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Radiation partitioning and its relation to environmental factors above a meadow ecosystem on the Qinghai-Tibetan Plateau

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[1] Understanding the energy balance on the Qinghai-Tibetan Plateau is essential for better prediction of global climate change. To characterize the energy balance on the plateau, we examined the radiation partitioning over a *Kobresia* meadow, the most widely distributed vegetation on the plateau, for the period from 2002 to 2005. The incident solar radiation (R_s) and net radiation (R_n) averaged 6298 and 2779 MJ m^{-2} yr^{-1}, respectively. The albedo averaged 0.220 annually, with a slightly low value of 0.202 in the growing season from May to September. An increase in soil water or leaf area index was correlated with a decrease of albedo over the meadow. The annual solar radiation lost 34% as longwave radiation, which was higher than values reported for lowland grasslands. The annual radiation efficiency (R_n/R_s) over the meadow, at an average of 0.44, was, however, much lower than that for lowland grasslands. The net longwave radiation (L_n) and the normalized effective radiation (L_n/R_s) over the meadow were much higher than that for the global surface or for lowland grasslands, indicating that the longwave exchange between alpine meadow and atmosphere is the most important component of energy losses. A path analysis suggests that the water vapor pressure, air temperature, and cloud cover are the major factors governing the variations of both the net radiation and the net longwave radiation in the alpine meadow ecosystem.

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1. Introduction

[2] Earth's radiation balance, a measure of the energy exchange between the atmosphere and the surface, plays a major role in climatic change [*Iziomon et al.*, 2001; *Smith et al.*, 2002]. Solar radiation is the fundamental energy driving the processes of photosynthesis, evapotranspiration, heating of the soil, and energy storage in vegetation [*Spittlehouse and Black*, 1980; *Jegede*, 1997b; *Gu et al.*, 2005]. Changes in the radiation balance are closely related to the sensible and latent fluxes, plant growth, vegetation variation, wind circulation, and melting of snow. Knowledge about the radiation balance and its relation to environmental factors is therefore important for understanding the current climate system, as well as for predicting climate changes in the future [*Kalma et al.*, 2000; *Berbert and Costa*, 2003; *Schaeffer et al.*, 2006].

[3] The radiation balance of deforested areas is largely affected by land cover characteristics [*Giambelluca et al.*, 1999; *Ogunjemiyo et al.*, 2005]. A model study demonstrated that the net radiation is dependent on longwave net radiation in semiarid shrub land [*Alados et al.*, 2003]. Radiation partitioning is often used to describe ecosystem radiation characteristics and shows significant differences at different altitudes; the proportion of absorbed solar radiation decreases with increase in altitude [*Rosset et al.*, 1997; *Iziomon et al.*, 2001, *Iziomon and Mayer*, 2002]. However, little information is available to clarify the radiation partitioning in alpine grassland ecosystems.

[4] The Qinghai-Tibetan Plateau, with a mean altitude of higher than 4000 m, is the highest alpine ecosystem in the world. With its unique topographical and landscape features, the plateau has been considered to play an important role in both local and global climate systems [*Sun and Zheng*, 1996; *Yabuki et al.*, 1998a, 1998b; *Li et al.*, 1999]. There are various vegetations on the plateau, but alpine meadow covers more than 60% of its vast grasslands [*Zheng*, 2000]. The behavior of solar radiation on the Qinghai-Tibetan Plateau has been reported in several studies [*Gong et al.*, 2005; *Zhu et al.*, 2006]. However, little information is available concerning the radiation balance in relation to environ-

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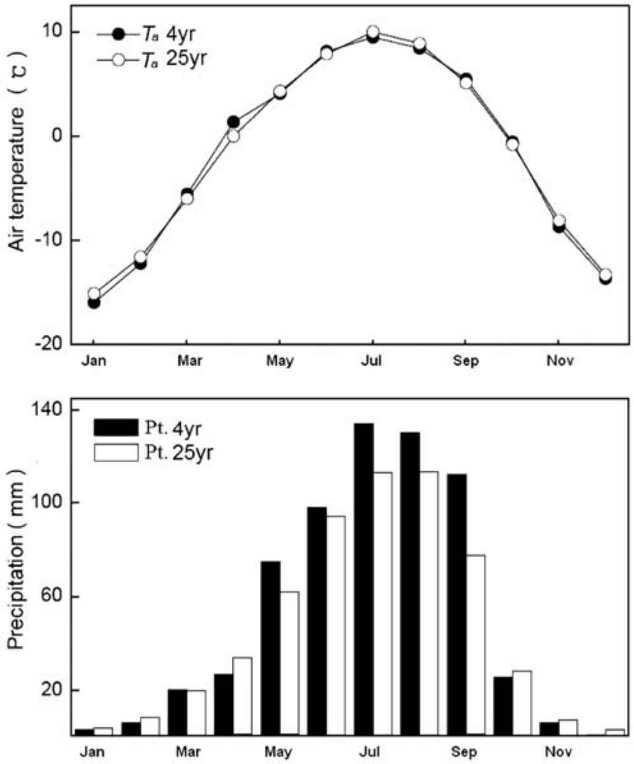

