SCIENCE CHINA
Earth Sciences

• RESEARCH PAPER •

November 2015 Vol.58 No.11: 2002–2014
doi: 10.1007/s11430-015-5133-3

Influence of environmental factors on land-surface water and heat exchange during dry and wet periods in the growing season of semiarid grassland on the Loess Plateau

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Received January 20, 2015; accepted April 14, 2015; published online July 13, 2015

On the basis of information from the project "Land-surface Processes and their Experimental Study on the Chinese Loess Plateau", we analyzed differences in land-surface water and heat processes during the main dry and wet periods of the semiarid grassland growing season in Yuzhong County, as well as the influences of these environmental factors. Studies have shown that there are significant differences in changes of land-surface temperature and humidity during dry and wet periods. Daily average normalized temperature has an overall vertical distribution of "forward tilting" and "backward tilting" during dry and wet periods, respectively. During the dry period, shallow soil above 20-cm depth is the active temperature layer. The heat transfer rate in soil is obviously different during dry and wet periods. During the dry period, the ratio of sensible heat flux to net radiation (H/Rn) and the value of latent heat flux to net radiation (LE/Rn) have a linear relationship with 5-cm soil temperature; during the wet period, these have a nonlinear relationship with 5-cm soil temperature, and soil temperature of 16°C is the critical temperature for changes in the land-surface water and heat exchange trend on a daily scale. During the dry period, H/Rn and LE/Rn have a linear relationship with soil water content. During the wet period, these have a nonlinear relationship with 5-cm soil water content, and 0.21 m^3 m^{-3} is the critical point for changes in the land-surface water and heat exchange trend at daily scale. During the dry period, for vapor pressure deficit less than 0.7 kPa, H/Rn rises with increased vapor pressure deficit, whereas LE/Rn decreases with that increase. When that deficit is greater than 0.7 kPa, both H/Rn and LE/Rn tend to be constant. During the wet period, H/Rn increases with the vapor pressure deficit, whereas LE/Rn decreases. The above characteristics directly reflect the effect of differences in land-surface environmental factors during land-surface water and heat exchange processes, and indirectly reflect the influences of cloud precipitation processes on those processes.

Loess Plateau, dry and wet periods, environmental factors, land-surface water and heat exchange

Citation: Yue P, Zhang Q, Zhao W, Wang R Y, Zhang L, Wang W Y, Shi J S, Hao X C. 2015. Influence of environmental factors on land-surface water and heat exchange during dry and wet periods in the growing season of semiarid grassland on the Loess Plateau. Science China: Earth Sciences, 58: 2002−2014, doi: 10.1007/s11430-015-5133-3

Regional response to global change and the influences of land-surface change and human activities on climate are realized through land-surface processes and land-atmosphere interaction (Fu and Ma, 2008; Huenneke et al., 2002). Systematic research on land-surface water and heat exchange processes aids understanding of the regular water and heat cycle of regional climate systems and its response to climate change (Zhang Q et al., 2012a; Zhang and Wang, 2008;

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Gettelman et al., 2004). Research shows that under the background of global warming, arid and semiarid regions present vegetation degradation, rising land-surface temperature, increasing sensible heat fluxes, evaporation reduction and other phenomena, which cause a series of changes and chain reactions of land-surface processes, atmospheric boundary layer structure, and others (Huang et al., 2012; Gettelman et al., 2004). Based on the important influence of land-surface processes and land-atmosphere interaction on climate, their observation is one of the most important research objectives of Climate and Ocean: Variability, Predictability and Change (CLIVAR), Global Energy and Water Cycle Exchanges (GEWEX), and other research projects (Zhang R H et al., 2012; Xu and Chen, 2006).

Currently, the study of land-atmosphere interaction in arid and semiarid regions is attracting attention in developed countries of Europe and the Americas (Oncley et al., 2007; Wilson, 2002) and in less-developed Asian and African countries and regions (Zhang and Wang, 2011; Lauwaet et al., 2009; Wen et al., 2007; Lü et al., 2002a). Since the 1980s, a series of large field observation experiments have been carried out in China, e.g., the Heihe River Basin Field Experiment (HEIFE) (Hu et al., 1994), "Inner Mongolia Semi-arid Grassland Soil-Vegetation-Atmosphere Interaction (IMGRASS)" (Lü et al., 2002a, 2002b), and "Field Experimental in Aridification and Ordered Human Activity in Semi-arid Areas" (Liu et al., 2008). These have greatly promoted the progress of land-atmosphere interaction research and laid a foundation for improving numerical modeling and the predictability of weather and climate.

The Chinese Loess Plateau has complex topography, diverse vegetation, and significant differences in the distribution of land-surface radiation and energy flux for various vegetation types (Yue et al., 2012; Zhang and Wang, 2008; Wei et al., 2005). The Loess Plateau region not only is a transition zone from an inland arid climate zone to monsoon climate but also is the main coupling area between winter and summer monsoon circulations in China (Zhang Q et al., 2012a). Therefore, climate fluctuations are strong there, and land-surface water and heat characteristics are very different during the annual dry and wet periods. Further, land-surface water and heat exchange processes are dependent very much on environmental factors (Zhang et al., 2014). In addition, land-surface water and heat exchange on the Loess Plateau not only directly affects the regional climate and environmental changes, but also may have important influences on changes in East Asia and even the global climate and environment (Huang et al., 2008; Zhang and Wang, 2008).

The latest research on land-surface processes of the Loess Plateau have been aimed mainly at radiation and energy exchange in the underlying surface of farmland (Zhang et al., 2011; Wen et al., 2007; Wei et al., 2005). Land-surface water and heat exchange characteristics under different hydrologic conditions in the semiarid grassland of the plateau, which are little affected by human activities, have been less studied (Yue et al., 2013a; Zhang Q et al., 2012a; Wang et al., 2010). There have been few studies on the effects of land-surface environmental factors on surface energy exchange. This situation restricts a comprehensive understanding of typical land-surface water and heat exchange and the essence of land-surface processes on the plateau. In addition, parametric relations between environmental factors and land-surface water-heat conversion efficiency have not been established, which restricts the contribution of land-surface process research to weather and climate prediction (Zhang Q et al., 2012a; Zhang and Wang, 2008).

For this reason, we compared land-surface temperature and humidity during the main dry and wet periods of the growing season of semiarid grassland in Yuzhong County on the Loess Plateau, and their influence on the land-surface energy process. We used observation data of the key project of National Natural Science Foundation of China "Land-surface Processes and their Experimental Study on the Chinese Loess Plateau" (LOPEX). Moreover, basic laws of land-surface water and heat exchange during the dry and wet periods are clarified, for providing a scientific reference for building parametric relations between environmental factors at daily scale and land-surface water-heat conversion efficiency, and for improving regional climate numerical simulation and prediction.

