Surface energy partitioning in alpine swamp meadow in the Qinghai Tibetan Plateau

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Abstract: Based on surface energy flux data measured by eddy covariance methods from China Flux in alpine swamp meadow of the Qinghai Tibetan Plateau in 2005, the daily and seasonal dynamic of surface energy fluxes and their partitioning, as well as abiotic factors effects were analyzed. The results suggested that LE (Latent heat flux) was the largest consumer of the incoming energy. Rn (Net radiation flux) and LE showed clear seasonal variations in sharp hump and up to their maximums in August and July, respectively. H (Sensible heat flux) increased to its peak in August whereafter declined slowly. Precipitation could reduce the components of surface energy. As to Rn and LE, their correlations with abiotic factors were evident while it was not significant in H. Average EBR (Energy balance ratio) was 50.7%, which was much larger in growing season than non-growing season.

Key words: surface energy partitioning; eddy covariance methods; alpine swamp meadow; Qinghai-Tibetan Plateau

CLC number: S152.8 **Document code:** A **Article ID:** 1001-0629(2008)04-0014-09

The Qinghai Tibetan Plateau covers 2.5 million km^2, with average altitude of more than 4 000 m above sea level. The alpine swamp meadow occupies 0.049 million km^2, as one of the largest types of grassland ecosystem[1,2], and play an important role in protecting biodiversity, improving environment, providing resources and so on[3,4]. Because it effects on the ecosystem variables such as temperature, water transport, plant growth and productivity, surface energy partitioning is considered as one of the most important processes in wetland ecosystems. The main components of surface energy balance are net radiation, sensible heat, latent heat and stored energy in water and soil[5,6]. The thermal behavior of a swamp is affected by botanical composition, volumetric heat capacity and thermal conductivity, and water transformations are important factors in establishing soil and air moisture and temperature in swamp[7]. These processes have not been well documented especially in alpine swamp meadow in high-altitude area.

Previous researches on energy fluxes in wetland reported the abiotic and biotic factors' influences on energy partitioning, such as temperature[8], wind speed[9], vapor pressure deficit[10] and variables related plant[11,12] (stomatal resistance and leaf area index). The common conclusions can be summarized that the net radiation is the largest and latent heat flux dominated the energy cycle. The soil heat

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收稿日期:2006-11-20 **修回日期**:2007-12-18
基金项目:中国科学院知识创新工程重大项目(KZCX1-SW-01-01A);国家重点基础研究发展规划项目(2002CB412501)
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flux of a steep vertical soil temperature gradient is quantitative during growing season while the annual average is stable[13]. However, those study sites concentrated in plain regions and little information is related to energy balance on the plateau wetland.

Based on the data measured in 2005 by the eddy covariance methods, which established in the northeast of the Qinghai-Tibetan Plateau, we analyzed the surface energy partitioning of the alpine swamp meadow. Because of the difficulties in measuring the heat stored in water and soil, we lost some information on energy balance. To better understand the energy partitioning, we examined not only the diurnal and seasonal variations of the energy components, but also the influences of meteorological factors and precipitation events.

1 Materials and Methods

1.1 Site Description The study site was located in Luanhaizi swamp meadow, 37°29′N, 102°12′E which about 4 km from the Haibei Alpine Meadow Ecosystem Research Station, the Chinese Academy of Sciences (CAS). The annual mean air temperature was - 1.7 ℃ (according the meteorological station data from 1980 - 2000), the coldest month was January (- 15 ℃), and the warmest month was July (10 ℃). The annual average total radiation level could be up to 5.8×10^3 MJ/m^2; daily total radiation up to 22 MJ/m^2 in July and August. Annual precipitation was 580 mm, over 80 % of that was concentrated in the growing season from May to September[14]. The annual average potential evaporation was 1 235 mm and 680 mm during growing season.

The eddy covariance system was established in the homogenous and flat area. There were two-dominated plant species in study regions, where the Carex pamirensis was dominated in center and Kobresia tibetica in margin of the swamp meadow. The vegetation coverage was up to 98 % in the growing season while the species abundance was a little low. The catchments were flooded at an average water depth of 30 cm in growing season[15-17].

