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Geography

Observation of mega-dune evaporation after various rain events in the hinterland of Badain Jaran Desert, China

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Abstract The formation mechanisms of the mega-dunes and lakes in the hinterland of Badain Jaran Desert, China, is the focus of extensive academic research in the field of geoscience, and an often debated topic is whether atmospheric precipitation on the mega-dune can infiltrate to recharge groundwater. In the present study, the probability distribution functions and the return period analysis of extreme daily precipitation based on long-term precipitation records for the southern margin of Badain Jaran Desert and 2-year observation of hinterland precipitation were used to classify precipitation in the desert region. The data of automatic weather station and eddy covariance system in the desert hinterland were used to analyze evaporation on the mega-dune surface after various rain events. The results showed that the rain events in the desert could be divided into three categories. The first is conventional precipitation (CP), which is below 5 mm, accounting for roughly 90 % of all rain events in the desert. The second and third categories are ordinary annual maximum (OAM) and extreme precipitation (EP), in which precipitation is roughly 20 mm and more than 40 mm, respectively. The atmospheric precipitation of CP and OAM evaporated from the mega-dune surface in 1–3 days and 3–4 weeks, respectively. Following an EP event, the mega-dune evaporation was negatively influenced by the upper dry sand layer, and a lengthy period was required for its complete removal. The accumulative evaporation and accumulative precipitation of all three types of rain events indicated that local atmospheric precipitation had no significant contribution to recharging the groundwater system in the hinterland of Badain Jaran Desert. This research will benefit comprehensive elucidation of the formation mechanism of lakes in the hinterland of Badain Jaran Desert.

Keywords Atmospheric precipitation · Evaporation · Infiltration · Extreme value return · Eddy covariance · Badain Jaran Desert

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1 Introduction

The formation mechanisms of mega-dunes with relative heights of more than 300 m and numerous lakes in the hinterland of Badain Jarain desert has been extensively studied in the field of geoscience [1–10]. These lakes in the hinterland are inevitably recharged by groundwater due to the extremely low precipitation and substantial potential evaporation, but not by surface runoff in the Badain Jaran Desert. However, the origin of this groundwater has been long debated. Early scholars who believed the groundwater in the mega-dune field originated from local precipitation considered that atmospheric precipitation could infiltrate rapidly to recharge groundwater owing to the loose structure of the sand during a rain event [2, 8–11]. That is, the mega-dunes in the desert may play a role as "impoundment" in the formation of lakes. Although precipitation in the desert is rare, this effect could also balance the lake evaporation losses because the impoundment area is ten times that of the lake. Nevertheless, Chen et al. [3] proposed that the water of ice and snow melt from the Qilian Mountain and the Tibetan Plateau leaks through the underground fault maintain the groundwater system in the Badain Jaran Desert. Consequently, whether the atmospheric precipitation on mega-dune in the Badain Jaran

Desert could really infiltrate to recharge the groundwater has brought about considerable controversy in recent years. Yang et al. [1] used water balance calculations and analysis of chemistry data of these lakes and groundwater to determine that local rainfall makes a significant contribution to the recharge of the groundwater in the southeastern area of Badain Jaran Desert. Zhao et al. [12] measured the vertical variation trend of the water content in the sand layer in various areas of the mega dunes and asserted that the positive water budget in this desert, particularly the atmospheric precipitation can infiltrate into the mega dune quickly and deeply to recharge the groundwater. On the contrary, Chen et al. [5] conducted a continuous observation of the water content in the sand layer in the Badain Jaran Desert after a rain event and suggested that 10.6 mm precipitation can infiltrate ∼13 cm underground in the desert and completely evaporate within 1 week. Dong [13] performed an artificial rainfall experiment in the hinterland of Badain Jaran Desert to demonstrate that 30 mm precipitation was unable to infiltrate to recharge the groundwater. The energy budget experiment also indicated that all atmospheric precipitation and condensed water could be evaporated completely through the extremely strong evaporation power in desert area [6]. Considering these theories, we conducted a series of continuous in situ observations by using automatic weather stations and eddy covariance (EC) system in the hinterland of Badain Jaran Desert and collected a substantial amount of first-hand data on the precipitation and evaporation of mega-dunes in the desert. In this paper, the characteristics of precipitation in the Badain Jaran Desert are discussed, and the mega-dune evaporation processes following various rain events are then analyzed. The aim of this paper is shedding light upon the issue whether the atmospheric precipitation on mega-dunes can infiltrate to recharge the groundwater in the Badain Jaran Desert.

