J Arid Land (2015) 7(5): 579–589
doi: 10.1007/s40333-015-0129-6
jal.xjegi.com; www.springer.com/40333

Surface energy and water vapor fluxes observed on a megadune in the Badain Jaran Desert, China

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Abstract: The Badain Jaran Desert is the second-largest area of shifting sands in China. Our first measurements of the energy components and water vapor fluxes on a megadune using eddy covariance technology were taken from April 2012 to April 2013. The results indicate that the longwave and shortwave radiative fluxes exhibited large fluctuations and seasonal dynamics. The total radiative energy loss by longwave and shortwave radiation was greater on the megadune than from other underlying surfaces. The radiation partitioning was different in different seasons. The land-atmosphere interaction was primarily represented by the sensible heat flux. The average sensible heat flux (40.1 W/m^2) was much larger than the average latent heat flux (14.5 W/m^2). Soil heat flux played an important role in the energy balance. The mean actual evaporation was 0.41 mm/d, and the cumulative actual evaporation was approximately 150 mm/a. The water vapor would transport downwardly and appear as dew condensation water. The amount of precipitation determined the actual evaporation. The actual evaporation was supposed to be equal to the precipitation on the megadune and the precipitation was difficult to recharge the groundwater. Our study can provide a foundation for further research on land-atmosphere interactions in this area.

Keywords: eddy covariance technology; energy and water vapor fluxes; precipitation; evaporation

Citation: HU Wenfeng, WANG Nai'ang, ZHAO Liqiang, NING Kai, ZHANG Xunhe, SUN Jie. 2015. Surface energy and water vapor fluxes observed on a megadune in the Badain Jaran Desert, China. Journal of Arid Land, 7(5): 579–589. doi: 10.1007/s40333-015-0129-6

Understanding desert ecosystems, such as exchanges of radiation, heat and water between the ground surface and atmosphere, is critical for the performance of forecasting models for improved climate and weather predictions as well as for the parameterization of surface schemes in global climate models. Furthermore, IPCC (2007) reported that subtropical and tropical desert regions are predicted to experience more intense aridity due to reduced precipitation, higher evaporation rates and higher temperatures as a result of anthropogenic climate change. Even so, arid environments, especially deserts, have received relatively little attention to underpin parameterizations of surface schemes. Previous studies have focused on the interaction of a variety of underlying surfaces with the atmosphere (Alongi et al., 2004; Gu et al., 2005; Bittelli et al., 2008; Schwärzel et al., 2009; Oliphant et al., 2011; Mohr et al., 2013). To date, most land- atmosphere interface observations in arid regions have been taken in North America (Kustas et al., 2000; Prater and DeLucia, 2006), South America (Kampf et al., 2005; Kalthoff et al., 2006) and Australia (Beringer and Tapper, 2000; Sturman and McGowan, 2009). These observations have achieved great progress in understanding the energy exchange and energy balance. However, there is a lack of detailed information characterizing land-atmosphere interaction in China, particularly in the Badain Jaran Desert.

The Badain Jaran Desert is the second-largest area of shifting sands in China. It has a unique landscape that contains the world's highest shifting sand dunes. There are also a large number of permanent lakes in

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Received 2014-11-24; revised 2015-02-15; accepted 2015-03-16

the inter-dune depressions (Yang and Williams, 2003). This unique desert environment has attracted researchers who have focused on the formation and evolution of the expanses of sand and their relation to the environment, and the formation of the megadunes and lakes (Dong et al., 2009; Yang et al., 2011). Previous studies about the formation processes of the megadunes had three hypotheses (Yang and Williams, 2003; Chen et al., 2004; Dong et al., 2004; Chen et al., 2006; Dong et al., 2009; Yang et al., 2011). Unfortunately, our knowledge of the land-atmosphere exchange in the desert is limited. Therefore, information on the surface energy partitioning and evaporation conditions, which are crucial factors involved in the formation and evolution of the megadunes and lakes, is important.

The objectives of this study were (1) to provide detailed information on the component radiative fluxes on a megadune, (2) to understand variations in turbulent heat flux and heat storage changes on its surface, and (3) to calculate water vapor fluxes from the megadune.

1 Study area

The Badain Jaran Desert is located in western Inner Mongolia, China. It is the second-largest desert of the country (Zhu, 2010). The mean winter and summer temperatures in this area are –9.1°C and 25.3°C, respectively. The annual mean diurnal temperature range is 34.4°C (Ma et al., 2014), which categorizes this region as a "cold desert" (Warner, 2004). The desert is characterized by a strongly continental climate with a mean annual precipitation of 35.2–42.9 mm at its northern margin and 90.1–115.4 mm at its southern margin. The annual mean wind speed ranges from 2.8 to 4.6 m/s, increasing from south to north and with the strongest winds occurring in April and May. The area possesses a unique landscape with 119 perennial water lakes (Zhang et al., 2012), mainly in the inter-dune depressions of sandhill leeward slopes in the southeastern part of the desert. Springs and shallow groundwater exist near some of the lakes, with the total dissolved solids (TDS) content being less than 1 g/L.