1.2 Field Measurements The eddy covariance method included the three-dimensional sonic anemometer (CSAT3, Campbell, USA) and open-path infrared CO_2/H_2O concentrations analyzers (LI-7500, LI-Cor Lnc., USA) at 250 cm above the ground. The net radiation (Rn), which was calculated from the four observation meters, including up-going, down-coming short-wave, long-wave radiation (CNR-1, Kipp &Zonen, Netherlands), and photosynthetic photon flux density (PPFD) (Li-190SB, Li-Cor, USA) was installed at 150 cm height. Other meteorological variables were also measured. The air temperature and humidity were observed at 110 and 220 cm with a temperature and humidity probe (HMP45C, CSI, USA), the wind speed and direction, soil temperature (0, 2, 5, 10, 20, 40 cm) and precipitation were also measured. All the data, including mean, variance, covariance values were calculated and recorded with a data acquisition system (CR23X and CR5000, CSI, USA) at 30 minute intervals

1.3 Methods and Calculations According to the principle of eddy covariance method, the sensible heat flux (H) and latent heat flux (LE) could calculate as follows:

$$H = \rho Cp W'T' \tag{1}$$

$$LE = L\rho W'q' \tag{2}$$

where, ρ is the air density (kg/m^3), Cp is the air special heat in constant pressure [1 004 J/(kg · K)], W is the vertical wind speed (m/s), T is the air temperature (K), L is the water gasification latent heat (2.5 ×106 J/kg), E is the vertical water vapor flux (g/s), q is the relative humidity (g/g), “ ′”is the symbol of instantaneous fluctuations of parameters and “ —”represents the mean value of parameters in certain time.

Because of the absence of soil heat flux, the energy balance ratio (EBR) had to be calculated by the following equation:

$$EBR = (H + LE)/Rn$$

Energy imbalance was very common and even up to 40 % in global flux system[18], such as America Fluxnet, Europe Fluxnet and Asian Fluxnet. However, EBR was considered as the symbol of data quality control and this approach was accepted. We used EBR to assess our data quality. Missing data were filled with the linear equation.

2 Results and Discussions

2.1 Microclimate and water depth conditions The annual variations of meteorological factors were showed in Fig. 1. In 2005, annual mean air temperature was -1.05 ℃, ranged from -18.37 ℃in January 10th to 14.30 ℃in August 9th, and a little higher than -1.7 ℃that calculated from the alpine meadow meteorological station twenty-year-data(1980-2000). There was some difference between 5 cm-depth soil temperature and air temperature. From the beginning of April to the middle of August, the 5 cm-depth soil temperature was little lower than air temperature because of vegetation growth, reflection, and energy consumption. While the 5 cm-depth soil temperature began to be higher than air temperature and the differences was up to maximum in the middle periods of winter. Song[19] found the similar phenomena and reported there was a strong exponential correlation between 5 cm-depth soil temperature and air temperature in plain marsh. PPFD had similar variations with air