2 Site description and data processing

2.1 Site description and measurements

The Badain Jaran Desert (Fig. 1) lies in western part of the Alxa Plateau in Inner Mongolia, China. The desert is bounded by Heli Hill and Great North Hill to the south, Yabulai Mountain to the southeast, Guaizi Lake and ancient Juyan Lake to the north, and Zhengyi Gorge of Heihe River and ancient Gurinai Lake to the west. With an area about 52,100 km^2 (442 km from north to south and 354 km from east to west), it is the second-largest desert in China [14]. The mean summer and winter temperatures in this area are 25.3 and −9.1 °C, respectively. The annual mean diurnal temperature range is 34.4 °C, which is categorized as a "cold desert" [15]. The desert is characterized by a strongly continental climate with mean annual precipitation of 90.1–115.4 mm in the southern margin and 35.2–42.9 mm in the northern margin. The regional average annual precipitation is ∼76.9 mm [16]. First established on the inter-dune beside Sumubarunjilin Lake in late 2009, an automatic weather station (MAWS301, Vaisala, Finland) observed precipitation in 1 h intervals (hereinafter referred to as V1, Fig. 1) in the desert hinterland. An additional station including EC and meteorological measurement systems, hereinafter referred to E1 (Fig. 1), was installed on March 22, 2013, on the lower part of a mega-dune beside V1. The altitude of E1 relative to Sumubarunjilin Lake is roughly 80 m.

The EC system was equipped with a three-dimensional sonic anemometer (R3-50, Gill,UK) to measure three-dimensional wind velocity and temperature, in addition to an open-path infrared CO_2/H_2O gas analyzer (LI-7500A, LI-COR, USA) to measure CO_2 and H_2O density. The installation height of the EC was 2.5 m and the EC was sampled at 10 Hz. Regarding meteorological measurements, the air temperature (T_a) and relative humidity were measured with an HMP155 probe (HMP155, Vaisala, Finland) at a height of 2 m. A four-component net radiometer (NR01, Hukseflux, Netherlands) was installed at a height of 1.5 m to measure the downward/upward short- and long-wave radiation. A soil heat flux plate (HFP01SC, Hukseflux, Netherlands) was buried at a depth of 15 cm to observe soil heat flux. Two additional soil temperature probes (ST-100, Campbell Scientific, USA) were buried at depths of 2 and 15 cm. The data of the soil temperature at these two depths can be used to estimate the soil flux of the sand layer from 0 to 15 cm depths [24]. T_a, relative humidity, four-component radiation, soil heat flux, and soil temperature were measured as 30 min averages of ∼4 s readings and were recorded in a data logger (CR3000, Campbell Scientific, USA). Two soil moisture sensors (EC-

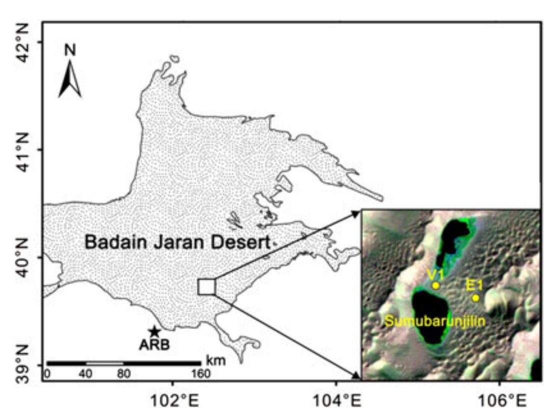

Fig. 1 Location of the Badain Jaran Desert and observation sites in the hinterland

5, Decagon, USA) were installed at depths of 45 and 65 cm. Soil moisture was sampled every half an hour and recorded in the EM50 Data logger (EM50, Decagon, USA). A tipping-bucket rain gauge (HOBO R3-GM, Onset, USA) used to measure atmospheric precipitation at E1 was also installed at a height of 1.5 m. The observational data of the V1 station in this paper were from January 1, 2010 to December 31, 2011. The observational data of the E1 station in this paper were from March 25, 2012 to October 31, 2012, excluding the period of May 9, 2012 to June 26, 2012, in which data recording failed due to a malfunction of the CO_2/H_2O gas analyzer. Notice that all observational data of V1station and E1 station used in this paper were on the basis of Beijing time (UTC +08). Additionally, the daily precipitation of Alxa Right Banner, hereafter referred as to ARB (Fig. 1), located in the southern margin of Badain Jaran Desert, was downloaded from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/home.do).