The study was carried out on a megadune in the Badain Jaran Desert (39°47′35″N, 102°26′06″E; 1,257 m asl), where the ground surface was relatively flat without vegetation (Fig. 1).

2 Experimental equipment and data processing

2.1 Experimental equipment

The eddy covariance method for measuring exchanges

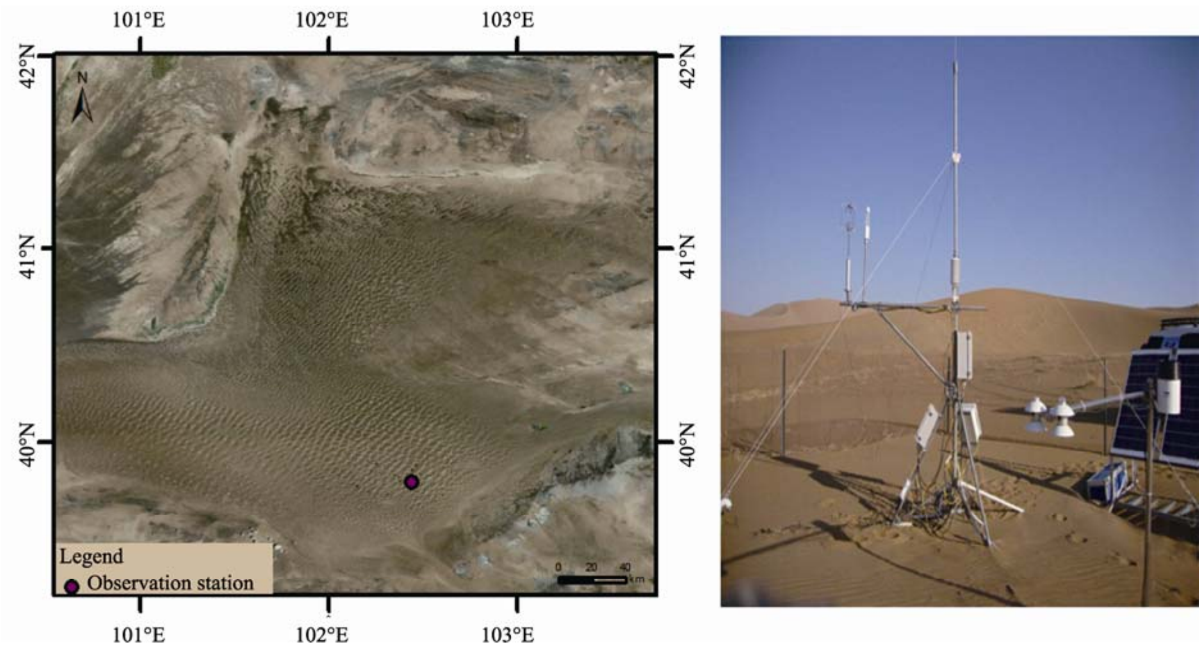

Fig. 1 Map of the study area in the Badain Jaran Desert (left) and the eddy covariance system used for monitoring (right)

of heat, mass and momentum between the ground surface and the overlying atmosphere was proposed by Montgomery (1948) and Obukhov (1951). Net transport between the ground surface and atmosphere is one-dimensional and the vertical flux density can be calculated by the covariance between turbulent fluctuations of the vertical wind and quantity of interest (Aubinet et al., 2012).

In this study, the turbulent fluxes of sensible heat (Hs), latent heat (LE) and water vapor were measured with the eddy covariance system, which consisted of a three-dimensional sonic anemometer (R3-50, GILL, UK) and an open-path carbon dioxide/water vapor (CO_2/H_2O) infrared gas analyzer (LI-7500A, LI-COR, USA). These instruments were separated by a distance of 20 cm and were placed at a height of 2.6 m. The fluctuations of virtual air temperature and the three wind velocity components were measured using the sonic anemometer. The infrared gas analyzer measured water vapor density variations. Sensor signals from the eddy covariance system were recorded by a data logger (model LI-7550, LI-COR, USA) with a frequency of 10 Hz. The net radiation was measured 1.0 m above the dune surface using a quantum sensor and a four-component net radiometer (NR01, Hukseflux, Netherlands). The relative humidity and air temperature were measured with Humicap sensors (HMP155, Vaisala, Finland) that were placed on unaspirated double steel radiation shields at a height of 2.5 m. The total precipitation was recorded at half-hour intervals using an automated tipping bucket rain gauge (HOBO RG3-M, Onset, USA). The soil surface temperature was obtained with an SI-111 sensor, and the soil temperature was also measured at six depths (10, 30, 50, 70, 90 and 110 cm) by thermistors (ST-100, Campbell, USA). Soil water content was measured at the same five depths (30, 50, 70, 90 and 110 cm) by soil moisture probes (EC-5, USA), and the soil heat flux was measured by two soil heat pates (HFP01-SC, Holland), at separate locations 10 cm below the soil surface. All instruments were powered by batteries and solar panels. Sensor signals from all slow-response sensors were recorded by the CR-3000 data logger at 30-minute mean intervals.