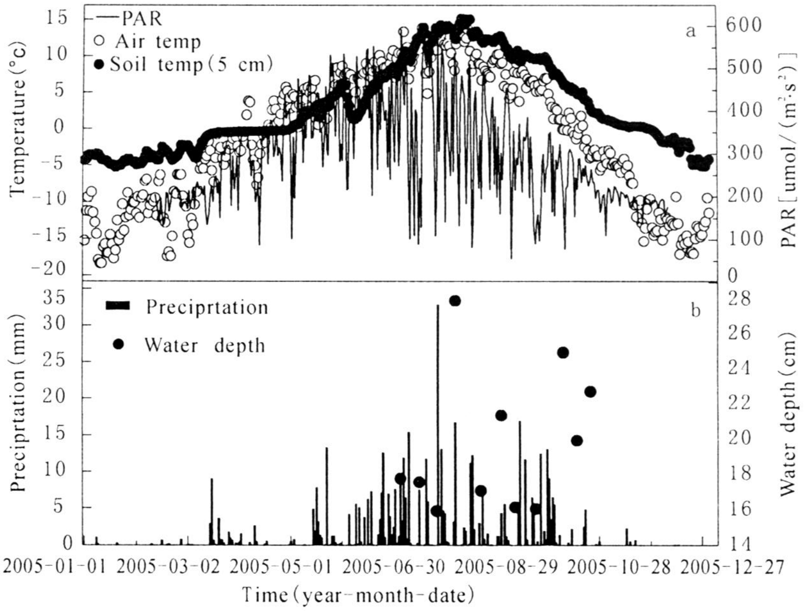

Fig. 1 Variations of meteorological factors in alpine swamp meadow on Qinghai-Tibetan Plateau

Note: graph “a ”is PAR, air and soil temperature, graph “b ”is precipitation and water depth.

temperature, and was up to its maximum in August. While it was more scattered because rainfall was concentrated in growing season and cloud cover was complex in the sky. The annual total precipitation was 475 mm, obviously lower than twenty-year's mean 567 mm. The mean water depth was 20 cm in growing season, and little complex variations while was influenced by rainfall strongly. One representative example was in July 26 that the precipitation was up to 32.8 mm and the water depth measured in few days later came to its maximum 28 cm. Because of plant consumption and less precipitation, the water depths decreased gradually and reached its minimum at the beginning of August, and then were restored by rainfall. The similar variations were reported by Hirtoa[20].

2.2 Diurnal variations of energy partitioning Fig. 2 showed that the diurnal average variations of LE, H and Rn in January (Winter), April (Spring), July (Summer) and October (Autumn) in alpine swamp meadow. All those variables discussed displayed the similar hump variations in all season. After the sunrise, the energy fluxes became positive and then up to their maximums about 14:00 (BST, Beijing Standard Time) with the development of solar angle. Subsequently, the solar angle declined and the solar energy came to the alpine swamp meadow decreased. Therefore, LE, H and Rn declined and fall into negative value after the sunset and this situation was stable at nighttime.

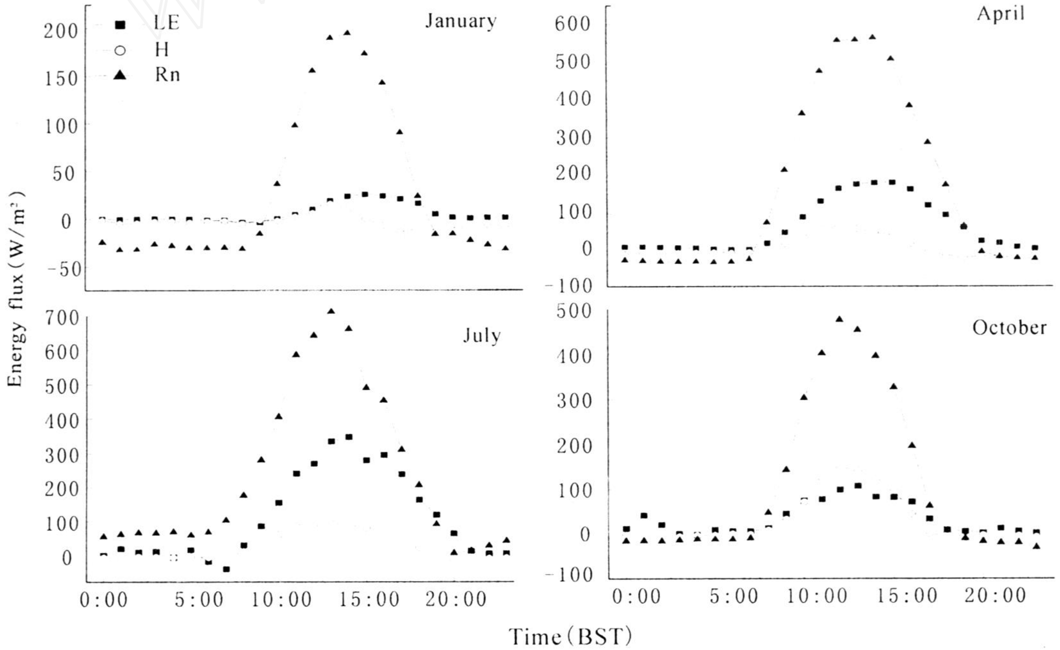

Fig. 2 The diurnal variations of LE, H and Rn in January, April, July and October in alpine swamp meadow on the Qinghai-Tibetan Plateau (BST was Beijing Stand Time)