2.2 Data processing

The raw data of EC acquired at 10 Hz was processed by using the EddyPro Express post-processing software (LI-COR, USA). Corrections made to the raw data include spike removal; detrending of raw time series with the block averaging method; double rotation [17]; compensation of time lag between sonic anemometer and gas analyzer measurement; sonic temperature correction [18]; frequency response correction [19]; and WPL correction [20]. The half-hourly values of sensible heat flux (H) and latent heat flux (LE) were finally calculated. To estimate the flux footprint, the method proposed by Kljun et al. [21] was implemented to obtain the flux source area of E1. The greatest contribution to the source area was located 42.7 m away from E1 station, and 90 % of the source area was limited to 116.9 m. This result implies that our observational data essentially met the requirements of flux observation because it is relatively flat in this area. Moreover, the distance between E1 station and Sumubarunjilin Lake is more than 1,000 m. Thus, our EC measurement successfully represented the energy and water vapor flux from the mega-dune surface and entirely avoided the potential effect of heterogeneity resulting from the staggered distribution of the mega-dunes and the lakes [22]. After considering the heat storage of the upper layer of 0–15 cm, the OLS method [23] was used to estimate the overall quality of the EC data. The results indicate an energy closure fraction of 85.9 % for E1 (the specific calculation process was presented in [24]). Since this energy closure fraction is relatively good and is similar to other observational experiments in other regions [23, 25, 26], the observed data of EC in this paper is highly reliable.

3 Characteristics of desert precipitation

3.1 Precipitation observation in the desert hinterland

A better understanding of the regularity of hinterland precipitation is necessary to effectively elucidate the mega-dune evaporation and infiltration processes that occur following various rain events in the desert hinterland. The data of V1, located in the hinterland, recorded from January 1, 2010 to December 31, 2011 were first selected to analyze the precipitation characteristics in that area. As shown in Fig. 2, the annual precipitation and the number of rainy days (refer to the daily precipitation $\geq$0.1 mm) of V1 were quite low. The annual precipitation was 100.6 and 72.8 mm in 2010 and 2011, respectively, and the number of rainy days in those 2 years was 48 and 23, respectively. In addition, 91.5 % of the daily precipitation in the hinterland of the desert was <5 mm. Only two rain events were observed in which precipitation was >20 mm. The first was 23.8 mm on May 25, 2010, and the second was 22.4 mm on September 20, 2010. After comparing the precipitation characteristics of the hinterland with the ARB situated at the southern margin of Badain Jaran Desert, we determined that the occurrence of rain events during the year, mainly from May to September, and the grade distribution of daily precipitation, generally <5 mm, are quite similar (Fig. 2).

3.2 Long-term desert precipitation characteristics

As the above hinterland precipitation analysis is based on 2-year observation, we used the data of daily precipitation from 1960 to 2011 of the ARB weather station which is located at the southern margin of Badain Jaran Desert to discuss the long-term precipitation characteristics in desert. The annual precipitation and the number of rainy days recorded at ARB fluctuated significantly with a coefficients of variation of 0.25 and 0.14 for annual precipitation and the number of rainy days, respectively. The maximum and minimum annual precipitation in these 52 years was 188.1 and 59.2 mm, respectively, and the number of rainy days ranged from 28 to 54 days year^{-1} with an average of 40 days year^{-1}. The annual maximum (AM) daily precipitation was <20 mm for 24 years of the analysis period and exceeded that level only one to three times per year during the other 28 years (Fig. 3). These results indicate that 2-year observation values recorded in the desert hinterland are similar to the average long-term precipitation characteristics in the desert area; therefore, our in situ observation can accurately represent the hinterland precipitation characteristics. Furthermore, these results demonstrate that the majority of daily precipitation in the Badain Jaran Desert is below 5 mm and those events of