2.2 Data processing

The fluxes of Hs and LE were determined by the eddy covariance method as follows:

$$\mathrm{Hs} = \rho_a c_\rho \overline{w'T'}. \quad (1)$$

$$\mathrm{LE} = \rho_a L_v \overline{w'q'}. \quad (2)$$

Where ρ_a is the air density (kg/m^3), c_p=1,004 J/kg is the specific heat of air at constant pressure, and L_v (J/kg) is the latent heat of water vaporization calculated as a function of air temperature according to Aubinet et al. (2000). The variables w′, q′ and T′ represent the deviations from the time averages of vertical wind speed (m/s), specific humidity (kg water vapor/kg air) and air temperature (K), respectively. The over-bar denotes a time average (30-min window in this study).

The raw data were corrected for angles of attack errors resulting from the imperfect response of the sonic anemometer (Gash and Dolman, 2003; van der Molen et al., 2004) using the correction functions of Nakai (2006). A double rotation (Aubinet et al., 2000) was applied to the wind data. Moreover, a time lag compensation between the sonic anemometer and the gas analyzer measurements was also used. A sonic temperature correction (van Dijk et al., 2004), a frequency response correction (Moncrieff et al., 2005) and a WPL correction (Webb et al., 1980) were also employed. The average vertical deflection angle for the wind directions was –1.1°. The half-hourly Hs and LE were finally calculated. Data during rain or dew events were not used in the analysis to avoid possible errors caused by liquid water on the sensor window of the CO_2/H_2O analyzer. Nighttime data gaps were filled by linearly interpolating the preceding and following dates. Considering that the solar radiative flux data are relatively continuous and reliable and the solar radiative fluxes are the main source of energy for the LE, Hs and evaporation, so the daytime date gaps were filled using the relationship between the solar radiative fluxes and the measured Hs, LE and evaporation. In this paper, the date gaps were filled by cumulative calculation.

Component fluxes of the radiation balance are described as:

$$\mathrm{Rn{=}DR{-}UR{+}DLR{-}ULR}. \quad (3)$$

Where Rn, DR and UR represent the net all-wave radiation, incident solar radiation and reflected solar radiation, respectively. DLR is incoming longwave radiation, and ULR is outgoing longwave radiation from the megadune surface, and the surface is a flat area. All fluxes have units of W/m^2.

We define the soil heat flux ($G_{(0)}$) as positive when the surface is gaining heat. The $G_{(0)}$ is described as:

$$G_{(0)} = G_{(10)} + \frac{C_S \Delta d \Delta T_s}{t}. \quad (4)$$

Where $G_{(10)}$ is the soil heat flux measured using heat flux plates at 10 cm below the soil surface, and $\triangle d$ is the difference at the depth of 10 cm. Storage above the heat flux plate was calculated using the soil heat capacity (C_S=1.52×10^3 KJ/(m^3·K), measured in the laboratory), and the measured temperature gradient ($\triangle T_s$, K) of the soil layer above the heat flux plate was over a 30-min period. The analysis concentrated in four months of different seasons: April (spring), July (summer), October (autumn) and January (winter).

3 Results

3.1 Changes in radiation and turbulent heat fluxes

The fluxes of the DR, UR, DLR and UR on the megadune are shown in Fig. 2. The DR, UR and ULR had significant diurnal changes and were symmetric, but different in amplitude. The diurnal variation of DLR was smaller and less obvious than those of the other three quantities. Over the course of a day, the DR and UR were positive during daytime and zero at night; however, the DLR and ULR were positive and greater during the daytime than at night. The peaks of each radiation occurred at different times of a day.

In general, the radiation flux was greater in summer (July) than in winter (January). Due to the precipitation, dust storms and other weather events in spring (April) and summer (July), the radiation exhibited fluctuations. However, since it was mostly sunny in autumn (October) and winter (January), the radiation showed stability.

The maximum and minimum Rn were 682.8 and 50.8 W/m^2, appearing in July and April, respectively. The maximum DR and UR were 1,098.2 and 436.5 W/m^2, appearing in July and April, respectively. The maximum DLR and ULR were 450.2 and 707.1W/m^2, respectively, appearing in July; and the minimum values were 303.5 and 420.5 W/m^2, respectively, appearing