1 Experiment site, observation method and data

1.1 Study area

The Loess Plateau has a geographic scope of the Taihang Mountains of Shanxi Province in the east, the Riyue Mountains in Qinghai Province to the west, the Qinling Mountains in Shaanxi Province to the south, and the Yinshan Mountains in Inner Mongolia to the north. The plateau has a total area of more than 62.68×10^4 km^2. There is a typical continental climate. Regional annual average rainfall is about 466 mm, and rainfall has significant spatial change, gradually decreasing from southeast to northwest. The area is a transition zone from a southeastern humid monsoon climate to northwest inland arid climate, and from warm temperate broadleaf deciduous forest to typical steppe and desert steppe. LOPEX is a large field observation project supported by the National Natural Science Foundation. The Semi-Arid Climate and Environment Observatory of Lanzhou University (SACOL station) is one of the main observation sites of LOPEX (Zhang Q et al., 2012a). SACOL is located in the Loess Plateau of Yuzhong County, Gansu Province (35°57′N, 104°08′E) at altitude 1966 m. There is a temperate semiarid climate zone, with annual rainfall of 381.8 mm and annual average temperature of 6.7°C. Yellow soil is dominant, with deep soil layers, loose texture, strong ventilation and permeability; most soil of the plateau belongs to this type (Zhang Q et al., 2012a). The observation area of SACOL station is about 120 mu (mu equal to 1/15 of a hectare) with basically flat terrain, and vegetation is natural desert grassland. Eugenic vegetation is the perennial herb *Stipa bungeana*, and associated vegetation includes *Leymus chinensis* and *Artemisia frigida* (Yue et al., 2012; Huang et al., 2008). Viewed from a wider spatial scale, the site has an inhomogeneous surface with strong terrain fluctuation, basically representing typical geomorphic characteristics of the Loess Plateau in central Gansu Province (Zhang Q et al., 2012b; Wang et al., 2010). To understand the representativeness of SACOL station observation for the typical Loess Plateau surface, Yue et al. (2011) analyzed the spatial correlation of daily average ground-air temperature difference at SACOL and 16 surrounding meteorological observatories (ground-air temperature difference can usually be used to characterize sensible heat flux intensity). High correlation of ground-air temperature difference between the 16 observatories and SACOL shows that this station has a spatial representation that can faithfully portray land-surface characteristics of semiarid areas on the western Loess Plateau.

1.2 Observation method

We used an eddy covariance system and micrometeorological gradient observation data from 2008, along with temperature and precipitation data of Yuzhong weather station from the past 50 years. The eddy covariance system consists mainly of an open-path H_2O/CO_2 analyzer (Li-7500; LI-COR), three-dimensional ultrasonic anemometer (CSAT-3; Campbell), and data acquisition unit (CR5000; Campbell). The open eddy covariance system was set up at a height of 3 m with sampling frequency 10 Hz. Six-layer meteorological element sensors at heights 2, 4, 8, 12, 16, and 32 m were installed on a micrometeorological gradient observation tower. Measurement elements included air temperature, humidity (HMP45C-l; Vaisala), and wind velocity (014A-L; Met One Instruments). The wind direction instrument (034B-L; Met One Instruments) was installed at a height of 8 m. Soil temperature was observed in six layers at depths of 2, 5, 10, 20, 50, and 80 cm (STP01-L50; Hukseflux). Soil moisture was observed in five layers at depths of 5, 10, 20, 40, and 80 cm (CS616-l; Campbell). Land-surface radiation included upward and downward shortwave radiation (CM21; Kipp & Zonen) as well as upward and downward longwave radiation (CG4; Kipp & Zonen), measured at a height of 1.5 m above the surface. Soil heat flux was determined by a self-correcting heat flux plate (HFP01SC-L50; Hukseflux) at measurement depths 5 and 10 cm.

1.3 Data quality control

First, measurement data of the eddy covariance system were partitioned into 30-min durations. Referring to the method of Oncley et al. (2007), secondary coordinate rotation was performed on the original 30-min data. Then ultrasonic virtual temperature correction was conducted for sensible heat flux (*H*), and Webb-Pearman-Lenuing correction of latent heat flux (*LE*). The eddy covariance system is vulnerable to the effects of weather such as rainfall and dew, resulting in abnormal flux observations. These outliers must be eliminated in data processing (Xu et al., 2009; Falge et al., 2001). To fully understand dynamic changes of water heat flux, continuity of the data must be ensured. Therefore, it is necessary to interpolate data loss and outliers caused by equipment malfunction, system calibration, and precipitation (Xu et al., 2009). These gaps were filled by following the strategies (Falge et al., 2001): linear interpolation was used to fill the gaps that were less than 6 h; other data gaps were filled using the empirical relationship (look-up table method), i.e., the bin-average values for LE or H in connection with their environmental factors, such as net radiation and vapor pressure deficit.

1.4 Calculation of heat flux

Surface net radiation (*Rn*) can be calculated by

$$Rn = (DSR - USR) + (DLR - ULR), \tag{1}$$

where *DSR* is total radiation, *USR* reflected radiation, *DLR* atmospheric downward longwave radiation, and *ULR* surface upward longwave radiation; units are W m^{-2}.

Near-surface *H* and *LE* can be obtained by the eddy covariance method:

$$H = \rho Cp\overline{w'\theta'}, \tag{2}$$

$$LE = \lambda\rho\overline{w'q'}, \tag{3}$$

where ρ is air density; *Cp* is specific heat at constant pressure; $\overline{w'\theta'}$ and $\overline{w'q'}$ are the warm and wet pulse covariance, respectively. Surface soil heat flux was calculated as below.

Based on observations of the HFP01SC-L50 heat flux plate and temperatures of the 0-cm, 2-cm and 5-cm soil layers, the temperature integral method was used for correcting HFP01SC-L50 measurement data to the surface (Zhang Q et al., 2012b):

$$G = G_5 + \frac{\rho_s c_s}{\Delta t}\sum_{z=5\text{ cm}}^{z=0}\left[T\left((z_i,t)+\Delta t\right) - T(z_i,t)\right]\Delta z, \tag{4}$$

where *G* is soil heat flux corrected to the surface (W m^{-2}); G_5 is soil heat flux at depth 5 cm, observed by the heat flux plate; $\rho_s c_s$ is soil volumetric heat capacity (J m^{-3} K^{-1}); $T(z_i, t)$ is soil temperature at depths of 0, 2 and 5 cm (°C). $\rho_s c_s$ is calculated by eq. (5) (Wang et al., 2005):

$$\rho_s c_s = -\left(\frac{\partial G_i}{\delta z}\right)\Bigg/\left(\frac{\partial G_g}{\partial t}\right), \quad i\text{=5, 10 cm}. \tag{5}$$

Soil temperatures at depths 2 and 5 cm were obtained by observation, whereas that at depth 0 cm was obtained by surface longwave radiation conversion (Yang and Wang, 2008):

$$T_0 = \left(\frac{ULR - \left(1 - \varepsilon_g\right) DLR}{\varepsilon_g \sigma} \right)^{1/4}, \tag{6}$$

where ε_g is surface emissivity, set to 0.96; σ is the Stefan-Boltzmann constant, 5.67×10^{-8} W m^{-2} K^{-4}.

1.5 Determination of dry and wet periods

Figure 1 shows the seasonal distribution of daily average environmental factors of semiarid grassland in Yuzhong during 2008. The semiarid grassland of the Loess Plateau has significant seasonal variations of temperature, with daily average maximum temperature 24.6°C and minimum −17.8°C. Atmospheric relative humidity also has clear seasonal changes, but because it is sensitive to rainfall, variations of daily rainfall cause it to fluctuate dramatically. The vapor pressure deficit is large during the growing season (March 16 through October 15), with maximum 2.10 kPa and average 0.85 kPa. These values are smaller in the non- growing season (January 1 through March 14, October 16 through December 31), with maximum 1.05 kPa and average 0.29 kPa. Variations of soil moisture are controlled mainly by rainfall. The greatest rainfall during the 2008 growing season was concentrated from early August through mid-October, when daily average soil volumetric water content was greater than 0.13 m^3 m^{-3} at depth 5 cm, on average 0.19 m^3 m^{-3}. From mid-June through early August 2008, soil volumetric water content was less than 0.12 m^3 m^{-3}, on average 0.10 m^3 m^{-3}. The difference in daily average soil volumetric water content is nearly doubled between the two periods. On this basis, the period June 23 through August 6 was defined as the dry period, and August 7 through October 15 as the wet period.

