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Variation characteristics of non-rainfall water and its contribution to crop water requirements in China's summer monsoon transition zone

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ABSTRACT

Comprising mainly fog water, dew water, and water-vapor adsorption (WVA), non-rainfall water (NRW) makes an important contribution to the local ecology in the arid and semi-arid regions. Although NRW components have been studied individually in previous work, little attention has been paid to the integrated characteristics of NRW and the corresponding relationships among the components. In fact, few other studies have considered how NRW components form and change, let alone how they contribute to land surface water (LSW) balance and influence crop water requirements in China. In this paper, a method will be established for identifying components of NRW, based on a combination of lysimeter measurements and micro-meteorological data from Dingxi Station in the summer monsoon transition zone (SMTZ) of China. Diurnal time series of NRW components will be given. The relationship between NRW and climatic and environmental factors is then analyzed. Finally, the diurnal and annual variations of NRW and how they contribute to LSW balance and crop water requirements are discussed. The results show that the influence of climatic and environmental conditions to occur dew and WVA is different even opposite affects such as relative humidity to that. There is negative feedback between soil moisture and WVA; this does not hold, however, for dew. The variation characteristics of dew and WVA are different. Their diurnal variation shows the complementary characteristics of each other. Not only that, the annual distribution of NRW also complemented with that of precipitation. Although NRW contributes to no more than 15% of the water balance in a full year, NRW plays a leading role during the non-monsoon period, wherein the amount of NRW is 1–3.5 times that of precipitation. Moreover, it is just the period of soil water conservation and sowing date for crops such as winter wheat. Therefore, the existence of NRW is fundamental for alleviating agricultural drought. It explained that NRW has great significance for reducing agricultural losses and understanding the LSW balance in the SMTZ.

1. Introduction

Non-rainfall water (NRW) refers to land surface water (LSW) in liquid form from sources other than natural rainfall and irrigation (Agam and Berliner, 2006) and comprises fog water, dew water, and water–-vapor adsorption (WVA) from the atmosphere, as well as soil distilled water, capillary water, and guttation (Zhang et al., 2010; Uclés et al., 2013) from the soil. Sometimes, NRW exceeds even rainfall as one of the primary water source (Malek et al., 1999) and plays a role to maintain the ecological system not only in arid and semi-arid regions (Shachak and Steinberger, 1980; Kidron, 2000; Henschel and Seely, 2008; Weber et al., 2016; Kaseke et al., 2017) but also in humid areas (Meissner et al., 2007; Xiao et al., 2009; Groh et al.,2018a). As a typical semi-arid region, the summer monsoon transition zone (SMTZ) in China is an ecologically fragile region in the Asian summer monsoon system. Therefore, NRW in this area is of great significance for ecology and water resource utilization.

Compared to rainfall, NRW has more particular ecological and climatic effects on the SMTZ in China. As a factor in sustaining productivity in arid/semi-arid environments (Kaseke et al., 2017), rainfall in the SMTZ occurs mainly in the summer monsoon period from June to September. By contrast, NRW appears throughout the year, occurring even more frequently than that of rainfall during the non-monsoon period, and can therefore reduce the internal water deficit of plants and supplement plant water content during the non-monsoon period, which is a key period for conserving moisture and the sowing date of winter

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wheat. Moreover, the efficiency of absorption and utilization of NRW is much greater than that of rainfall (Kidron et al., 2000, 2011). It plays a crucial role over the semi-arid/arid regions of the SMTZ where precipitation is critically low, as far as plant water requirements are concerned. NRW is also an important water source for the survival of insects and small animals in desert regions (Wang et al., 2016). Furthermore, in simulations, soil moisture often dries too quickly in numerical models involving the arid/semi-arid regions of the SMTZ (Sakaguchi and Zeng, 2009), which we assume is closely related to neglecting the contribution of NRW. Therefore, NRW has important effects on soil water and ecological systems, especially over the arid and semi-arid regions of the SMTZ. The NRW variation and the relationship between NRW components and impact factors deserve special attention in water resource management and agro-ecological planning over the unique climatic and environmental region of the SMTZ.