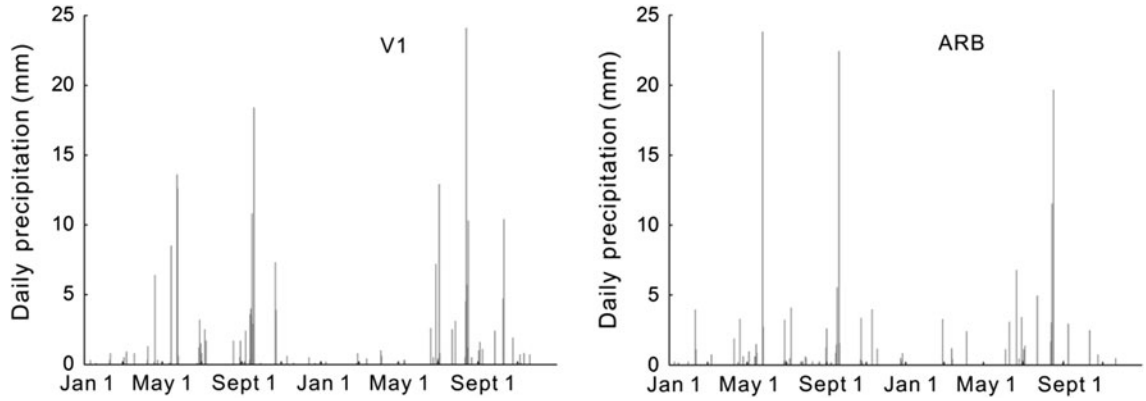

Fig. 2 Daily precipitation recorded of the automatic weather station at the hinterland of Badain Jaran Desert (V1) and that measured at alxa right banner (ARB) station at the southern margin from 2010 to 2011

more than 20 mm are uncommon. This fact has also been supported by previous research conducted in the adjacent area of Badain Jaran Desert [27].

A heavy rain event of 50.3 mm that occurred on July 30, 1974 marked the highest value of AM in ARB from 1960 to 2011 (Fig. 3). However, daily precipitation of 30–40 mm was observed at ARB on only 7 days; that higher than 40 mm was observed on only 2 days (Fig. 3). These results suggest that the frequency of strong precipitation in the Badain Jaran Desert is extremely low. Previous studies on the strong precipitation of Taklimakan Desert in China [28] and Atacama Desert in South America [29] reported similar conclusions. To reconstruct the probability distribution characteristics of strong precipitation in ARB, we analyzed the AM sequence [30] during the period of 1960–2011 and compared the fitting effects of 60 types of probability distribution functions. The goodness-of-fit test of every PDF was conducted by using Kolmogorov–Smirnov's statistic D [31, 32]. The results showed that the Burr probability distribution with four parameters (Fig. 4) performed best because of its minimum D (0.05561). According to the definition of the return period of extreme value [33], if the PDF of a climatic extreme value is $F(x)$, then its return period year T is equal to $1/F(x)$. As shown in Fig. 4, if $T = 50$ ($F(x) = 0.02$), the corresponding AM is 45.3 mm, which means that the AM daily precipitation that occurred every 50 years in the ARB is $\sim$45.3 mm. Similarly, the probability for AM $\geq$20 mm is about 0.335, which implies that, in theory, the phenomenon of daily precipitation of more than 20 mm occurred every 3 years (1/0.335) in the Badain Jaran Desert.

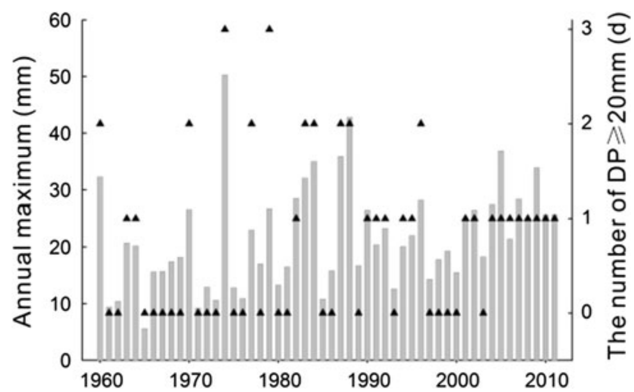

Fig. 3 Annual maximum (*gray bars*) and the number of days in which daily precipitation (DP) was >20 mm (*black triangles*) at the Alxa Right Banner (ARB) station from 1960 to 2011