1.6 Evaluation of data reliability

Determining surface energy closure based on observation data from the eddy covariance system is one of the principal ways to test the data quality (Oncley et al., 2007; Wilson et al., 2002). In theory, the surface energy budget remains balanced. However, a large number of observations shows that the measured turbulent flux (*H*+*LE*) of the eddy covariance system is less than the surface effective energy (*Rn*−*G*); i.e., lack of closure of surface energy is widespread. Therefore, a series of international observational studies on surface energy balance have been done (Oncley et al., 2007; Wilson et al., 2002) to classify and address effects on surface energy closure (Mauder and Foken, 2006). In the present study, through comparative analysis of the surface energy

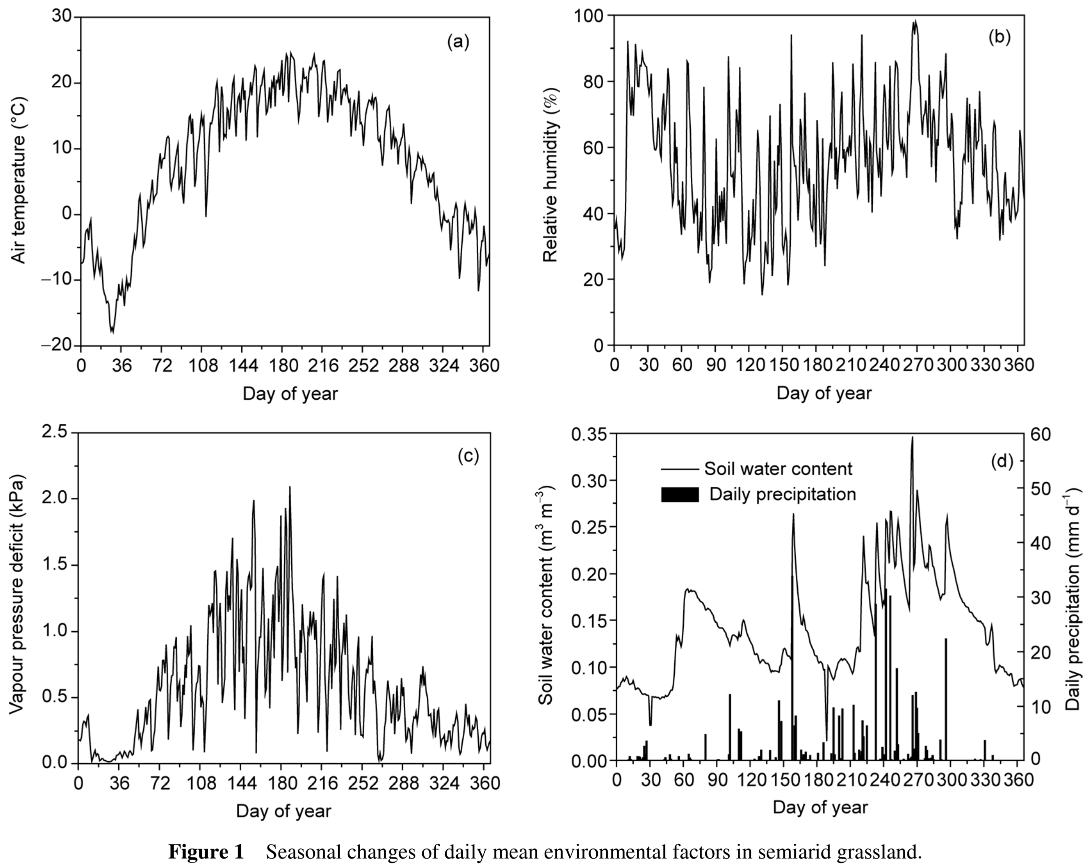

Figure 1 Seasonal changes of daily mean environmental factors in semiarid grassland.

closure condition in the semiarid grassland of the Loess Plateau during the dry and wet periods, we objectively evaluated observation data quality. This validated later analysis of land-surface water and heat exchange in semiarid regions and enhanced understanding of the influences of semiarid land-surface dry and wet changes of surface energy closure.

Figure 2 shows scatter correlation of near-surface (*H*+*LE*) and (*Rn*−*G*) of SACOL station during the dry and wet periods of the 2008 grassland growing season. Under confidence level 0.1‰, slope of the fit line was 0.824 during the dry period (R^2=0.949, where *R* is the correlation coefficient), i.e., surface energy closure was 82.4%. During the wet period, the slope was 0.801 (R^2=0.887), i.e., surface energy closure was 80.1%. Regarding the influence of moisture on surface energy closure, that closure of the semiarid grassland on the Loess Plateau during the dry period was significantly greater than during the wet period. The main reasons are: (1) Solar radiation is intense during the dry period, when surface warming enhances heating of the near-surface atmosphere, increasing turbulence exchange. The wet period is influenced by precipitation, reducing surface shortwave radiation and radioactive heating. The near-surface layer is dominated by stable or weakly unstable stratification with weak turbulent exchange, which is one of the key causes of the reduction of surface energy closure during the wet period (Yue et al., 2013b). (2) During the wet period, surface vegetation is vigorous and relative humidity is higher. Contributions of shrub vegetation and the near-surface water vapor heat storage term to surface energy balance is ignored in the energy balance equation, which is an important reason of reduced energy closure during the wet period (Li et al., 2012). (3) There are differences in the times of surface energy conversion and transmission. Especially during the wet period, changes in soil moisture content can alter soil thermal properties, thereby affecting the transfer of soil heat flux from the surface to the heat flow plate. This significantly increases the phase difference between soil heat flux and net radiation, which is an important cause of reduced energy closure during the wet period (Yue et al., 2011; Heusinkveld et al., 2004; Gao et al., 2003). (4) The wet period is influenced by rainfall, which disturbs the accuracy of flux observation equipment and is an objective cause of reduced energy closure (Mauder and Foken, 2006).

Compared with energy closure of other ecosystems in home and abroad 60% to 90% (Wang et al., 2010; Yang and Wang, 2008; Oncley et al., 2007; Wilson et al., 2002; Guo et al., 2006), surface energy closure of the Yuzhong semiarid grassland is still above average, even if the influences of advection losses, local circulation, nocturnal discharge from inhomogeneous terrain, energy storage of shrub vegetation, near-surface water vapor heat storage and other factors are not considered. Therefore, observation data of the eddy covariance system at SACOL station were used to study land- surface water and heat exchange processes of Loess Plateau semiarid grassland. The accuracy of these data can fully meet the requirements of our study (Yue et al., 2011; Wang et al., 2010; Huang et al., 2008).

2 Average daily variation and vertical distribution of soil temperature and humidity

Soil temperature and humidity variation are basic characteristics of the land surface and are important effects on land-surface water and heat exchange (Zhang Q et al., 2012a). Analysis of soil temperature and humidity differences during dry and wet periods is important for comprehensive knowledge and understanding of land-surface characteristics. Change of soil temperature is affected by the season and by cloud and rainfall (Yue et al., 2013b). Figure 3 shows the vertical distribution of normalized daily average temperature in the semiarid grassland in Yuzhong during dry and wet periods. This normalized temperature is the sum of soil temperature of each layer divided by soil temperature of the entire layer, and its vertical profile reflects the proportion of each layer temperature of the entire layer's accumulated temperature. It has been found that the "active layer" of soil temperature in the growing season of Loess

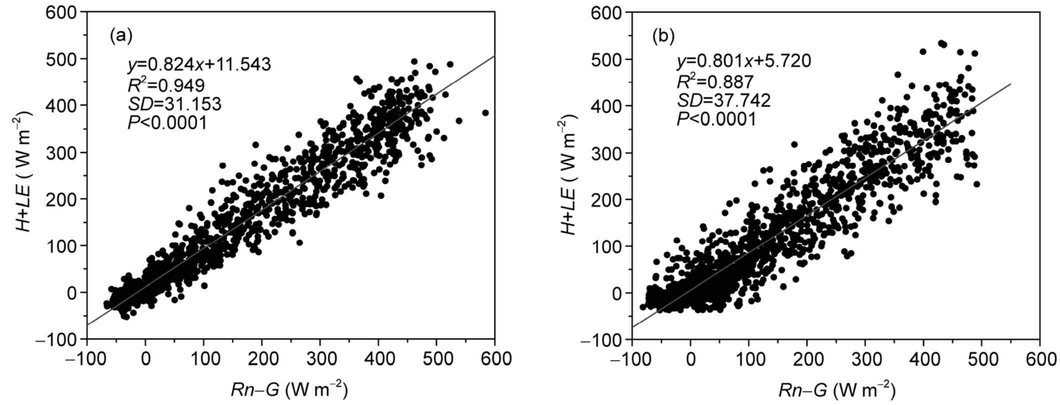

Figure 2 Energy balance closure of semiarid grassland in dry period (a) and wet period (b).