There were some differences in energy daily partition among January, April, July and October. In January, the average daily LE was the primary consumer of available energy, which up to 20%. While it meant the alpine swamp meadow absorbed the energy from the atmosphere when H was kept negative value. In spring, the mean daily H increased and became the positive value with the development of air temperature. Meanwhile, LE was the main component in the energy partition all the time and up to 40%. In the middle and end of growing season, the mean daily H was always kept increasing and up to 11% and 28% in July and October, respectively. LE came to its maximum in July, up to

47 %. It declined to 31 % in October subsequently; however, it was still the biggest sink of the incoming energy. From the whole year, LE was the biggest components in available energy in alpine swamp meadow. The daily change of energy exchange was discussed in the adjacent alpine meadow[18]. Gu suggested that H was the biggest the consumer in the whole year, expect during growth-period (July - August). The alpine swamp ecosystem provided enough water for evaporation in non-growing season and transpiration in growing season, so LE was the prime consumer of incoming energy. The similar phenomenon was found in Ballards Marsh, USA in growing season in 1994[2].

2.3 Seasonal variations of energy partitioning The seasonal variations of Rn, H and LE were shown in Fig. 3. The annual average Rn was 125.0 W/m^2, ranged from 23.0 to 443.0 W/m^2. There was single-peak in Rn seasonal dynamics. With the development of the solar angle, the Rn increased from January to August, up to 221.5 W/m^2 (month average value), and then declined gradually. Moreover, there were much more scatters in growing season, because of more sunny days in non-growing season. The annual mean H was 17.6 W/m^2, ranged from -15.3 to 72.1 W/m^2. In the periods of January to March, the alpine swamp meadow ecosystem's surface layer was frozen and absorbed the available energy from the atmosphere, so H was negative and its three-month-mean value was -1.7 W/m^2. With the increase of temperature, the swamp ecosystem absorbed the energy and stored some energy in water in daytime and released the stored energy considerably to the atmosphere in nighttime, then H was enhanced and up to 36.5 W/m^2 in August. Because of large energy stored in swamp ecosystem in growing season, the ecosystem released the energy continually then H declined little and even was 12.0 W/m^2 in December. Rouse[12] reported that H was larger in cold air than that in warm air in high-latitude wetlands, and the reasonable explanation was the ground heat flux was enhanced in warmer air. The year average LE was 49.0 W/m^2, ranged from -24.6 to 188.3 W/m^2. From January to April, the frozen layer thawed piece by piece and evaporation was enhanced with the increase of air temperature. In the growing season, the vegetation developed, thieved and then senesced, and the transpiration changed like that. However, evaporation changed differently as well as latent heat flux, the sum of evaporation and transpiration. There was not too much vapor pressure deficit in alpine swamp meadow, and the evaporation and transpiration should be influenced by meteorological factors, like temperature, air humidity, wind speed, and so on. So LE increased to its maximum in July, and was up to 102.1 W/m^2, when the air temperature up to its peak, and then evaporation and transpiration came to their maximum. The seasonal variations of Rn and LE were single-peak obviously while H was only much larger in growing season than that in non-growing season.

The seasonal variations of surface energy partition were little surprised. LE was the biggest consumer in available energy, and up to 59.1 % in September while it's maximum in July. From January to March, the ratio of H/Rn was negative, and then it was enhanced till November, up to 28.9 %, which was little more than that of LE/Rn (28.7 %) at the same periods. In the December, the ratio of H/Rn declined a little, and was 23.5 %, which was little less than that of LE/Rn (27.8 %). Energy Balance Ratio was 50.7 %, and obviously less than other sites' EBR of China Flux[22], primarily because of soil heat flux absence and other reasons like sampling mismatch, systematic bias, low and high frequency loss and so on. As to the seasonal change of EBR, the growing season EBR was 67.0 %, much larger than non-growing season EBR (40.0 %). Because of large water in swamp ecosystem surface layer and strong ability of storing energy in water, the much energy gapes should at-