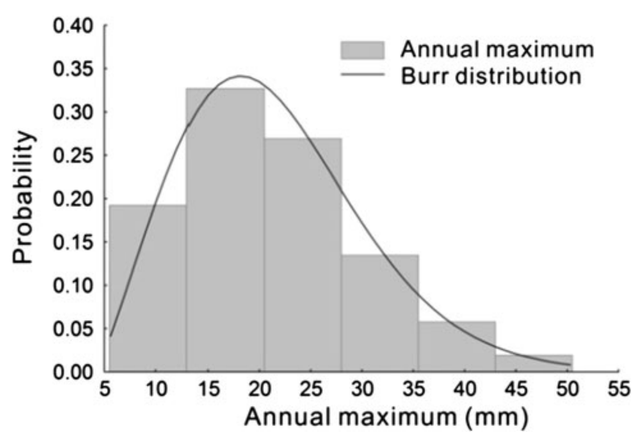

Fig. 4 Probability of annual maximum (AM) daily precipitation (*gray bars*) at the Alxa Right Banner (ARB) station and the fitted curve of the Burr probability distribution function

4 Characteristics of mega-dune evaporation in the hinterland of desert

We classified daily precipitation into three types on the basis of the aforementioned analysis of precipitation characteristics in the Badain Jaran Desert. The first, conventional precipitation (CP) refers to daily precipitation of <5 mm, and more than 90 % of the daily precipitation recorded in the desert is attributed to this category (Fig. 2).

The second is ordinary annual maximum (OAM), which refers to daily precipitation of ∼20 mm. During the past 52 years, such rainfall occurred only one to three times in some years, but even no such kind of rainfall emerged in other years (Fig. 3). The third is extreme precipitation (EP), which refers to daily precipitation of more than 40 mm. EP was particularly rare and it occurred only once in several decades, for instance, only two EP events were recorded between 1960 and 2011 (Fig. 3).

4.1 Mega-dune evaporation after CP

The rain gauge at E1 station recorded a rain event in the desert (Fig. 5a) with 4.0 mm precipitation from 09:56 to 11:15 on April 11, 2012. As Fig. 5b shows, the LE of the mega-dune surface even reached 500 W m^{-2} at 16:00. Additionally, the Bowen ratio, which refers to H/LE, was lower than 0.1, far below than that of sunny days. Due to the increased moisture content in the air following the rainfall, obvious condensation came into being ($LE < 0$) when the desert surface temperature dropped below the dew point temperature at midnight on April 11 (Fig. 5b). The LE gradually increased in the morning of April 12, indicating that a substantial amount of water evaporated from the mega-dune surface. All in all, the accumulative evaporation (AE) was more than 4.0 mm for 22 h from 16:00 on April 11 to 14:00 on April 12, demonstrating that all of the atmospheric precipitation evaporated from the mega-dune in roughly one day after the end of CP.

4.2 Mega-dune evaporation after OAM

On June 27, 2012, a rain event occurred with 12.6 mm from 02:37 to 12:19 and another event with 7.8 mm followed from 17:13 to 20:09 on June 28, 2012. The total precipitation for these two rain events was 20.4 mm. Therefore, these two events could be regarded as OAM since the interval was only one day.

Figure 6a indicates that the evaporation of mega-dune reached 2.3 mm in only 12 h after the rain stopped at noon on June 27. The evaporation increased steadily to 2.8 mm

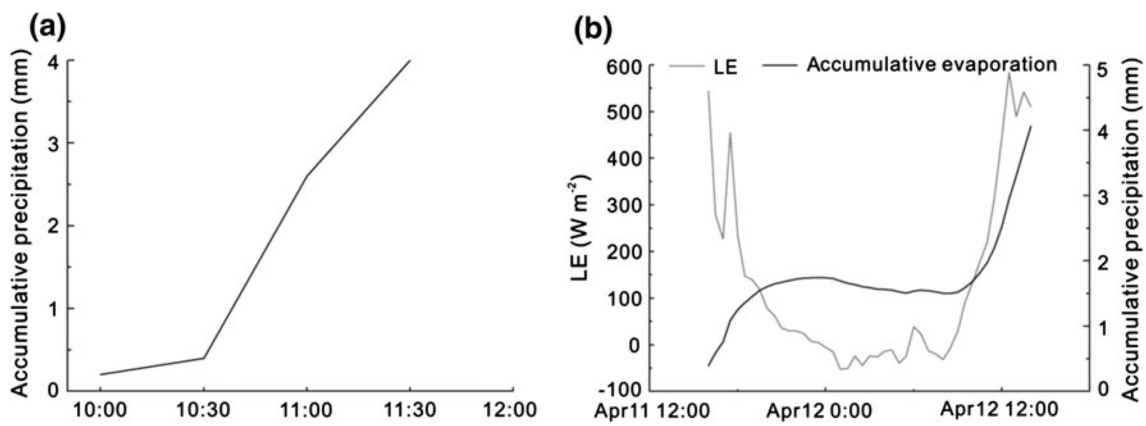

Fig. 5 **a** Precipitation-duration *curve* on April 11, 2012, at E1 and **b** LE and accumulative evaporation following a rain event. All time in figures of this paper is based on Beijing time