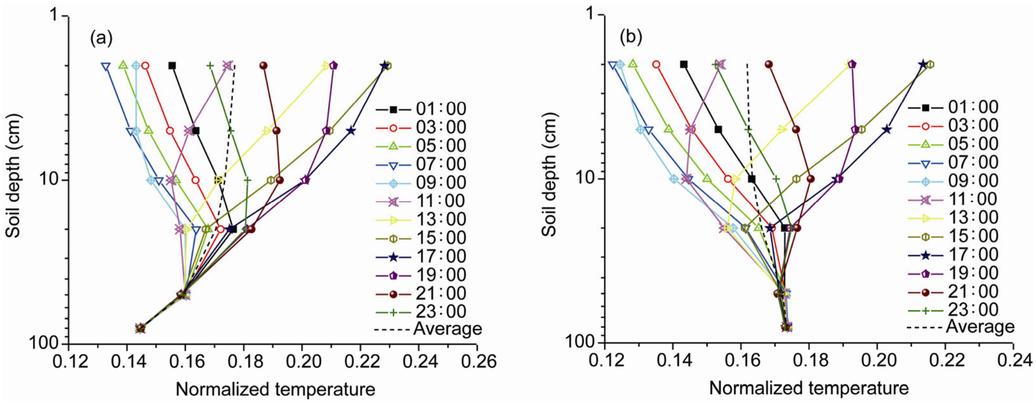

Figure 3 Vertical distribution of normalized daily mean temperature in semiarid grassland during dry period (a) and wet period (b).

Plateau semiarid grassland is mainly shallow soil above 20-cm depth, where there are obvious daily cycles. The inactive layer refers to soil beneath depth 50 cm, where soil temperature has no daily cycle characteristics.

The vertical profile of normalized soil temperature for each layer during different periods shows obvious differences in heat transfer time of the soil. During the dry period, the proportion of soil temperature at depths 2 and 5 cm to the temperature cumulant of the entire layer significantly increased at 09∶00, indicating that solar radiation energy has heavily influenced soil at those depths. At 11∶00, heat transfer reached the soil layer at 5–10 cm depths and, at 13∶00, the layer at 10–20 cm. During the wet period, 09∶00 normalized soil temperature at 2-cm depth slightly increased over that at 07∶00, suggesting that solar radiation has an insignificant influence on soil temperature at this depth. At 11∶00, heat transfer influenced the soil at 5-cm depth; at 13∶00, it affected soil temperature near 10-cm depth. Between the dry and wet periods, there were temporal differences in the heat transfer. This reflects that clouds and precipitation have different damping effects on solar radiation, and soil water content influences soil heat capacity and thermal conductivity. During the dry period, clouds and precipitation had weaker damping effects on solar shortwave radiation. That radiation has strong heating effects on the surface and soil heat capacity is small, such that the energy transfer rate is greater in the soil. By contrast, clouds and precipitation have strong damping effects on solar radiation during the wet period, weakening the heating effect of the surface. Coupled with wet soil with larger heat capacity, the heat transfer rate is smaller in the soil.

During the dry period, the vertical distribution of daily average normalized temperature had an overall "forward tilting" shape, indicating that overall heat transfer characteristics in the soil result from transfer from shallow to deep soil. During the wet period, the vertical distribution of daily average normalized temperature had a slightly "backward tilting" shape, indicating that overall heat transfer characteristics in the soil result from transfer from deep to shallow soil. The above characteristics have not been revealed in previous land-surface process research. Heat stored in deep soil during the dry period is gradually transferred to shallow soil during the wet period, which can make up for a lack of heat caused by wet weather and furnish the necessary heat for vegetation growth. Understanding heat transfer in the soil of semiarid areas on the Loess Plateau during dry and wet periods is important in the adjustment of farming time and planting regionalization, for reasonable use of heat and water resources to effectively cope with the adverse impacts of climate change on agricultural production.

In general, cloud and precipitation during the wet season can change soil water content. This affects thermal conductivity, such that the heat transfer rate in the soil significantly changes, thereby causing differences in the time of soil temperature peak. Figure 4 shows the daily mean variation of soil temperature during dry and wet periods. It is seen that the daily peak of shallow soil temperature is delayed about 30 min longer during the wet period than during the dry period. There is also less cloud cover during the dry period, so heating from solar radiation at the surface is strong in the daytime, and the soil maximum temperature is correspondingly higher. The night atmosphere has a weak heat preservation effect in the land-atmosphere system and the surface radiation cooling rate is substantial, leading to a larger land-atmosphere temperature daily range. During the dry period, average daily ranges of soil temperature at depths 2, 5, and 10 cm are 12.7, 10.4, and 7.4°C, respectively. The wet period is affected by clouds and precipitation so the daily average temperature is relatively low, and the daily range of soil temperature is smaller. During the wet period, average daily ranges of shallow soil temperature at depths 2, 5 and 10 cm are 9.4, 7.1, and 4.8°C, respectively.

Figure 5 shows the vertical distribution of normalized daily average humidity in semiarid grassland of Yuzhong during the dry and wet periods. This normalized humidity equals the soil water content of each layer divided by total water content of the 80-cm soil column, and its vertical profile reflects the proportion of soil volumetric water content in each layer to the cumulative volumetric water content of

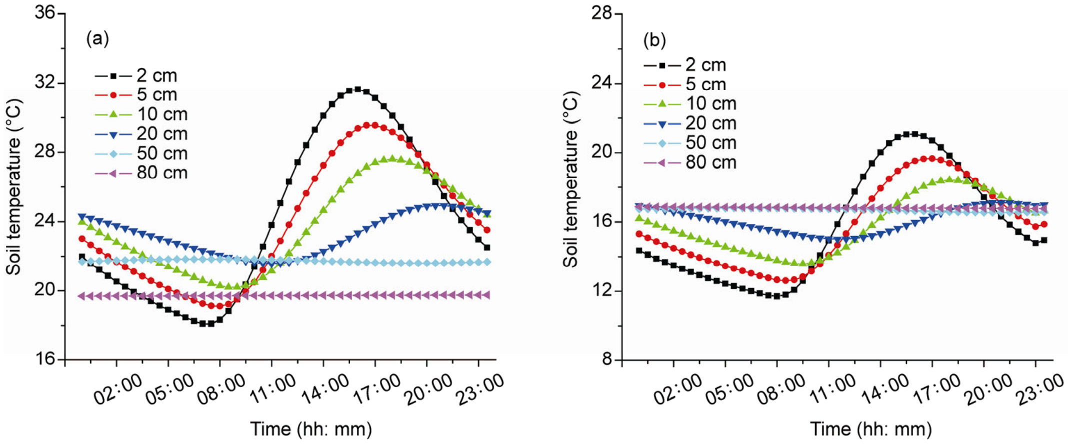

Figure 4 Daily mean variation of soil temperature in semiarid grassland during dry period (a) and wet period (b).