Figure 1. Annual variation in the average monthly air temperature (T_a) and monthly precipitation (Pt.) from 2002 to 2005 (4 years) and the averages from 1980 to 2005 (26 years).

mental factors on the plateau [*Gu et al.*, 2005]. It is necessary to clarify the radiation partitioning and its controlling factors if we are to understand the potential role of this unique geographical unit in both local and global climates.

[5] Radiation balance is determined by surface incident solar radiation, albedo, water vapor pressure, and temperature, and the balance varies spatially and temporally [*Bakry*, 1994; *Jegede*, 1997a; *Smith et al.*, 2002; *Chambers et al.*, 2005]. Since the climate on the Qinghai-Tibetan Plateau is characterized by strong incident solar radiation and low temperature and water vapor pressure, the radiation efficiency (R_n/R_s), that is, the ratio of net radiation (R_n) to incident solar radiation (R_s), on this plateau may be different from that in lowland regions. To quantify the radiation balance on the plateau, we examined the radiation partitioning and its relation to environmental factors in a *Kobresia* meadow ecosystem using a 4 year data set.

2. Measurement and Analysis Methods

2.1. Study Site

[6] The study site (l37°36′ N, 101°18′ E, altitude 3250 m) is a *Kobresia* meadow located in the northeast of the Qinghai-Tibetan Plateau. The annual solar radiation was 6242 ± 83 MJ m^{-2} during the period from 1980 to 2005. The annual mean air temperature is −1.7°C ± 0.7°C, and mean air temperatures in January and July are −15.0°C ± 1.4°C and 10.0°C ± 0.8°C, respectively. There is no difference between monthly mean air temperature measured from 2002 to 2005 and an average value from 1980 to 2005 (Figure 1a). The annual mean precipitation is 567 ± 119 mm, of which over 80% falls in the growing season from May to September. The precipitation from May to September over the 4 study years is slightly higher than that for the same period averaged from 1980 to 2005 (Figure 1).

[7] The alpine meadow is dominated by *Kobresia humilis* (C. A. Mey Ex Trautv.) Serg.. The foliage starts growing in early May and senesces in September [*Shi et al.*, 2001]. The aboveground biomass is very low in May and reaches its maximum of about 300–350 g m^{-2} in late August, then decreases from September (Figure 2). Other details about the study site can be found elsewhere [*Gu et al.*, 2003; *Kato et al.*, 2004].

2.2. Measurements

[8] A 2.5 m high meteorological observation system was installed in the alpine meadow in August 2001. The downward and upward components of shortwave and longwave radiation from the sky and the land surface were measured separately with a net radiometer (CNR-1; Kipp and Zonen, Delft, Netherlands) at 1.5 m above the ground. Air temperature and humidity were measured with a temperature and relative humidity probe (HMP45C; Campbell Scientific, North Logan, UT, USA), and wind speeds at 1.1 and 2.2 m above the ground were measured with cup anemometers (034A-L and 014A; Campbell Scientific). Soil water contents were measured with TDR sensors (CS615; Campbell Scientific) at a soil depth of 0.05 m, and soil surface temperatures were measured with temperature probes (107; Campbell Scientific) buried at three different points at a soil depth of 0.0 m (soil surface), and the averaged value was used in this study. Precipitation was measured with a tipping bucket rain gauge (TE525MM; Campbell Scientific) at 0.7 m above the ground surface. All the data were recorded with a data logger (CR23X; Campbell Scientific) at 15 min intervals. The net radiometer was kept horizontal, and all the instruments were stable during the measurement period.

[9] The aboveground biomass was measured consecutively at about 2 week intervals by clipping aboveground vegetation within a 50 × 50 cm^2 quadrat. Biomass was determined gravimetrically after being dried at 65°C for 72 h.