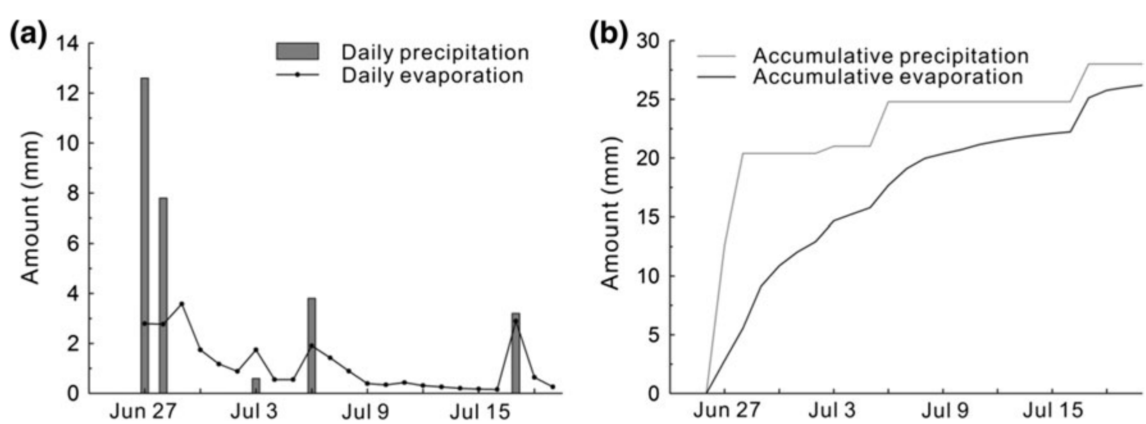

Fig. 6 **a** Daily precipitation and evaporation and **b** accumulative precipitation and accumulative evaporation from 00:00 on June 27 to 12:00 July 20, 2012, at E1

on June 28, which was recorded as a cloudy day, and reached nearly 3.6 mm by June 29 before declining rapidly due to the drop of water content on the dune surface. The AE reached 13.4 mm at 15:00 on July 3 prior to another rain event, indicating that nearly 70 % of precipitation of OAM was evaporated within 6 days after it stopped. The evaporation increased along with another rain event on July 6 before rapidly reducing during the following several days. A similar trend occurred on July 17 (Fig. 6a). Overall, from 00:00 on June 27 to 12:00 on July 20 the accumulative precipitation (AP) and AE at E1 station were 28.0 and 26.2 mm, respectively (Fig. 6b). The remaining atmospheric precipitation in the sand layer was only 1.8 mm, which would have been evaporated completely within 1 week in the absence of precipitation. Moreover, soil moisture observation of the sand layer also illustrates the infiltration process during this period. As shown in Fig. 7, the volumetric water content at a depth of 45 cm increased after the OAM, but showed no significant variation at a depth of 65 cm. This result clearly proves that the wetting front just descended to a location between 45 and 65 cm following the OAM event. Since the 20 mm precipitation did not infiltrate underground as deep as 65 cm, it unquestionably could not recharge the groundwater. This conclusion was also supported by earlier continuous in situ measurement for the thickness changes of wet layer of the dune in the Badain Jaran Desert after precipitation of 10.6 mm [5].

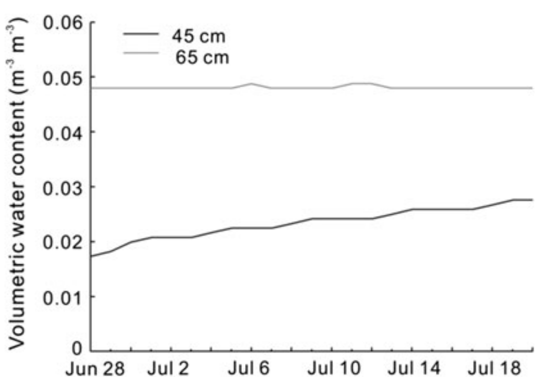

Fig. 7 Variation of volumetric water content (45 and 65 cm deep) from 00:00 on June 28 to 00:00 on July 20, 2012, at E1

4.3 Mega-dune evaporation after EP

The rain gauge at the E1 station recorded an extremely heavy rain with 43 mm precipitation from 12:42 to 18:06 on July 20, 2012 (Fig. 8a). The maximum hourly precipitation was 26 mm from 13:00 to 14:00, which was stronger than the maximum hourly precipitation intensity of 19.6 mm h^{-1} reported in Taklimakan desert [34]. Moreover, the precipitation record at ARB was 48.8 mm on the same day, which also demonstrated that the precipitation observation at E1 station was reliable.