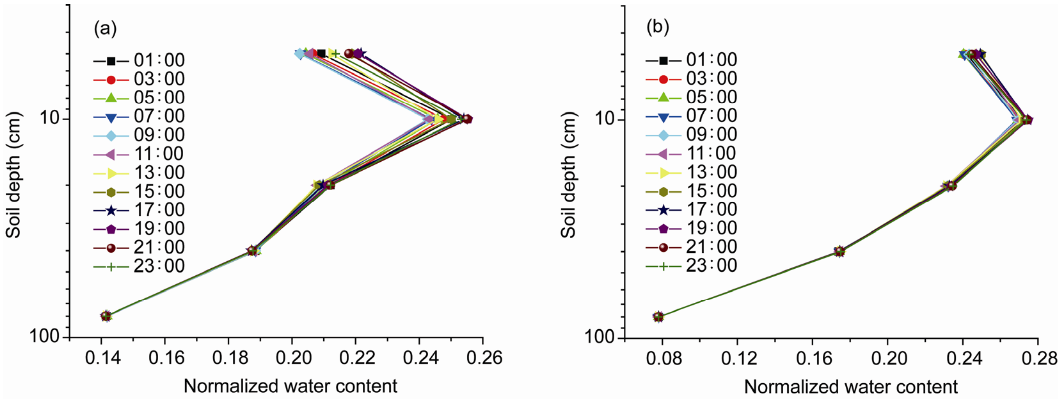

Figure 5 Vertical distribution of normalized daily average humidity in semiarid grassland during dry period (a) and wet period (b).

the entire layer. It is seen that there was a maximum moisture layer in the soil at depth 10 cm during the dry and wet periods of the semiarid grassland growing season, significantly different from the maximum moisture layer in the soil at depth 20 cm in the northwest arid region and farming area of the Loess Plateau in central Gansu Province (Zhang Q et al., 2011, 2012a). Because there is very little rainfall in the former region with strong surface evaporation, that evaporation can affect the dry and wet structure of deeper soil. In the farming area of the Loess Plateau in central Gansu Province, there is little rainfall difference from that of Yuzhong semiarid grassland. Surface evaporation potential is similar between the two types, but soil is relatively loose in the Gansu farming area, which is advantageous for rainfall moisture transfer to deep soil. Moreover, the active layer of the vegetation root system in the farming area is deeper than that of the semiarid grassland, leading to very prominent differences in the vertical structure of soil moisture. By comparing normalized humidity during dry and wet periods, it was seen that during the dry period, soil water content was less in the entire soil layer, and the water content of deep soil accounted for a higher proportion of the total column. During the wet period, which is affected by clouds and precipitation, the proportion of shallow soil water content to the total was greater.

Figure 6 shows the daily average distribution of soil volumetric water content in the semiarid grassland on the Loess Plateau. During the dry period, average contents at depths 5, 10, 20, 40, and 80 cm in the Yuzhong grassland were 0.099, 0.117, 0.099, 0.089, and 0.066 $m^3 m^{-3}$, respectively, and the content of the entire layer was 0.472 $m^3 m^{-3}$. During the wet period, average soil volumetric water contents at depths 5, 10, 20, 40, and 80 cm were 0.203, 0.225, 0.193, 0.145, and 0.065 $m^3 m^{-3}$ respectively, and the content of the entire layer was 0.830 $m^3 m^{-3}$. It is seen that there was almost no difference in 80-cm soil moisture between the dry and wet periods, and the major active layers of soil water on the plateau were distributed mainly above depth 40 cm. During the dry and wet periods, shallow soil water contents above 20-cm depth (including 20 cm) accounted for 67% and 75% of the entire layer water content, respectively. In addition, from 23:00 to the following 11:00 during the dry period, 20-cm soil moisture was greater than that at 5 cm, indicating that deep soil makes certain adjustments complementary to shallow soil water.

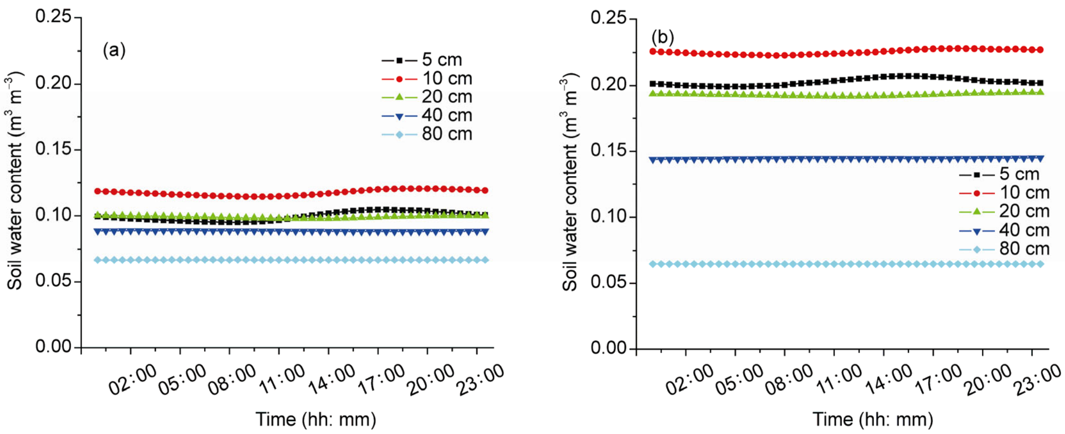

Figure 6 Daily mean variation of soil moisture in semiarid grassland during dry period (a) and wet period (b).

3 Influences of soil dry and wet conditions on surface albedo and net radiation conversion rate

Surface albedo is a key parameter of the land surface, which can comprehensively reflect the forcing of solar radiation on land-surface processes. Surface albedo varies strongly with soil humidity, color, and clearance degree, along with vegetation growth state and coverage (Liu et al., 2008). The main impacts on surface albedo include soil humidity and surface vegetation. Figure 7(a) shows daily average variations of surface albedo in the plateau semiarid grassland during the dry and wet periods. During the dry period, soil water content was low, water stress significant, the growth condition of vegetation poor, vegetation coverage reduced, and surface albedo higher with daily average 0.19. This is consistent with observations in the northwest arid region (Zhang et al., 2002). During the wet period, daily average albedo was 0.17, similar to observations in semi-humid regions on the Loess Plateau (Wei et al., 2005). Such differences in surface albedo significantly affect the conversion efficiency of shortwave radiation to net radiation (Zhang Q et al., 2012a).

Surface net radiation is a comprehensive characteristic of land-surface radiation balance. Its variations are impacted not only by solar radiation but also by land-surface water and heat properties and reflection characteristics. In addition, differences in the longwave radiation budget in the ground-air system caused by cloud and precipitation are also very important (Yue et al., 2013b). To eliminate seasonal differences in solar radiation during the dry and wet periods and highlight the influence of land-surface dry and wet conditions caused by cloud precipitation on surface net radiation conversion efficiency, Figure 7(b) shows the ratio of surface net radiation to total solar radiation during the dry and wet periods (i.e., the conversion efficiency of shortwave radiation to net radiation). During the wet period, because of high soil water content, extensive vegetation coverage and small surface albedo, the ratio of surface net radiation to total radiation is large. The situation during the dry period is the opposite. During the wet period, the maximum conversion efficiency of total radiation to net radiation is 0.64, with a mean of 0.60. During the dry period, the maximum efficiency was 0.58 with a mean of 0.55. Such a difference reflects the effect of land-surface water and heat properties and vegetation status on net radiation, as well as the influence of clouds and precipitation on surface radiation in semi-

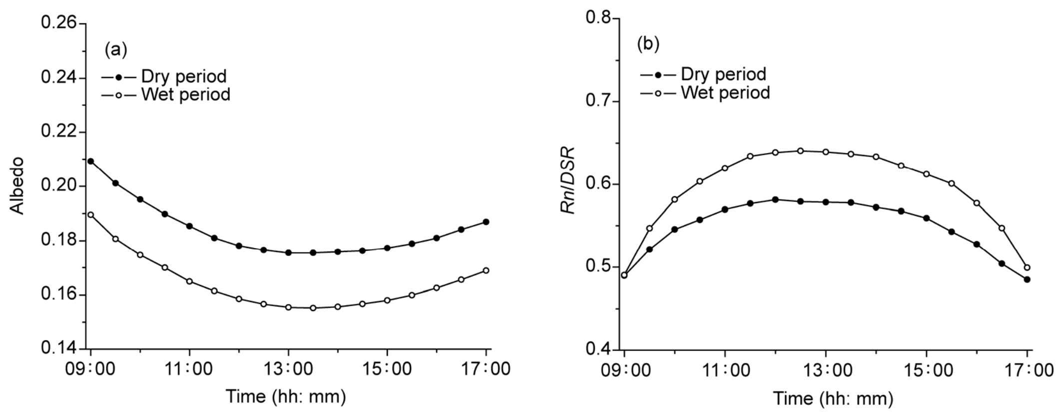

Figure 7 Daily variations of surface albedo and net radiation conversion efficiency. (a) Albedo; (b) net radiation conversion rate.

arid areas of the Loess Plateau.