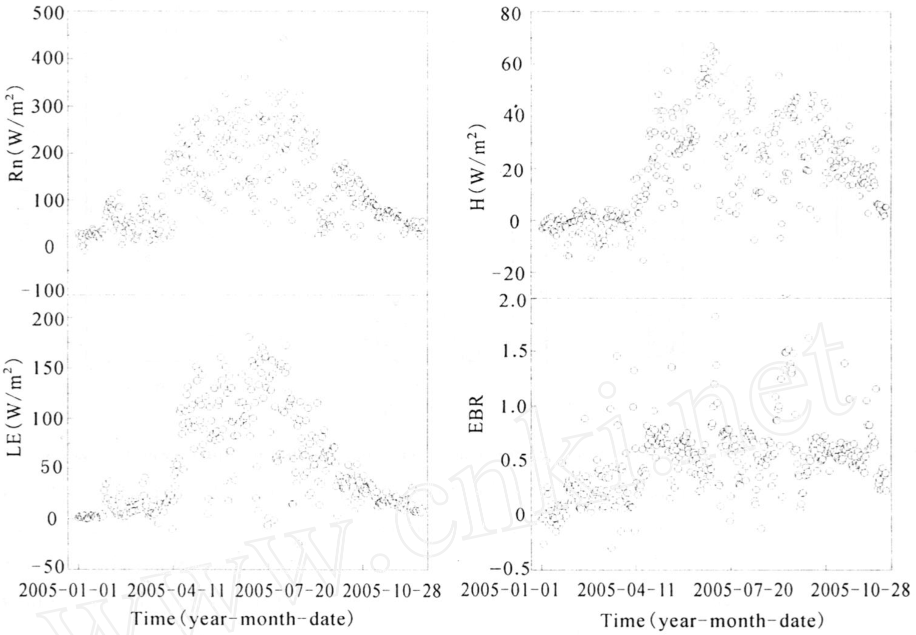

Fig. 3 Seasonal variations of surface energy components and EBR in alpine swamp meadow on Qinghai-Tibetan Plateau

tribute to the lack of soil heat flux.

2.4 Precipitation event's influences on energy flux Precipitation was very common. However, there was no enough information to know how it affected energy flux. The relatively independent rainfall, occurred in the end of July, was selected to avoid other precipitation's influence (Fig. 4). In July 26, the daily accumulative precipitation was up to 32.8 mm, and the sunlight hours were only 1.8 h while the rainfall was 0.2 mm and sunlight hours was up to 7.5 h in July 27, so the energy flux descended evidently. Because of short sunlight hours, Rn declined from 271.8 (daily mean value, in July 25) to 97.1 W/m^2. With the improvement of the atmospheric transparency though a great precipitation, Rn was enhanced to 305.4 W/m^2 in July 27, a little more than the value in July 25. H and LE went though the similar process. H was 27.6 W/m^2 before the precipitation, and down to 2.5 W/m^2, then rapidly up to 38.2 W/m^2 in the sunny day after the rainfall. LE was declined too, and became negative (- 0.9 W/m^2) in rainy day. Although LE rose to 112.0 W/m^2, it was a bit less than 144.4 W/m^2 on July 25th. It was different with the variations of Rn and H. The influence on EBR was similar with LE. EBR was almost descended to 0, the value were 53 % and 37 % before and after the precipitation, respectively.