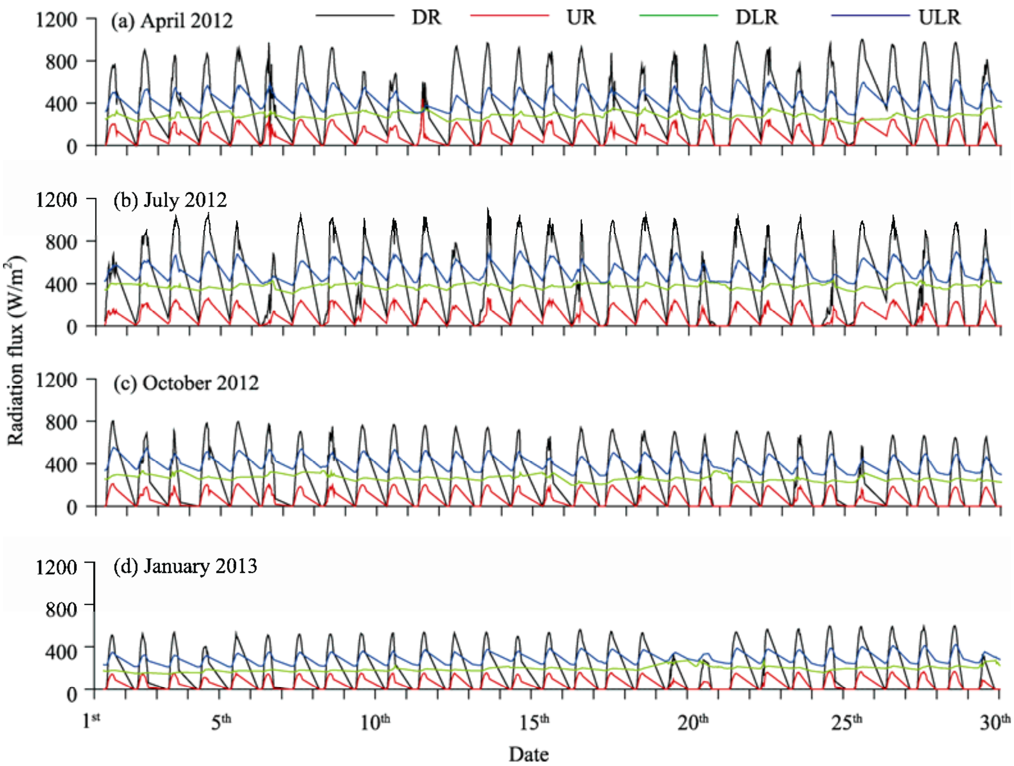

Fig. 2 Changes of radiation fluxes in different seasons of the study period

in January. The heat fluxes of Hs and LE are shown in Fig. 3. Positive values indicate that the megadune surface absorbs heat, while negative values indicate that the megadune surface releases heat. During the study period, the sensible heat flux dominated, and the latent heat flux contributed a very small proportion of the energy. The Hs showed obvious diurnal variations in the spring (April) and summer (July) (Fig. 4). In

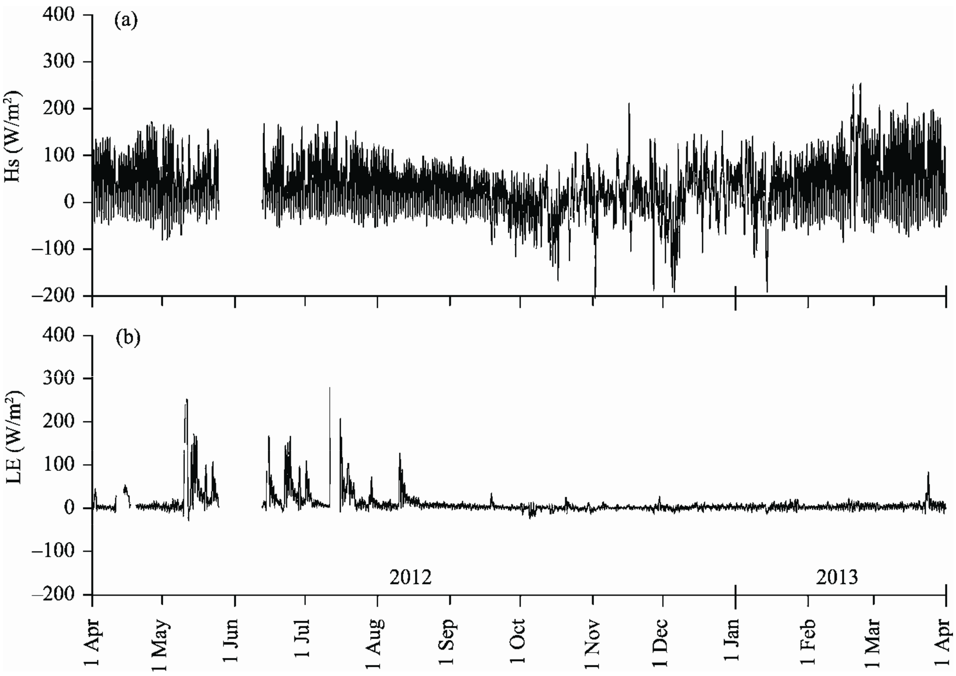

Fig. 3 Variations of the sensible heat (Hs) and latent heat (LE) fluxes during the study period