4 Land-surface water-heat exchange characteristics and conversion efficiency during dry and wet periods

Through conversion to sensible, latent and soil heat fluxes, net radiation provides heat to the atmosphere and soil. To understand differences in surface heat distribution between the dry and wet periods, Figure 8 shows daily changes in the proportions of sensible heat and latent heat fluxes in net radiation. It is seen that the ratio between sensible heat flux and net radiation on the Loess Plateau was significantly larger during the dry period than during the wet period. The average is 0.45 and 0.32 during the dry and wet periods, respectively. During the dry period, the ratio largely remained above 0.40, with maximum 0.51. During the wet period, the ratio was between 0.25 and 0.35. In contrast, the ratio between latent heat flux and net radiation during the wet period was significantly greater than that during the dry period. During the wet period, that ratio was between 0.27 and 0.57, whereas during the dry period it was 0.19–0.27. This suggests that land-surface dry and wet conditions on the plateau significantly control surface heat conversion. During the dry period, the sensible heat conversion rate was high, and water-heat exchange intensity of semiarid grassland on the plateau and overall characteristics approximate those of the northwest arid region. During the wet period, the latent heat conversion rate was higher, and the water-heat exchange intensity and overall characteristics approximate humid and semi-humid climate regions. Compared with the northwest arid region and northeast humid and semi-humid regions of China, the ratio between sensible heat flux and net radiation in semiarid areas on the Loess Plateau was generally smaller than that in the northwest arid region of China, but greater than that in the northeast humid and semi-humid regions of China. The ratio between latent heat flux and net radiation in the latter regions is greater than that in semi-arid areas on the Loess Plateau, and the minimum was in northwest arid region of China (Zhang Q et al., 2012a). This suggests that the surface latent heat conversion rate is high in the northeast humid and semi-humid regions that are significantly affected by the monsoon, and the surface sensible heat conversion rate is high in the northwest arid region that is hardly influenced by the monsoon. Conversion rates of surface sensible heat and latent heat in semiarid areas on the Loess Plateau in the monsoon marginal belt are between those of the northwest arid region and northeast humid and semi-humid regions.

Figure 8 shows proportions of sensible, latent, and surface soil heat fluxes. It is seen that during the dry period, the

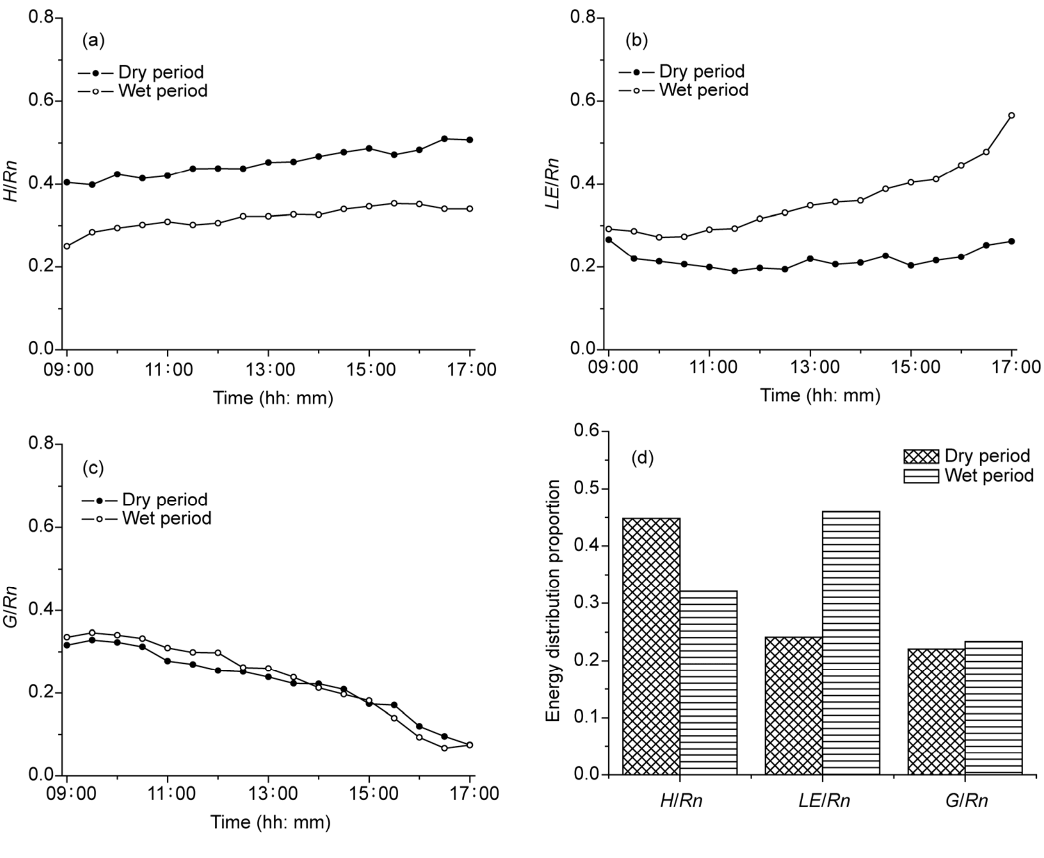

Figure 8 Daily variations and distributions of energy flux in semiarid grassland.

sensible and latent heat fluxes accounted for about 45% and 32% of net radiation, respectively. During the wet period, corresponding proportions were 46% and 24%. The proportions of soil heat flux ratio to net radiation were very similar during the dry and wet periods, at 22% and 23%, respectively. These are greater than proportions from other research, i.e., 10%–15% (Oncley et al., 2007; Yang and Wang, 2008; Claudia et al., 2005; Liebetha et al., 2005). Soil water holding capacity is less on the Loess Plateau, because of its loose soil. Even during the rainy period, average capacity at depth 5 cm was only about 20%. The relatively loose and dry yellow soil leads to stronger heating from solar radiation at the surface, and soil heat exchange is more efficient. In addition, as seen in Figure 8(c), during either the wet or dry period, the change in proportion of soil heat flux to net radiation was less before 10∶30, after which the proportion decreased with time. Such change is attributable mainly to the phase difference between surface soil heat flux and net radiation, as supported by the observations of Horton and Wierenga (1983) and the theoretical derivation of Gao et al. (2003). Recent research by Yue et al. (2011) has also shown that surface soil heat flux often maximizes prior to net radiation by 0–3 h, whereas the net radiation peak is reached around noon. The phase differences between the soil heat flux and net radiation lead to unique distributions of energy distribution proportion.