2.5 Correlation between energy flux and abiotic factors To get enough evidence to realize the surface energy partitioning, the correlations between energy flux and meteorological factors were analyzed (Fig. 5). The relationship between Rn and air temperature, albedo and vapor pressure deficit (VPD) was similar with that of LE. Air temperature rose from the minimum to about 5 ℃, this period was so-called the non-growing season, and Rn and LE were enhanced a little. However, the swamp alpine meadow came into the periods of growing season, and Rn and LE increased a lot while the air temperature didn't change too much. In one words, they were positive, exponential correlation in some con-

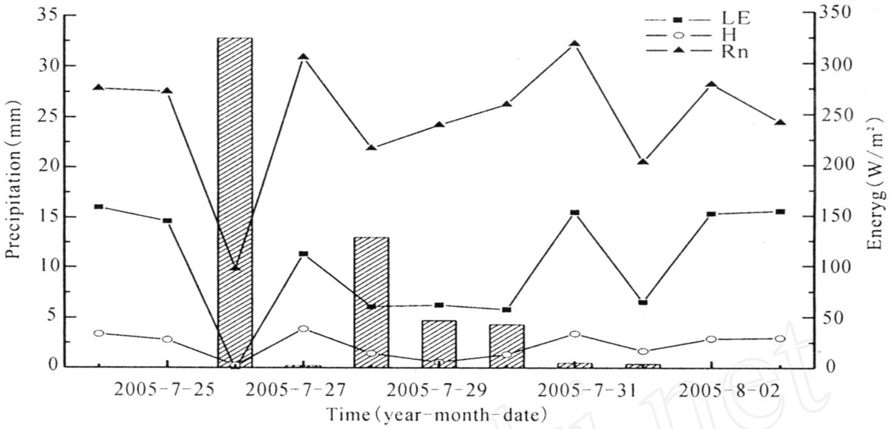

Fig. 4 The influence of precipitation on surface energy partitioning in alpine swamp meadow

tent ($R^2 = 0.57$, $P < 0.001$). The relationship between H and air temperature wasn't obvious ($R^2 = 0.30$, $P < 0.001$). That might because that H was at its maximum in October and November while temperature difference between April or May and October or November was slight. Surface albedo was the symbol of plant growth. Rn, H and LE were negative, approximate-power relationship with surface albedo ($R^2 > 0.49$, $P < 0.001$). The higher albedo suggested that the swamp ecosystem surface was dominated by snow, ice, naked earth, and so on, while the lower albedo meant the vegetation went into the growing season and developed very well. The average albedo was 0.37 and 0.16 in the whole growing season and non-growing season, respectively. Rn and LE were up to their maximums just in growing season, and H came into its most in non-growing season while the vegetation albedo was only 0.19 in October. Hence, Rn, H and LE were into the periods of their most when the swamp meadow ecosystem surface albedo became much less. As to VPD, Rn, H and LE were positive, linear correlation ($R^2 > 0.56$, $P < 0.001$) while the much more scattered points in graph between H and VPD ($R^2 = 0.22$, $P < 0.001$). The higher VPD happed in the periods of plant rapid growth and dry atmosphere, so it was 0.35 in growing season and 0.26 in December. Rn and LE increased in growing season while VPD was prompted too. As for H, its maximum was in October while VPD was 0.21, not too less than that of growing season.

3 Conclusions

In this paper, based on the data measured with eddy covariance methods in the alpine swamp meadow on the Qinghai-Tibetan Plateau during 2005, the daily and seasonal variations of surface energy partitioning, whose correlation with abiotic factors were discussed, as well as the influences on Rn, H and LE by precipitation. The conclusions were as follows:

1) In daily and seasonal variations of surface energy partitioning, LE was the biggest consumer in available energy. Although there were some differences in daily dynamic in January, April, July and October, the Rn, H and LE were kept negative value in nighttime and up to their maximums in 14:00 (BST). As to seasonal change, Rn and LE were hump, and up to their most in August and July, respectively. H increased to 36.5 W/m^2 in August while declined very slowly, even up to 23.3 W/m^2 in November. Mean H in growing season was larger than that in non-growing season. Average Energy Balance Ratio only was 50.7%, because of absence of soil heat flux. The growing season EBR was