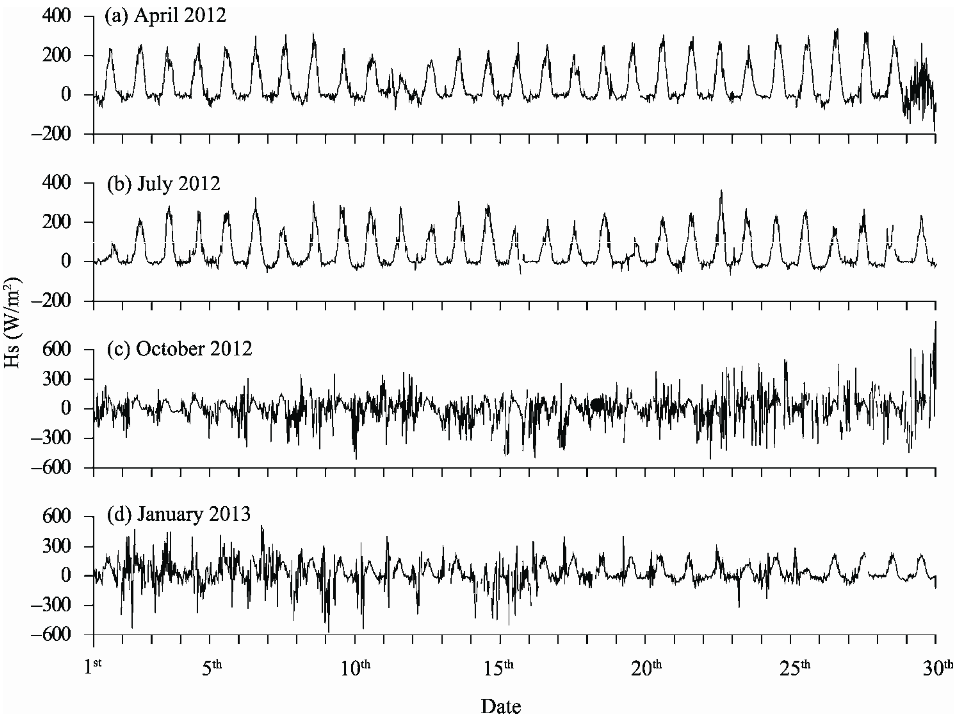

Fig. 4 Variations of the sensible heat (Hs) flux in different seasons of the study period

general, the Hs was positive in daytime and negative at night; however, in the autumn (October) and winter (January), the diurnal variation became more complex. The LE was greater in spring and summer than in autumn and winter, and this quantity had no obvious diurnal variations (Figs. 3 and 5).

The maximum Hs and LE were 443.1 and 892.8 W/m^2, respectively, appearing in July. The average sensible heat flux was much larger than the average latent heat flux, which were 40.1 and 14.5 W/m^2, respectively. Note that the latent heat flux exhibited negative values, this means that the water vapor transported downwardly and it would appear as condensate.

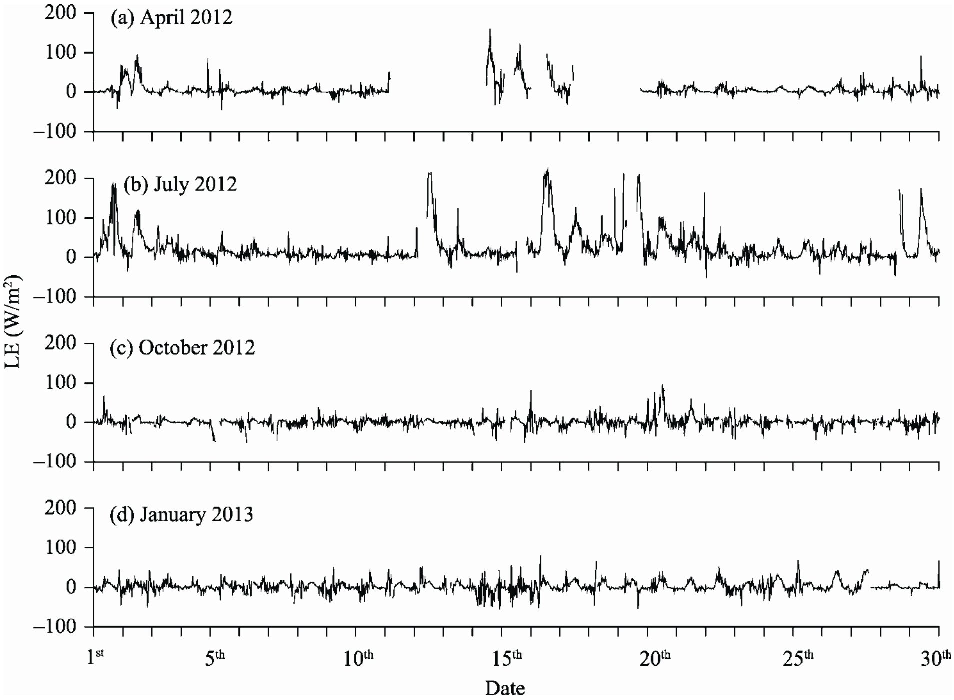

Fig. 5 Variations of the latent heat (LE) flux in different seasons of the study period

3.2 Variations in the soil heat flux and soil temperature

The values of soil heat fluxes ($G_{(0)}$) have significant diurnal variations (Fig. 6). The amplitudes of the diurnal cycles in spring (April) and autumn (October) were larger than those in summer (July) and winter (January). The average soil heat fluxes were 28.6, 13.4, –8.5 and –12.3 W/m^2 in April, July, October and January, respectively. The positive value indicates the heat transfers from the atmosphere to the soil and the negative value indicates the heat transfers from the soil to the atmosphere.