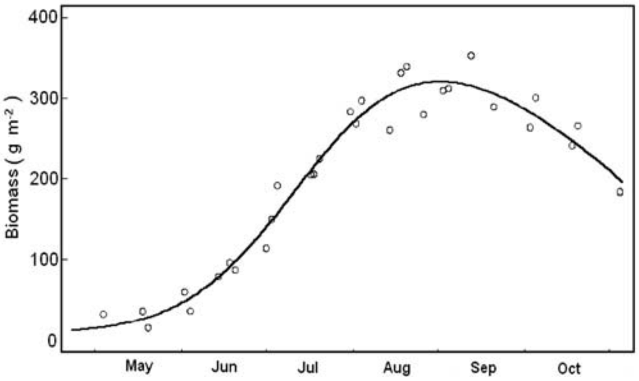

Figure 2. Annual variation in biomass during the growing period from 2002 to 2004.

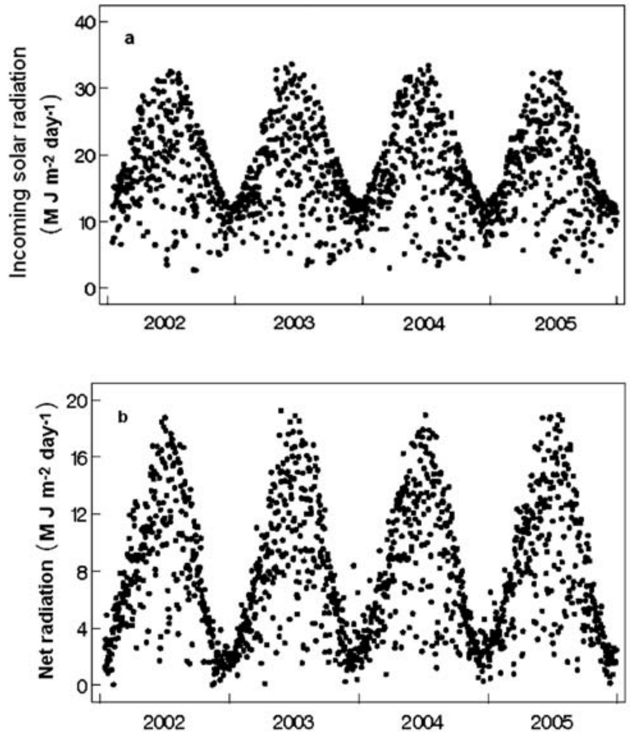

Figure 3. Annual variation in (a) daily solar radiation (R_s) and (b) net radiation (R_n) for the alpine meadow from 2002 to 2005.

2.3. Data Analysis

[10] The radiation balance in an ecosystem can be described as follows [*Qiu et al.*, 1998]:

$$R_n = (1 - \alpha)R_s - L_n, \tag{1}$$

where R_n is net radiation, R_s is incident solar radiation, α is the albedo of the surface, and L_n is the effective terrestrial radiation (net longwave radiation), which is the difference between upward longwave radiation emitted from the surface (L_u) and downward longwave radiation from the atmosphere (L_d), which can be expressed by the following equation [*Idso and Jackson*, 1960; *Qiu et al.*, 1998]:

$$L_n = L_u - L_d. \tag{2}$$

Equation (1) can be normalized as [*Iziomon et al.*, 2001]

$$\alpha + L + \eta = 1, \tag{3}$$

where $L = L_n/R_s$ and $\eta = R_n/R_s$, which denote the normalized effective radiation and radiation efficiency, respectively. α and L are the ecosystem's radiation partitioning of the shortwave and longwave radiation energy loss, respectively.

[11] Longwave radiation from atmosphere to the ecosystem is related to the effective emissivity of clouds and air temperature by

$$L_d = E_a(c)\sigma T_a^4, \tag{4}$$

where E_a(c) is the atmosphere's emissivity as a function of cloud cover (c), σ is the Stefan- Boltzmann constant (5.67 × 10^{-8} W m^{-2} K^{-4}), and T_a is air temperature in kelvins. To assess the effects of cloud on the normalized effective radiation, the emissivity of the atmosphere including clouds is calculated from the [*Monteith and Unsworth*, 1990].

$$E_a(c) = (1 - 0.84c)E_{ac} + 0.84c, \tag{5}$$

where E_{ac} is the clear-sky emissivity, which is given by [*Campbell and Norman*, 1998]

$$E_{ac} = 9.2 \times 10^{-6} T_a^2. \tag{6}$$

The cloud cover fraction (c) can be estimated from the solar radiation transmission coefficient (T_r) [*Mahmood and Hubbard*, 2002] through the expression [*Campbell*, 1985]

$$c = 2.33 - 3.33T_r. \tag{7}$$

The cloud cover fraction is constrained to values between 0 and 1.0. T_r can be calculated from

$$T_r = R_s/R_o, \tag{8}$$

where R_o is the solar radiation at the top of the atmosphere.