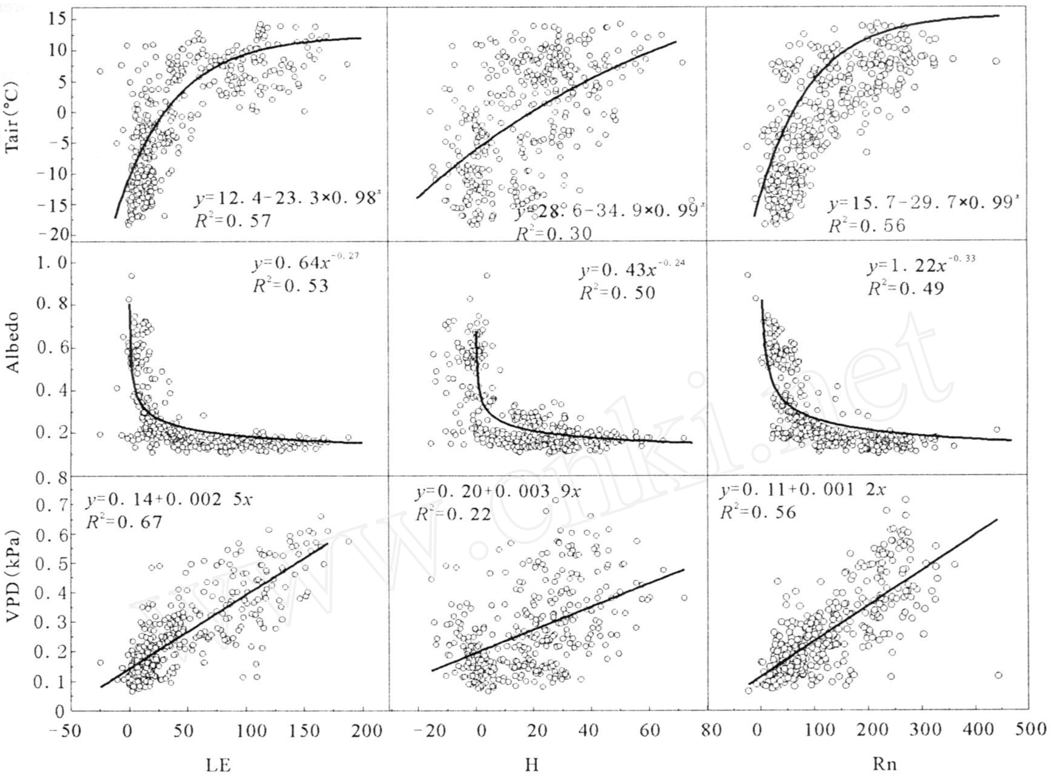

Fig. 5 The correlations between energy fluxes and abiotic factors (air temperature, albedo, VPD) in the alpine swamp meadow

67.0 %, much more than non-growing season EBR (40.0 %).

2) The surface energy partitioning and EBR were depressed by precipitation, very obviously. However, they were enhanced evidently of much more sunlight hours in daytime after the rainfall. Expect LE, Rn, H and EBR could be prompted, compared before precipitation. The correlations between Rn and abiotic factors were evident. Rn was positive, exponential correlation with air temperature in some content ($R^2 = 0.57$, $P < 0.001$). As for albedo and VPD, the relationships were negative approximate-power and positive linear, respectively ($R^2 > 0.53$, $P < 0.001$). There was little difference between LE and Rn in correlations with abiotic factors while that of LE was much more evident ($R^2 > 0.49$, $P < 0.001$). The relationships between H and those abiotic factors, expect surface albedo, were not illegibility ($R^2 < 0.30$, $P < 0.001$).

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青藏高原高寒湿地地表能量分配的动态变化

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摘要：依据中国通量网2005年在青藏高原高寒湿地观测的地表能量数据，分析了青藏高原高寒湿地地表能量分配的日变化和季节动态，及非生物因素对其的影响。结果表明，潜热通量是地表有效能量的主要消耗部分，净辐射通量和潜热通量呈现出明显的单峰式变化，分别在8月和7月达到其最大值，显热通量在8月达到最大，而后缓慢降低。降雨能显著降低能量通量的各分量。相关性分析的结果表明，净辐射通量和潜热通量与非生物要素的存在较为明显的相关性，显热通量的相关性则较差。能量平衡比率平均为50.7%，其在生长季节明显高于非生长季节。

关键词：地表能量分配；涡度相关；高寒湿地；青藏高原