Among the different NRW components, it remains difficult to measure the amounts of soil distilled water, capillary water, and guttation. Although the amounts of fog water, dew, and WVA cannot be measured directly by instruments, they can be estimated by observation and analysis (Agam and Berliner, 2004, 2006). As fog rarely occurs in the SMTZ of China, dew and WVA are the two most important NRW components there, and of the two, dew has been researched more in depth. Previous studies have shown that dew is formed by the condensation of water vapor in the atmosphere when the surface temperature is lower than the dew-point temperature (Agam and Berliner, 2006; Uclés et al., 2013). The earliest exploiting of dew can be traced back to the 16th century (Beysens et al., 2001), and the number of dew studies has increased gradually since the middle of the 20th century (Monteith, 1957; Garratt and Segal, 1988; Jacobs et al., 2000; Kim and Lee, 2011). The methods for observing dew have improved from artificial condensation surfaces to actual underlying surfaces (Zhang et al., 2011b). The conditions for dew to form and the effects of dew have been studied in many locations worldwide. A study in Athens (Malek et al., 1999) reported dew formation at levels of 0.068–0.09 mm/day. In the dry climate of Morocco, Lekouch et al. (2011) reported an average daily amount of 0.1 mm/day, while the maximum diurnal amount of dew for the semi-arid area of the Loess Plateau can reach 0.3 mm/day (Wang et al., 2016). Zhang et al. (2009) found that dew on the crust surface in the Gurbantunggut Desert of China was 0.1 mm/day. The maximum amount of dew reported in the literature was 0.8 mm/day as observed in the U.S. by Kabela et al. (2009), although the author states that this value may be overestimated. It is significant that the amounts of dew reported in various areas worldwide vary widely. The effect of dew on the overall water balance is very important in arid and semi-arid areas (Zhang et al., 2015). The total amount of NRW in humid areas is larger than that in arid and semi-arid area, accounting for about 5% of annual precipitation (Jacobs et al., 2006; Meissner et al., 2007, Groh et al., 2018a; Xiao et al., 2009). Still, the ecological and hydrological role of NRW should not be ignored in humid areas.

Compared to dew, there has been less research previously into WVA, but some primary knowledge does exist; for example, WVA is the direct absorption of water vapor from the air by soil (Agam and Berliner, 2006). Due to the limitations of current observation and measurement techniques, the magnitude of this absorption can only be estimated indirectly. Kosmas et al. (1998) showed that WVA is one reason for the diurnal variation of soil moisture. During an eight-month observation period, the total amount of WVA was observed to be 226 mm, whereas the rainfall in the same period was only 179 mm. By analyzing data collected from an inshore desert, Agam and Berliner (2004) concluded that the surface of bare soil supports very little dew and that WVA is the actual reason for the diurnal variation of soil moisture. Verhoef et al. (2006) studied WVA in the south of Spain and found that the amount of WVA accumulated in one day could reach 0.7 mm. Those previous studies indicate that WVA is important in arid and semi-arid areas.

Influence factors of NRW are the premise to calculating NRW's amount and also help to understand the formation mechanism of NRW. Some results show that not only air temperature, humidity, wind speed and cloud cover are important for NRW occurrence (Muselli, et al., 2002; Wang and Zhang, 2011; Xiao et al., 2013), but also daily amplitude of relative humidity (RH), soil structure, soil water content and soil temperature (Kosmas et al., 2001; Verhoef et al., 2006; Zhang et al., 2015).

Some studies involved the ecological relevance of NRW for crop growth so far, which mostly appeared in dew research. In general, dew has two different effects on crops; on the one hand, it can help recover the crops state due to water loss (Went, 1955; Nikolayev et al., 1996; Agam and Berliner, 2006) by increasing the water use efficiency (Ben Asher et al., 2010); on the other hand, dew also provides a moist environment for pathogens that may lead to the spread of crop diseases (Zuberer and Kenerley, 1993; Wilson et al., 1999). There are almost no results about the influence of WVA on crop growth. In the aforementioned, more results have pointed out that dew has advantages and disadvantages for the growth of summer crops, while the role of dew in winter and spring has not been studied.