3. Results

3.1. Radiation Fluxes

[12] The annual variation of incoming solar radiation (R_s) was markedly affected by solar elevation and weather conditions (Figure 3a). The upper boundary value represented clear-sky data, with the lowest and highest values corresponding to late December and late June, respectively. The daily solar radiation on clear days ranged from about 12 to 34 MJ m^{-2} d^{-1}, with an average of 17.1 ± 0.3 MJ m^{-2} d^{-1} over the 4 years. The annual solar radiation averaged 6298 ± 96 MJ m^{-2} yr^{-1}, and 48% was recorded in the growing season from May to September.

[13] The upward longwave radiation (L_u) and downward longwave radiation (L_d) showed a similar temporal variation pattern (Figures 4b and 4c), with the lowest value in January and the highest in July (L_u and L_n are negative quantities here; the discussion, however, is much more intuitive and convenient when conducted in terms of their magnitude). The daily L_u was significantly higher than the daily L_d, with averages of 27.5 ± 0.1 and 21.6 ± 0.2 MJ m^{-2} d^{-1}, respectively. In comparison with L_u and L_d, the annual variation of daily L_n was relatively small, with a range of about 0–12 MJ m^{-2} d^{-1}. The average value was 5.8 ± 0.1 MJ m^{-2} d^{-1}, and the value of L_n in the growing season was slightly lower than that in the nongrowing season (Figure 4a).

[14] Higher net radiation (R_n) was recorded in late June and lower values were in late December (Figure 3b). The daily R_n was positive throughout the year, with an average of 7.6 ± 0.1 MJ m^{-2} d^{-1} for the 4 years. The annual R_n averaged 2779 ± 51 MJ m^{-2} yr^{-1}, with 60% within the growing season.

3.2. Radiation Partitioning

[15] Daily albedo (α), the ratio of daily reflected to incident solar radiation, was relatively conservative, with an

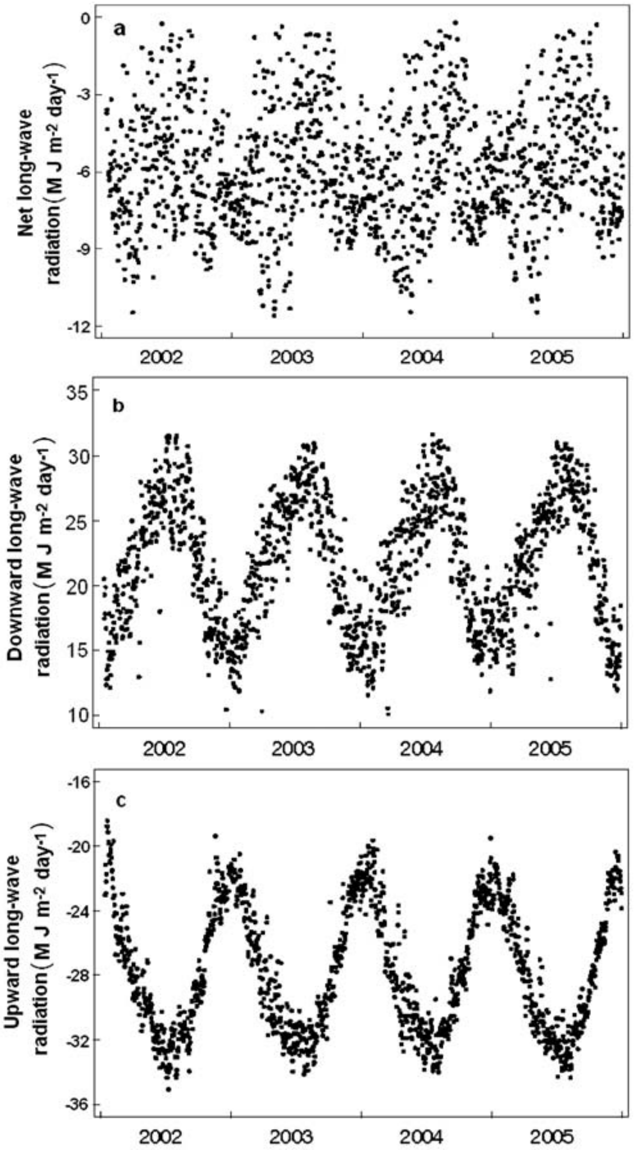

Figure 4. Annual variation in (a) longwave radiation emitted by the surface (L_u), (b) longwave radiation from the atmosphere (L_d), and (c) effective terrestrial radiation (L_n) for the alpine meadow from 2002 to 2005.