On July 21, the first day after EP, the maximum mega-dune surface evaporation was 3.3 mm, and the average daily evaporation was 1.7 mm during the following 5 days, which suggests a continuation of the strong evaporation process. As expected, the evaporation rate decreased significantly as a result of the decrease of water content in the upper layer of the mega-dune, which explains why the evaporation was only 0.5 mm per day on July 27 and 28. Later, the mega-dune surface evaporation increased again when another rainfall event occurred. The daily evaporation on August 6 was up to 3.2 mm due to the 7.4 mm precipitation that occurred on August 5; however, this evaporation rate also gradually decreased over time (Fig. 8a). Although the evaporation on the mega-dune surface continued to decrease after the rainfall ended, the atmospheric precipitation did not infiltrate the groundwater because the soil moisture was quite small. Notice that the greater precipitation, the larger depth that

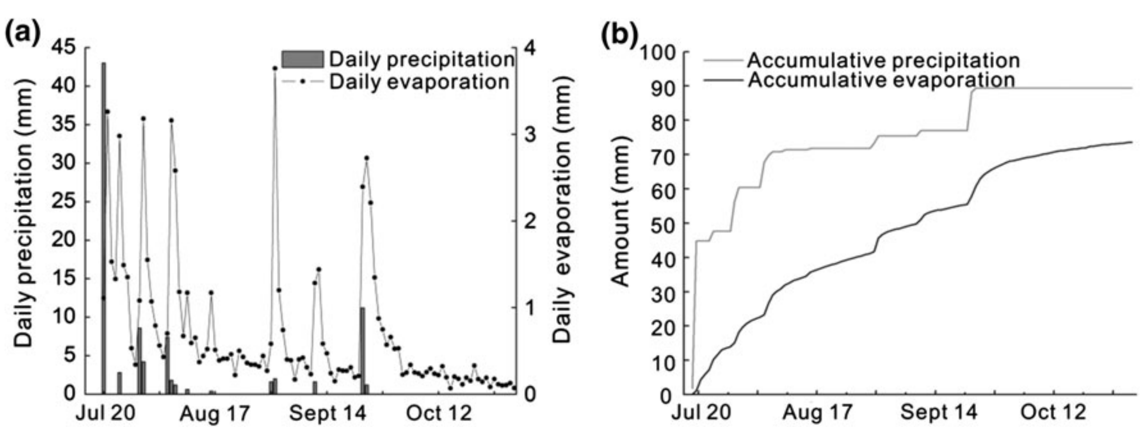

Fig. 8 **a** Daily precipitation and evaporation and **b** accumulative precipitation and accumulative evaporation from July 20 to October 31, 2012 at E1

wetting front could arrive, the time that required for evaporating from the dune surface is longer; however, it is unlikely to infiltrate several meters deep to recharge the groundwater because more and more water had been evaporated out with extension of time. In particular, during a 43-day period from July 20 to September 1, 2012, the AE reached 45.5 mm, which surpassed the 43 mm EP event (Fig. 8b). This result implies that the atmospheric precipitation of EP had been evaporated from the mega-dune surface.

5 Discussions

Over the past decades, the EC method has become a standard tool for studying the exchange of water vapor and energy between the Earth and the atmosphere although the energy imbalance [23] as well as the random error of the EC system [35] is inevitable. Therefore, this method has been widely applied to many types of ecosystems including forest [37], grassland [38, 39], cropland [26], and desert [40, 41] and has been regarded as the most accurate avenue for measuring evapotranspiration [36]. For this reason, we used this method to reveal the relationship between atmospheric precipitation and groundwater in the desert area. The variation of AE and AP after various rain events implies that the atmospheric precipitation could not infiltrate to recharge groundwater even though the precipitation exceeded 40 mm. This result signifies that the role of local precipitation is unimportant in the formation of lakes in the hinterland of Badain Jaran Desert except for that falling directly onto the lake surface. The duration of rainfall in the desert is always short, whereas, the evaporation on mega-dune surface is a continuous process. In particular, the wetting front penetrated the sand layer at a certain depth after the EP ended, but then the gap between the AE and AP event decreased over time, indicating that the AE was emulating AP on a daily basis. This demonstrates that the atmospheric precipitation of EP evaporated from the dune surface rather than infiltrating.