The soil temperature varied with depth (Fig. 7). The soil temperature resembled as sine function during the observation period, but the amplitude had a negative correlation with depth. The soil temperature was negatively correlated with depth from April 2012 to August 2012, however, the situation was reversed and the soil temperature was positively correlated with depth from November 2012 to March 2013. The other months showed a transition between these two states. Because the heat capacity of the soil was much greater than that of the atmosphere in the energy exchange process, the energy will transfer from the atmosphere into the deep soil during summer and heat will travel from the deep soil to the surface and atmosphere during winter. This conclusion was consistent with the research by Hanks and Ashcroft (1980).

3.3 Evaporation and precipitation

The evaporation and precipitation changed during the study period (Fig. 8). The precipitation mainly occurred from April 2012 to October 2012, with a small

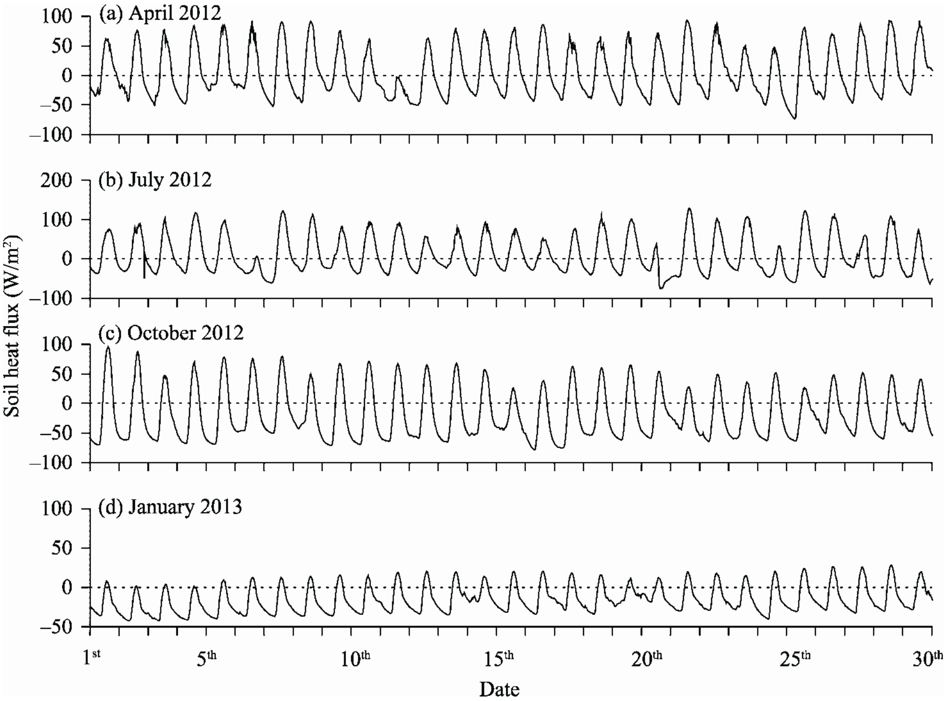

Fig. 6 Seasonal and daily variations of soil heat fluxes in different seasons of the study period

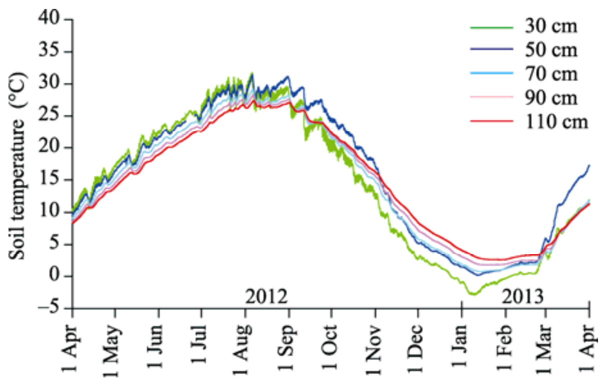

Fig. 7 Changes in soil temperature at different soil depths in the study period

proportion of the annual total in other months. The cumulative precipitation was approximately 145 mm during the observation. Evaporation mainly occurred in spring and summer, with larger evaporation rates from April 2012 to October 2012. The cumulative actual evaporation was quite close to the total precipitation, which was approximately 150 mm, and the precipitation was greater than the average years. Note that a small amount of dew water would occur after precipitation events, and this process was not analyzed in this paper.

The relationship between the precipitation and evaporation and soil volumetric water content were shown in Fig. 9. There were six extreme rainfall events from 20 July 2012 to 30 August 2012, with the rainfall reaching 47.0, 11.8 and 10.4 mm on 20 July, 29 July and 5 August, respectively. Less than 10 hours after the rainfall on 20 July, the soil volumetric water content at 50-cm depth increased suddenly, but the soil volumetric water content at 110-cm depth did not increase until 1 August 2012, indicating that the rainwater infiltrated to that layer much later. When the amount of rainfall was less than 10 mm, there was no effect on the soil moisture at 110-cm depth. There was a peak of evaporation after each rainfall event.