average value of 0.22 over the 4 years (Figure 5a). Albedo varied between 0.16 and 0.26 on snow-free days, with high values in winter and low values in the growing season. The lowest albedo was in September, after which the albedo quickly increased and reached a maximum of 0.90 during the period of snow cover. There was a small but significant variation in albedo during the growing period.

[16] Normalized effective radiation (L) showed a similar pattern to albedo but exhibited a large annual variation, with the highest value of about 0.7 in December, the lowest value of about 0.2 in August, and an annual mean of 0.34 (Figure 5b).

[17] Radiation efficiency (η) showed the opposite trend to L, with the high value in August and the lowest value in December. The annual mean value of η was only 0.44 (Figure 5c).

4. Discussions

4.1. Role of Geography in Radiation Balance

[18] Solar radiation reaching the Qinghai-Tibetan Plateau is about 1.2–2 times that of the same latitudes at low altitudes [*Ye and Gao*, 1979]. In this study, the maximum daily R_s of 35 MJ m^{-2} was much higher, while the average annual R_s was 31% higher than that reported for a grassland at about same latitude in Japan [*Li et al.*, 2005]. The ratio of daily global radiation received at the surface to the global radiation incident at the top of the atmosphere (R_s/R_o) [*Feister and Gericke*, 1998] showed an average of 0.60 at our site but was 0.44 at the lowland site, indicating a high atmospheric transparency over the alpine meadow.

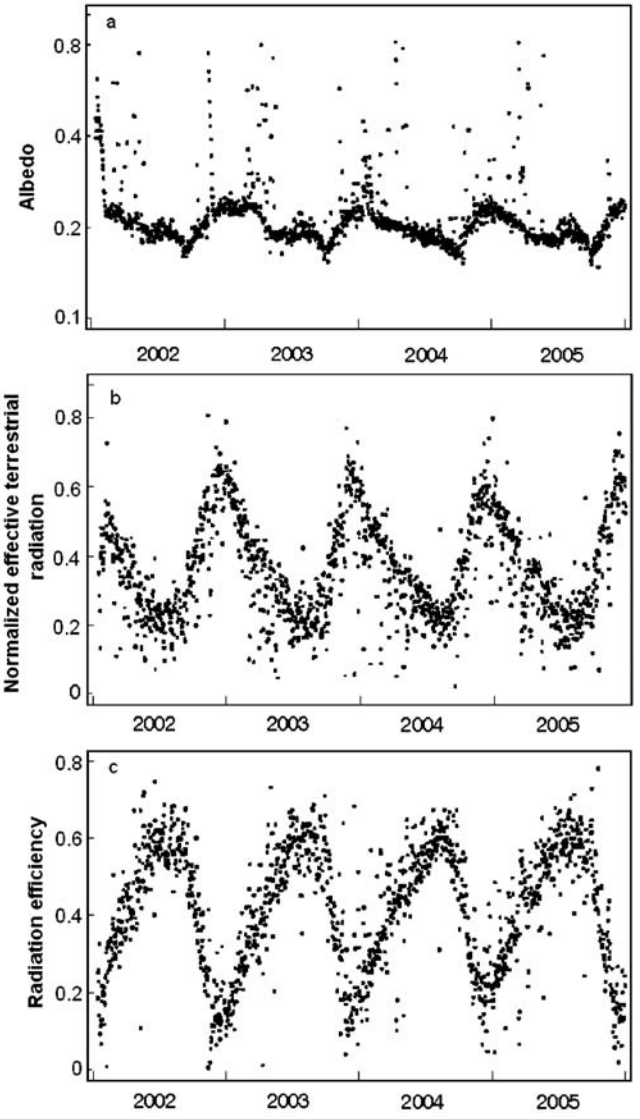

Figure 5. Annual variation in (a) daily albedo (α), (b) normalized effective radiation (L), and (c) radiation efficiency (η) from 2002 to 2005.

