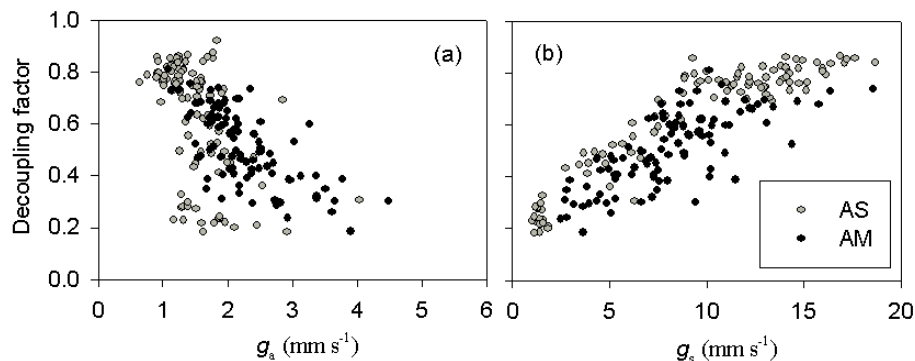


Fig. 12. Variation of the decoupling factor (Ω) versus **(a)** aerodynamic conductance (g_a) and **(b)** canopy surface conductance (g_s) in the growing season of 2004 at AM and AS.

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