4 Discussion

4.1 Radiative and turbulent heat fluxes

Radiation partitioning is often used to describe the radiation characteristics of an ecosystem. It often shows significant variations at different altitudes: the proportion of absorbed solar radiation decreases with increasing altitude (Rosset et al., 1997; Iziomon et al., 2001; Iziomon and Mayer, 2002). The DR was markedly affected by solar elevation and weather conditions such as solar reflection, scattering and atmospheric absorption. In desert areas, where the weather

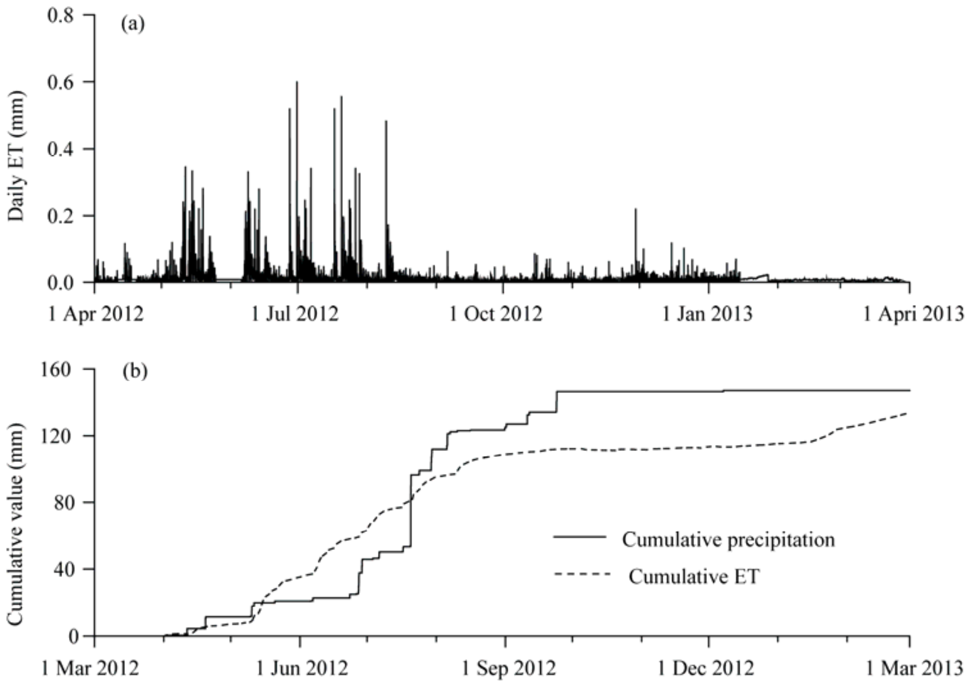

Fig. 8 Change in the evaporation (ET), cumulative precipitation and cumulative evaporation during the observation period

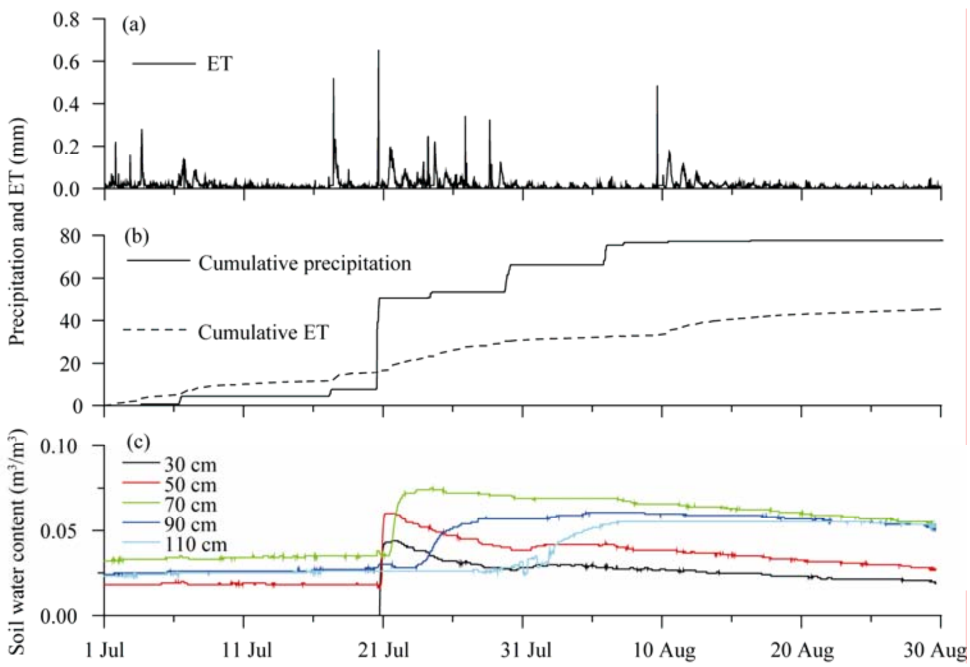

Fig. 9 The relationship between evaporation (ET), precipitation and soil moisture at different soil depths in 2012