Table 1. Comparison of the Radiation Partitioning Between Alpine Meadow and Global and Other Grasslands

Time Period	Observation Area	α	L	η	Reference
Annual	Alpine meadow	0.22	0.34	0.44	Our study
	Global	0.13	0.26	0.61	*Gupta et al.* [1999]
	Northern Hemisphere	0.14	0.28	0.58	*Gupta et al.* [1999]
	Dry grassland in Mexico	0.22	0.17	0.61	*Monteny et al.* [1998]
	Wet grassland in Mexico	0.23	0.10	0.67	*Monteny et al.* [1998]
	Grassland in Australia			0.50	*Kalma et al.* [2000]
	Savanna in Australia	0.19	0.22	0.59	*Beringer et al.* [2002]
	Pasture in Brazil	0.18			*Berbert and Costa* [2003]
	Grassland in United States	0.14	0.20	0.66	*Small et al.* [2003]
	Prairie in Iraq	0.20	0.10	0.70	*Al-Riahi et al.* [2003]
	Grassland in Germany	0.16–0.20			*Stiller et al.* [2005]
	Meadow in Austria			0.68	*Hammerle et al.* [2008]
January	Alpine meadow	0.28	0.50	0.22	Our study
	Global	0.14	0.26	0.60	*Gupta et al.* [1999]
	Northern Hemisphere	0.14	0.42	0.44	*Gupta et al.* [1999]
July	Alpine meadow	0.19	0.23	0.58	Our study
	Global	0.12	0.26	0.62	*Gupta et al.* [1999]
	Northern Hemisphere	0.14	0.19	0.67	*Gupta et al.* [1999]

[19] Albedo is both a forcing variable controlling the climate and a sensitive indicator of vegetation change. In this study, the average daily albedo during the growing period (May–September) was higher than that reported in the grasslands at similar latitudes [*Gao et al.*, 2005]. The high albedo values on the alpine meadow may be partly due to the alpine foliage having more hairy leaf surfaces than lowland foliage [*Liu*, 1997; *Gu et al.*, 2005]. One of the possible ecological consequences is that the high albedo may allow the alpine plants to avoid the damage caused by the strong radiation. Furthermore, the albedo of the alpine meadow is not only higher than the average albedo of Earth and the average obtained for the Northern Hemisphere, but it was also higher than that of most other grasslands (Table 1). The result suggests that the radiation energy loss by shortwave radiation from the alpine meadow ecosystem may be greater than that for other ecosystems due to the relatively high albedo.

[20] Longwave radiation exchange between the surface of the meadow and the atmosphere is mainly determined by surface feature, air temperatures, clouds, and water vapor pressure in the atmosphere. In this alpine meadow, the water vapor pressure ranged from 0.1 to 1.4 kPa (Figure 6), which is much lower than that for some lowlands, ranging from 2.0 to 5.0 kPa [*Verhoef et al.*, 1996; *Kellner*, 2001; *Hunt et al.*, 2002; *Wever et al.*, 2002]. However, the air temperature is also low in this meadow. The downward longwave radiation (L_d) was obviously low in this alpine ecosystem compared with that reported globally or for the Northern Hemisphere [*Gupta et al.*, 1999] according to the NASA data (http//eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi). Moreover, the energy loss from the effective terrestrial radiation (L_n) was much higher than that for some lowlands [*Gupta et al.*, 1999], which is partly because of the low downward longwave radiation in this meadow, indicating that the alpine meadow ecosystem always lost more energy through the exchange of longwave radiation compared with lowland sites throughout the whole year. The loss due to the annual average L_n on the plateau was higher than that at the same latitude of lowland grassland ecosystems except for extensive desert regions, such as the Sahara, where the very low humidity of the desert permits the large upwelling longwave radiation from the high-temperature surface to pass through the atmosphere without a matching large downward longwave radiation from the atmosphere [*Smith et al.*, 2002].

[21] In terms of the radiation balance, effective terrestrial radiation is the largest component of radiation losses from Earth's surface (Table 1). The alpine meadow emitted 34% of annual incident solar radiation back into atmosphere in the form of longwave radiation, which was 1.31 and 1.21 times that of the global surface and Northern Hemisphere, respectively, and was much higher than that of other grasslands (Table 1). In January, the L was 50% for the alpine meadow, which was 92% and 19% higher than those of the global surface and the Northern Hemisphere, respectively (Table 1). In July, L was higher than that of the Northern Hemisphere and lower than that of the global surface (Table 1).