5 Influences of environmental factors on land-surface water and heat processes

Land-surface water-heat exchange processes and conversion efficiencies are restricted by environmental factors, particularly land-surface temperature and humidity. To analyze the overall trend of the influences of soil temperature on land-surface water and heat conversion efficiency, soil temperature at 5-cm depth was stratified into groups at a 1°C interval for average processing of *LE*/*Rn* and *H*/*Rn* on the Loess Plateau during the wet and dry periods. Figure 9 shows distribution relationships between *LE*/*Rn*, *H*/*Rn* and soil temperature at 5 cm during the dry and wet periods. During the dry period, *H*/*Rn* increased with soil temperature, whereas *LE*/*Rn* declined with rising soil temperature. Rising soil temperature led to a greater ground-air temperature difference, enhanced sensible heat transfer, and increased *H*/*Rn*. *LE*/*Rn* decreased owing to the reduction of soil water content and latent heat flux.

During the wet period, *LE*/*Rn* and *H*/*Rn* met the quadratic curve change law with respect to soil temperature. Interestingly, when soil temperature at depth 5 cm was not warmer than 16°C, *H*/*Rn* tended to decrease with rising temperature. Because soil water content was high at this time, soil heat capacity was large, the near-surface atmosphere had high humidity, and heating from net radiation converted to sensible heat energy in the atmosphere was restricted. In addition, when soil temperature was lower, net radiation conversion to latent heat flux was enhanced with increasing temperature, suggesting that a rise of temperature under high humidity aids conversion of net radiation to latent heat energy. Therefore, *LE*/*Rn* increased with temperature. When soil temperature at depth 5 cm was not less than 16°C, *H*/*Rn* increased with temperature, while *LE*/*Rn* decreased with it. Compared with the low-temperature conditions, when the temperature rose, land-surface and near-surface water volume decreased, and water conditions inhibited conversion of net radiation to latent heat.

To analyze the influence of soil volumetric water content on land-surface water and heat transfer characteristics of semiarid grassland on the Loess Plateau, average processing was done for *LE*/*Rn* and *H*/*Rn* during the dry and wet periods, according to the intervals 0.05 and 0.1 $m^3\ m^{-3}$, respectively. Because soil volumetric water content was low and the humidity range small during the dry period, the classification was based on the interval of 0.05 $m^3\ m^{-3}$. Figure 10 shows relationships of *LE*/*Rn* and *H*/*Rn* with soil volumetric water content during the dry and wet periods.

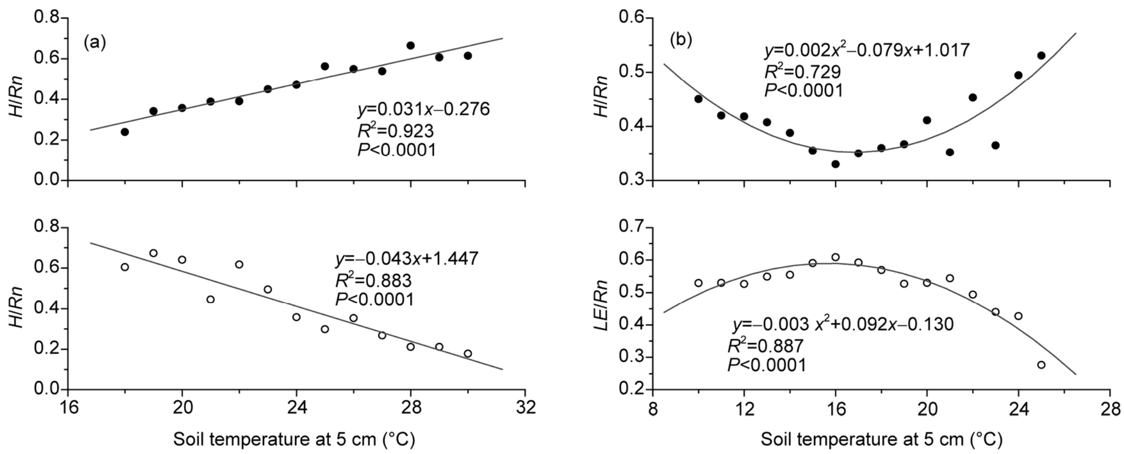

Figure 9 Variations of *LE*/*Rn* and *H*/*Rn* with 5-cm soil temperature in dry period (a) and wet period (b).

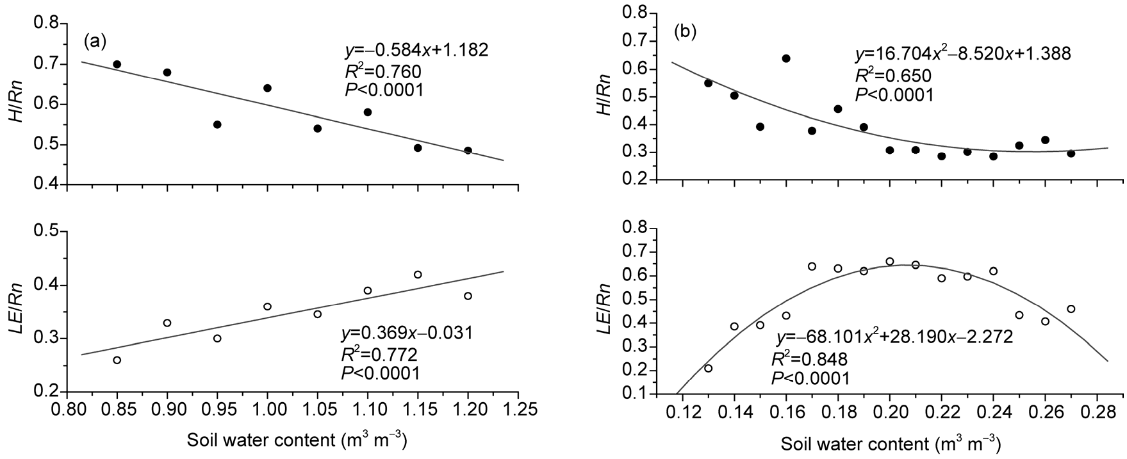

Figure 10 Changes of *LE*/*Rn* and *H*/*Rn* with 5-cm soil volumetric water content in dry period (a) and wet period (b).

During the dry period, *H*/*Rn* decreased with increased soil water content, whereas *LE*/*Rn* increased. During the wet period, *LE*/*Rn* and H/Rn met the quadratic curve change law with respect to soil water content. When the soil volumetric water content at depth 5 cm was less than 0.21 m^3 m^{-3}, *H*/*Rn* had a decreasing trend with increasing water content. The higher that content, the larger the soil heat capacity; the conversion efficiency of net radiation to sensible heat decreases. When water content was greater than 0.21 m^3 m^{-3} with increasing soil water content, *H*/*Rn* approximated 0.3, revealing a minimum threshold in conversion efficiency of net radiation to sensible heat flux during the wet period. In addition, when soil volumetric water content at depth 5 cm was less than 0.21 m^3 m^{-3}, *LE*/*Rn* increased with water content, and the conversion efficiency of net radiation to latent heat flux was about 65%. When the water content exceeded 0.21 m^3 m^{-3}, with further increase of soil water content, *LE*/*Rn* had a decreasing trend instead. A maximum threshold is evident in the conversion efficiency of net radiation to latent heat flux at daily scale in the semiarid grassland on the Loess Plateau.

Land-surface water and heat exchange is closely related not only to near-surface temperature but also to land-surface evapotranspiration. The vapor pressure deficit can comprehensively reflect temperature and humidity conditions of the near-surface atmosphere. Thus, establishing a relationship between vapor pressure deficit and land-surface water-heat conversion efficiency can effectively reflect differences in land-surface water and heat characteristics between the dry and wet periods. To reduce the influence of daily fluctuations in observation data on the overall trend of water and heat exchange, the vapor pressure deficit was separated into groups with interval 0.1 kPa for average processing of *LE*/*Rn* and *H*/*Rn* during the dry and wet periods. Figure 11 shows the quantitative relationship of *LE*/*Rn* and *H*/*Rn* with vapor pressure deficit during those periods.