was mostly cloudless and the DR was greater than in other places, the longwave radiation (DLR and ULR) exchange between the ground surface and the atmosphere was mainly determined by surface characteristics, air temperature, clouds and atmospheric water vapor pressure (Huang et al., 2011). According to the data we observed on the megadune in the desert, the water vapor pressure ranged from 0.01 to 1.50 kPa, which was much lower than that on other underlying surfaces, which ranged from 2.0 to 5.0 kPa (Kellner, 2001; Hunt et al., 2002; Wever et al., 2002). This was probably because the decreases in water vapor pressure cause the decreases in downward longwave radiation. It indicated that the radiative energy loss by the longwave radiation may be greater from the megadune than from other underlying surfaces due to the relatively lower water vapor pressure. In desert areas, it was often sunny, so the DLR was much lower than that reported globally or for the Northern Hemisphere according to NASA data (Gupta et al., 1999). The UR was mainly determined by the properties of the underlying surface, especially its albedo. According to the observation and calculation, the average albedo of the megadune was 0.26, which was close to the albedo of the desert surface (0.25) reported by Stull (1999). In other words, 26% of the annual incoming solar radiation was reflected back to space. This means that the radiative energy loss by shortwave radiation may be greater on the megadune of the desert than on the underlying surfaces of other ecosystems.

The partition of available energy transformed into sensible and latent heat fluxes is dependent on both the biological and climatological conditions of ecosystems (Wilson and Baldocchi, 2000). In our study, the land-atmosphere interaction was primarily represented by the sensible heat flux on the megadune. The sensible heat flux had a significant diurnal variation in spring and summer, but not significant in autumn and winter. It was mainly negative in autumn and winter, which means that sensible heat traveled from the ground to the atmosphere. Changes in the LE are often affected by the changes in air temperature as well as soil temperature, soil moisture and radiation (Baldocchi et al., 2000; Arain et al., 2003). The evaporation was weaker in the desert, and precipitation was the primary reason for the low LE during the study period. The significantly low LE fluxes suggested that the partitioning of the surface energy was very sensitive to changes in precipitation in the desert. Limited precipitation could cause a decrease in soil moisture and limit the refilling of dry soil, which would decrease the evaporation component of LE. Because the humidity of the air and soil were lower in the desert, the LE was small compared to the Hs. This is consistent with previous studies in other desert regions (Huang et al., 2011).

4.2 Precipitation, evaporation and soil moisture

The timing and magnitude of rainfall were critical to ecological communities in the desert. According to Ma et al. (2014), the conventional precipitation, which was below 5 mm, accounted for roughly 90% of all rain events, and extreme precipitation, which was more than 40 mm, occurred only once in several decades in the desert. During our observation, the rainfall primarily occurred in spring and summer; and the cumulative rainfall was 147 mm, which was considerably larger than that in a normal year, partly because an extreme precipitation event (45 mm) occurred in July.

Soil moisture was a very important parameter in land-atmosphere interactions (Yeh et al., 1984; Manabe and Delworth, 1990), especially at the surface, where there was a direct link with precipitation. In desert regions, where the soil and air were very dry, the frequency and magnitude of precipitation events were very small, and the soil moisture would be strongly influenced by even a small amount of precipitation. The soil moisture at the 80-cm depth was little affected by rainfall of less than 10 mm. This conclusion was consistent with the study of Huang et al. (2011).

The amount of precipitation determined the actual evaporation in this region. The cumulative evaporation was 149 mm during the observation period. Considering measurement error, the evaporation should be equal to the precipitation on the megadune. This means that over a long timescale, the precipitation was difficult to recharge the groundwater. Yang and Williams (2003) used geochemical dating and water-balance to suggest that precipitation recharge was an important source of groundwater, and they believed that approximately 5% of the modern precipitation could recharge groundwater, which is inconsistent with our observations.

5 Conclusions

We measured the components of the radiation and described the eddy covariance measurements of heat flux and evaporation on a megadune surface in the Badain Jaran Desert, China from April 2012 to April

2013. The results indicate that the longwave and shortwave radiative fluxes exhibited large fluctuations and seasonal dynamics, and radiation partitioning was different in different seasons. The land-atmosphere interaction was primarily represented by the sensible heat flux. The average sensible heat flux was much larger than the average latent heat flux, which were 40.1 and 14.5 W/m^2, respectively. The soil heat flux played an important role in energy balance. The mean evaporation was 0.41 mm/d, and the cumulative evaporation was approximately 150 mm/a. The amount of precipitation determined the amount of evaporation in this region: the evaporation should be equal to precipitation on the megadune over a long timescale, and precipitation was difficult to recharge the groundwater. The water vapor would transport downwardly and appear as dew condensation water.

Acknowledgements

This work is supported by Special Fund for National Environmental Protection Industry Scientific Research in the Public Welfare (201209034), the National Natural Science Foundation of China (41371114) and the Fundamental Research Funds for the Central Universities (lzujbky-2-14-275). We are grateful to ZHANG Zhenyu, SHEN Shiping, MA Ning and many other colleagues in the Center for Climate Change and Hydrologic Cycle in Arid Region of Lanzhou University who have contributed to the field work. The reviewers are also appreciated for their insightful comments on the earlier version of this manuscript.

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