A better understanding of the ability of atmospheric precipitation to infiltrate and recharge the groundwater is certainly crucial to the management and rational usage of local water resources in extremely arid regions due to the scarcity of rainfall. On the basis of the observation of matrix-distributed lysimeters, Xu et al. [42] deemed that at least 91 % of precipitation in the Hexi Desert could be evaporated, and the rest remained in the sand layer. Evaporation experiments in the Mu Us Desert manifested that 10 mm precipitation could be completely evaporated within 15 days [43]. Analysis of the stable isotopes of oxygen and hydrogen and chemistry data of soil water, precipitation, and groundwater samples suggested that the source of groundwater in the Loess Plateau was not local precipitation [44]. According to our field work in the Badain Jaran Desert, however, we found that the thickness of the upper dry layer of the mega-dune is only about 20 cm and it is conspicuous wet layer under the upper dry layer. The pore water content of the wet layer at 2 m depth in the mega-dune could be up to 65 %, which is impossible to be supported by the rare precipitation in the desert [6]. Earlier energy balance observation on sand dunes reported by Gu et al. [6] showed that the annual evaporation of mega-dunes was greater than the sum of precipitation and the amount of condensation water, which resulted in an assumption that groundwater under the mega-dunes recharging evaporation of the dune surface. Chen et al. [3, 5] reported that the groundwater ran into the unsaturated wet sand layer in the form of film water, which could be evaporated from the dune surface. The dune's resistance to wind erosion was greatly improved due to the strong bonding of sand particles resulting from groundwater evaporation. In such conditions, a stable mega-dune can be formed. Therefore, the groundwater maintains the landscapes of dunes and lakes [3]. Moreover, the concentrations of δD and δ^{18}O of groundwater in the Badain Jaran Desert were abnormal because the values deviated from the global precipitation line [1, 3, 5], further suggesting that groundwater in the desert was subjected to strong evaporation. The analysis of δD and δ^{18}O of the soil water in the sand layer of this desert at a depth of 40 cm also supported this speculation [45]. According to previous studies on groundwater evaporation, given the depth is above the evaporation threshold, the evaporation of groundwater decrease evidently with the increase in depth of groundwater level [46, 47]. In this study, the E1 station is located in the lower part of a mega-dune situated to the east of Sumubarunjilin Lake and the altitude of E1 relative to Sumubarunjilin Lake is ~80 m. The depth of groundwater is therefore substantial, and the applicability for measuring mega-dune evaporation by the EC system during a lengthy period without rainfall may be limited due to the increase in uncertainties. Therefore, we were unable to definitively determine whether the groundwater was evaporated through the mega-dune on the basis of our current in situ observations in the hinterland of the Badain Jaran Desert.

6 Conclusions

(1) Analysis of 2-year precipitation observation in the hinterland of Badain Jaran Desert and long-term precipitation records in its marginal area suggest that the precipitation could be classified into three categories. The first is CP, in which daily precipitation is <5 mm, accounting for ~90 % of all rain events in the desert. The second is OAM, in which daily precipitation is ~20 mm precipitation, occurring once

every 3 years theoretically. The third is EP, in which daily precipitation is more than 40 mm, occurring only once in several decades.

(2) According to the observation of rain gauge and the EC system located in the lower part of a mega-dune (the altitude of E1 station relative to Sumubarunjilin Lake is roughly 80 m), the atmospheric precipitation of CP and OAM could not infiltrate to recharge the groundwater. Such precipitation could be completely evaporated from the mega-dune surface in one to 2 days for CP and three to 4 weeks for OAM. With regard to EP, the time required for complete evaporation was slightly longer because the wetting front moved deeper; however, the precipitation in such case is still insufficient for infiltrating to recharge the groundwater. These observations demonstrate that atmospheric precipitation on mega-dunes has no significant contribution to recharging the groundwater system in the hinterland of Badain Jaran Desert.

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