[22] The R_n is determined by the incident solar radiation, albedo, and net longwave radiation. Although this plateau is characterized by strong solar radiation, the high albedo combined with the high L resulted in the low radiation efficiency (η) for this alpine meadow (Table 1). The η about of 0.44 for the 4 study years in this meadow was only 72%–76% of the values for global surface and the Northern

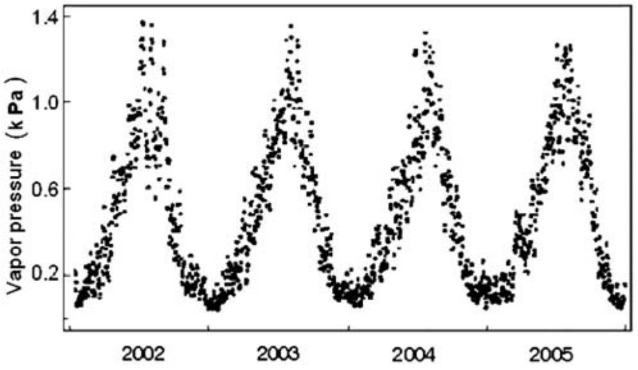

Figure 6. Annual variation in daily water vapor pressure (e) over the alpine meadow from 2002 to 2005.

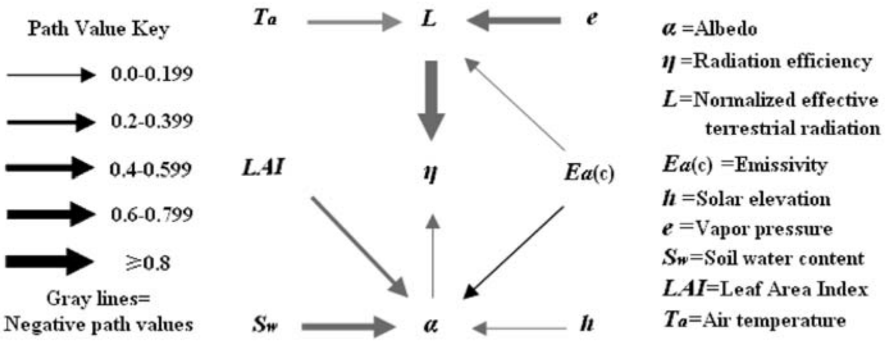

Figure 7. Path diagram illustrating the changing effects on different parameters related to radiation partitioning. Standardized correlation coefficients are as coded by the arrows. The data represent the pooled values for measurements on snow-free days in the alpine meadow from 2002 to 2005.

Hemisphere, respectively (Table 1). It is also lower compared with those reported for other grasslands, which ranged from 0.50 to 0.70 [*Shaw*, 1956; *Rosenberg*, 1969; *Kalma et al.*, 2000; *Iziomon et al.*, 2001; *Christen and Vogt*, 2004; *Rimoczi-Paal*, 2005] and for boreal vegetation [*Baldocchi et al.*, 2000; *Eugster et al.*, 2000]. R_s in this meadow was about 1000 MJ m^{-2} yr^{-1} higher than reported for a grassland in Japan [*Li et al.*, 2005]; however, the average annual R_n was comparable for both study sites. Especially in January, the η in the meadow fell to 0.22 due to the high albedo and L, with only one third of the global and one half of the Northern Hemisphere values (Table 1). These results indicate that the energy available for driving climatic processes is not high despite of high incident solar radiation in the alpine meadow. Such energy partitioning may also result in the low latent heat and sensible heat fluxes in this alpine meadow.

4.2. Effect of Vegetation on the Radiation Partitioning

[23] Vegetation is regarded as an active surface affecting radiation partitioning [*Ogunjemiyo et al.*, 2005]. The seasonal variation of albedo can be greatly affected by the vegetation phenology [*Eugster et al.*, 2000] and soil water content [*Gu et al.*, 2005]. The large seasonal variation of snow-free albedo (ranging from 0.16 to 0.26) in this study may be also caused by the changes in vegetation and soil water content (Figure 5a). During the growing season, the albedo of the alpine meadow showed low values when the vegetation cover and soil water content were high [*Gu et al.*, 2005]. The lowest albedo occurred in the late growing season when plants began to senesce while the soil maintained relatively high water content. During the nongrowing season, however, the high albedo was probably due to increase in dead leaves and/or decrease in vegetation cover [*Rechid et al.*, 2005]. The large difference of albedo between the growing and nongrowing seasons will influence the radiation partitioning in this meadow ecosystem.