During the dry period, when the vapor pressure deficit range was 0–0.7 kPa, *LE*/*Rn* decreased with increasing vapor pressure deficit, whereas *H*/*Rn* increased. In Figure 11, differences in the linear trend coefficient show that net radiation conversion to sensible heat was stronger than that to latent heat at the time. With further increase in vapor pressure

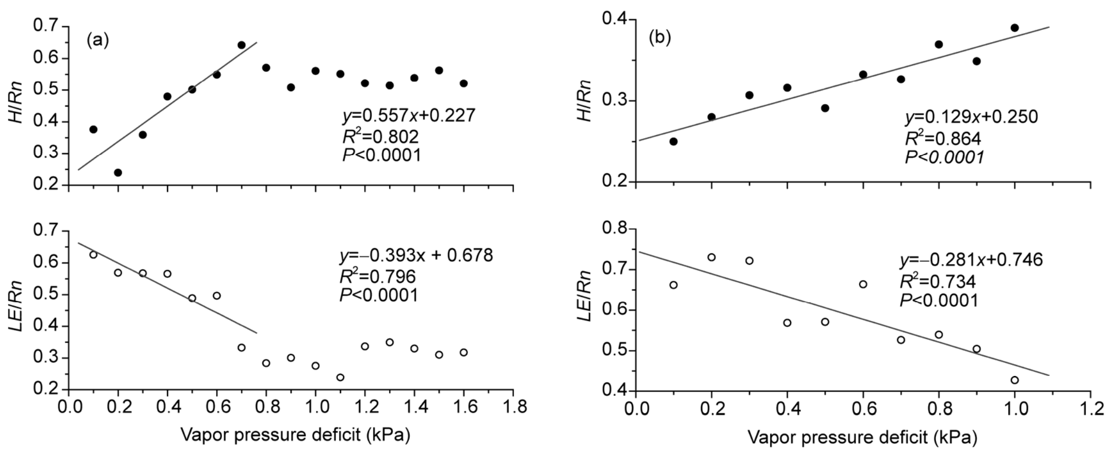

Figure 11 Distribution of *LE*/*Rn* and *H*/*Rn* with vapor pressure deficit in dry period (a) and wet period (b).

deficit, *LE*/*Rn* and *H*/*Rn* tended to be nearly constant. The smaller vapor pressure deficit indicates that the stress effect of soil water on vegetation was not obvious. With increased vapor pressure deficit, however, land-surface evapotranspiration decreases, the atmosphere tends toward a warm and dry state, net radiation conversion to latent heat is reduced, and conversion to sensible heat increases. However, together with further land-surface drying, the vapor pressure deficit of the near-surface atmosphere is further increased, and the stress effect of soil water is pronounced. Meanwhile, water release into the atmosphere through land-surface evapotranspiration is very limited, near-surface water vapor content tends to be stable, and the proportion of latent heat flux to net radiation tends to be constant. Although *LE*/*Rn* was generally constant, daily fluctuation remained substantial, which may be caused by differences in water vapor advection transport.

After the vapor pressure deficit increased during the dry period, net radiation conversion to sensible heat flux also tended to be constant. Because of long periods of drought, the weather was clear with fewer clouds. Thus, surface heating from solar shortwave radiation was strong and stable, surface temperature was persistently high, and the ground-air temperature difference was large with smaller average daily variation, so *H*/*Rn* variation was relatively stable. However, in the semiarid grassland of Yuzhong County, when the typical sunny near-surface atmospheric stratification is unstable, differences in vertical advection throughput of sensible heat flux form, owing to terrain variation. Local circulation effects can also generate strong fluctuations in daily *H*/*Rn* (Zhang Q et al., 2012 b).

The linear trend coefficient differences in Figure 11(b) show that during the wet period, net radiation conversion to latent heat is stronger than that to sensible heat. Comparing Figure 11(a) and (b), it is seen that when the vapor pressure deficit was small, *H*/*Rn* during the dry period was significantly larger than that during the wet period. This indicates that net radiation conversion to sensible heat flux is strong in cases of a dry near-surface; when the near-surface is wet, the conversion of net radiation to latent heat flux is strong.

6 Discussion and conclusions

Under the background of global warming, precipitation differences will increase between dry and wet areas as well as dry and wet seasons. China's semiarid areas on the Loess Plateau belong to a transition zone from inland arid to southeast humid climates. There, the seasonal precipitation difference is especially evident, leading to greater differences in land-surface temperature and humidity between dry and wet periods. From the standpoint of vertical structure of soil temperature at SACOL station during the dry and wet periods, heat transfer is rapid during the dry period but slow during the wet period, reflecting the influence of soil moisture on soil heat capacity and thermal conductivity. During the dry period, the overall heat transfer direction in the soil is from shallow to deep, whereas heat stored in deep soil is transferred to shallow soil during the wet period. This phenomenon can make up for a lack of heat in wet weather and provide heat for growth of autumn vegetation.

In semiarid grassland on the Loess Plateau during the dry and wet periods, changes in soil water content, surface vegetation growth, and vegetation coverage are indicated by surface albedo. During the dry and wet periods, the daily average difference in surface albedo can reach 0.2, and such a difference can significantly affect the conversion efficiency of solar shortwave radiation to net radiation. During the wet period, soil water content and vegetation coverage are high, surface albedo is small, the ratio between surface net radiation and total radiation is large, and the conversion efficiency of shortwave radiation flux to net radiation is high. In contrast, during the dry period, this conversion efficiency is low. Differences in conversion efficiency of net radiation during the dry and wet periods directly reflect the effects of land-surface water and heat characteristics as well as vegetation conditions.

Changes between drought and wet conditions in the semiarid grassland on the Loess Plateau strongly control surface heat conversion. During the dry period, the average conversion rate of sensible heat and latent heat was 0.45 and 0.32, respectively; during the wet period, these values were 0.45 and 0.24. During the dry period, land-surface water and heat exchange characteristics in the grassland are similar to those of the northwest arid region of China. During the wet period, water and heat exchange are similar to those in humid and semi-humid regions of China. During both periods, the proportions of soil heat flux to net radiation are very similar. Owing to the nature of the relatively loose and dry yellow soil in semiarid areas on the Loess Plateau, surface heating from solar radiation is stronger and the soil heat exchange more efficient, leading to a proportion of soil heat flux to net radiation in excess of 20%.

Environmental factors in semiarid grassland on the Loess Plateau very significantly restrict land-surface water and heat exchange. During the wet period at daily scale, *H*/*Rn* and *LE*/*Rn* met the quadratic curve change law with respect to soil temperature at depth 5 cm, and a soil temperature of 16°C was critical for land-surface water and heat transfer trends. *H*/*Rn* and *LE*/*Rn* had nonlinear changes with soil water content at 5-cm depth, and a volumetric water content of 0.21 m^3 m^{-3} was critical for a change in water and heat exchange trends. During the dry period, when the vapor pressure deficit was less than 0.7 kPa, *H*/*Rn* increased with that deficit, whereas *LE*/*Rn* decreased. But when the deficit was greater than 0.7 kPa, both *LE*/*Rn* and *H*/*Rn* tended to be constant. There were critical values of environmental factors affecting land-surface water and heat conversion efficiency in semiarid areas. Such a phenomenon has not been reported in previous research. Verifying whether similar laws exist in humid and semi-humid regions requires additional observation data.

This study was supported by the National Basic Research Program of China (Grant No. 2013CB430206, 2012CB955304), National Natural Science Foundation of China (Grant Nos. 41075008, 40830957, 41275118), China Postdoctoral Science Special Foundation (Grant No. 2013T60901), China Postdoctoral Science Foundation (Grant No. 20110490854), and the Ten Talents Program of Gansu Meteorology Bureau. The authors would like to thank SACOL for providing the data, and the anonymous reviewers for their critical review and comments on this manuscript.

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