Due to the difficulty in observing NRW components, a comprehensive understanding relationship between these components is not sufficient; NRW's contribution to land water balance and the role of NRW for crop water supply is not clear so far, especially in the SMTZ with particular rainfall and crop water requirements. To date, insufficient research attention has been paid to NRW and little research has been done on the integral characteristics of NRW. In the present paper, we address the following three main questions. 1) What are the overall performance and matching characteristics of NRW components, and how do the characteristics of NRW vary with impact factors in the SMTZ of China? 2) What is the relationship between NRW components and climatic and environmental factors? 3) How does NRW affect LSW balance and crop water supply in the SMTZ? In order to answer these questions, on the basis of effective NRW components obtained by a combination of lysimeter measurements and micro-meteorological observations, the present study begins by analyzing how climatic and environmental factors contribute to NRW formation. The discussion then progresses to how NRW contributes to the balance of water and surface energy in the SMTZ. Finally, the effect of NRW on crop water supply in the SMTZ is explored. The results provide a better understanding of the characteristics of NRW in the SMTZ and serve as a reference for water resource management and agricultural planning services and also for considering parameterization NRW in numerical modeling.

2. Materials and methods

2.1. Observation site

The data used in this study was collected from Dingxi Observational Station (35°33′22″N, 104°35′37″E). Dingxi is located in the SMTZ of China (Fig. 1a), which is in a typical loess foothill environment in a semi-arid region (Fig. 1b). The average annual precipitation there is 380 mm, making it prone to drought given the critical state of crop and ecological water requirements. Rainfall is concentrated in the period of May to October, providing almost 90% of the annual amount. The temperature difference between day and night is relatively large, with an annual average temperature of 6.7 °C and an annual potential evaporation of 1536 mm. The region is dominated by northwesterly wind in winter and spring but experiences mainly southeasterly wind in summer and autumn, as is typical of a semi-arid region. The station is located approximately 5 km from the edge of an urban area, with an elevation of 1860 m (Fig. 1b).

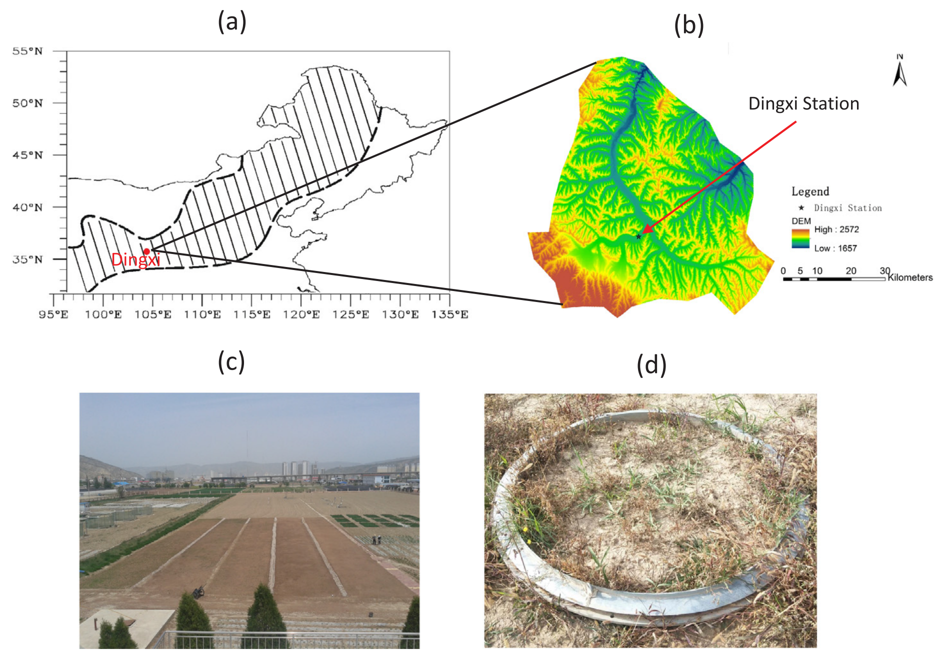

Fig. 1. (a) Summer monsoon transition zone (SMTZ) of China (shading area). (b) Terrain of Dingxi. (c) Environment of Dingxi Station. (d) Large lysimeter.