[24] L_n is determined by longwave radiation. The vegetation is close to a blackbody radiator in this part of the spectrum [*Strain and Billings*, 1974]. Thus the emissivity of the ground increases with the increase in vegetation cover. The vegetation cover can also influence the amount of longwave radiation transferred to atmosphere because of the dependence of L_u on the surface temperature. The surface temperature usually changes according to the variation in vegetation coverage, albedo, ecosystem evapotranspiration, and emissivity.

4.3. Influences of Environmental Conditions and Path Analysis

[25] We applied path analysis to evaluate the dependence of radiation partitioning on several environmental factors and biological elements (Figure 7). Relative mutual information was used as an indicator for a possible causal relationship between the two variables: the black arrows in Figure 7 represent an increasing trend, while the gray arrows represent a decreasing trend in this study. Since there are only about 25 snow cover dates for each year, we skipped the snow cover data (albedo >0.26) because of its extremely high albedo [*Gallimore and Kutzbach*, 1996]. We assumed that soil water content (S_w), cloud ($E_a(c)$), water vapor pressure (e), leaf area index (LAI), solar elevation (h), and air temperature (T_a) have a great influence on radiation partitioning in the alpine meadow ecosystem because these factors are often considered to influence albedo and longwave radiation. LAI was estimated according to the relation between biomass and LAI [*Shi et al.*, 2001]. The atmosphere's emissivity ($E_a(c)$) was used to assess the contribution of cloud to radiation partitioning [*Campbell and Norman*, 1998].

[26] The path analysis (Figure 7) indicates that soil water and LAI were clearly dominant factors affecting the albedo in the alpine meadow. $E_a(c)$ showed a weak positive effect, and the solar elevation exhibited a negative effect on albedo. As $E_a(c)$ increases, incident radiation has a higher proportion of diffuse radiation; diffuse solar radiation also penetrates the canopy more effectively and lessens shadows, which increases the albedo.

[27] Longwave radiation is strongly governed by air temperature, water vapor pressure, and cloudiness [*Iziomon et al.*, 2001]. In our study, water vapor pressure was identified as the most important factor affecting L, possibly because of the marked annual variation in the water vapor pressure in this meadow (Figure 6). An increase of water vapor pressure may cause the increase in downward longwave radiation. In this meadow, the highest water vapor pressure appeared in the growing season, which may result in low L_n and L. Low air temperature characterized the

temperate environments on the Tibetan Plateau [*Gu et al.*, 2005]. In this study, the air temperature was negatively correlated with L (Figure 7). Path analysis showed a small negative effect of $E_a(c)$ on L. The value of $E_a(c)$ often increases with cloud cover, which further results in a high L_n in this study.

[28] The results of path analysis indicated that the changes in water vapor pressure and air temperature have the most important influence on radiation efficiency in this meadow ecosystem.

5. Conclusions

[29] We examined the radiation balance and its environmental variables over an alpine meadow on the Qianghai-Tibetan Plateau for the period from 2002 to 2005. The ratio of net longwave radiation to incident solar radiation in this alpine meadow ecosystem was much higher than that for the global surface and the Northern Hemisphere, indicating that energy loss due to the longwave radiation exchange between the surface and the atmosphere is more important than in other ecosystems. Normalized effective radiation was greatly affected by the water vapor pressure, air temperature, and cloud conditions. Albedo was higher than for other temperate grasslands and was found to be largely dependent on soil water and vegetation conditions. Annual R_n/R_s over the alpine meadow was, however, significantly lower than that reported for the global surface, the Northern Hemisphere, or other grassland ecosystems. The results indicate that the alpine meadow ecosystem receives high incident solar radiation, but much energy is lost from this ecosystem through longwave radiation.

[30] **Acknowledgments.** This study was supported by the One Hundred Talent Project (0429091211). This study was also partly supported by the project Early Detection and Prediction of Climate Warming Based on the Long-Term Monitoring of Alpine Ecosystems on the Tibetan Plateau funded by the Ministry of Environment, Japan. The study was conducted under the National Key Basic Research Plan Project (2005CB422005-01, 2007CB106802) and the Tianjin Natural Science Foundation (07JCYBJC12400, 07JCYBJC12500).

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