2.2. Observation data

The primary meteorological elements observed at Dingxi (Fig. 1c) are wind, temperature, and humidity gradients (1/2/4/10/16 m) with a sampling rate of every 10 min in the surface layer. We used HMP45D sensors to measure the air temperature and humidity, WAA151 sensors to measure the wind speed, and WAV151 sensors to measure the wind direction (all from Vaisala Corporation, Finland). Radiation fluxes including global radiation, reflected radiation, and upward and downward long-wave radiation were measured by a set of radiometers (PIR & PSP; Eppley Inc., USA) at a height of 1.5 m with a sampling rate of every 10 min. Soil temperature (0/5/10/20/30/40/50/80 cm, model 107-L; Campbell Scientific), soil heat flux (5 cm, model HFP01; Hukse-flux, Netherlands), soil moisture (10/20/40/50/80 cm; model CS616; Campbell Scientific) with a sampling rate of every 20 min, and rainfall (TE525MM; Campbell Scientific) with a sampling rate of every 10 min were also measured. Land-surface actual evapotranspiration (ET) and NRW were measured with a large lysimeter (Fig. 1d) to an accuracy of 0.03 mm and a sensitivity of 0.01 mm. When the lysimeter data is less than the accuracy, the data is considered low quality data. The diameter of the lysimeter was 2.25 m and the effective evapotranspiration area was 4.0 m^2 at a depth of 2.65 m; data was recorded every hour. Evapotranspiration during twilight and night (Tolk et al., 2006; Groh et al., 2019), which can be considered to be an opposite water flux to NRẂs at night, naturally limit the occurrence of NRW. Using hourly values in our analyses, to a certain extent, might lead to an underestimation of NRW.

2.3. Data processing

The observation period was from 1st June 2004 to 31st May 2005. Hourly data was used to calculate the distribution of NRW, whilst monthly mean data was used to calculate the rate of NRW. Hourly data was then converted to monthly data by simple arithmetic averaging; namely, the value of every hour data in a whole day divided by 24, in order to obtain a daily mean value. The exception to this was the amount of rainfall and NRW which was calculated by a sum of every hour in a day. Then, in order to obtain monthly data, every daily mean value in a month divided by number of days (28, 30 or 31). The occurrence frequency of NRW was the simple arithmetic averaging of WVA and dew. The lysimeter was calibrated on May 23rd-24th 2004 to ensure data quality. The sampling frequency of lysimeter data was hourly. Lysimeter data pre-and post-processing was needed to reduce the impact of noise on the determination of water balance components from lysimeter observations (Hannes et al., 2015; Peters et al., 2017, Pütz et al., 2016; Gebler et al. 2015; Groh et al. 2018b, Herbrich et al., 2017). The data filtered (Hannes et al., 2015) was adopted in this paper. The proportion of efficiency data after filtering is about 71%. Firstly, the data during rainfall, snowfall and sandstorm periods were removed. Secondly, outliers during unreliable periods were eliminated by visual detection. Then, a threshold filter was implemented to remove the unrealistic data. The threshold value in this paper was set to 0.08 mm/h which based on the literature results (Kabela et al., 2009); the data greater than 0.08 mm/h was eliminated. Finally, we extrapolated short-term missing data by the linear trend interpolation method. Namely, when a quantity was once an hour or twice in two hours, the linear interpolation was adapted by using 2 adjacent points average according to the linear changing trend of quantity. There is no imputation for long-term missing data. The same data have been applied (Zhang et al., 2011a, 2015). Note that Beijing Time (BT) was used for all the data herein. The specific method used to estimate the NRW from the lysimeter data is described in Section 2.4. All observation data was quality controlled.

2.4. Determination of NRW component of land surface water

In addition to precipitation, NRW is also an important component of LSW. Previous studies have showed that the LSW balance should include the component of NRW (Fig. 2a). An important reason for this is that the technology for observing NRW is not yet fully developed. The most reliable way to observe and measure NRW is by means of a lysimeter (Van de Griend and Owe, 1994). However, this also needs to be combined with micro-meteorological and conventional meteorological observation data, in order to distinguish between different types of NRW observed with lysimeter weight changes. Herein, we use the method described in Fig. 2b to calculate the NRW.

2.5. Several definitions

The NRW component observed by a weighing lysimeter can be

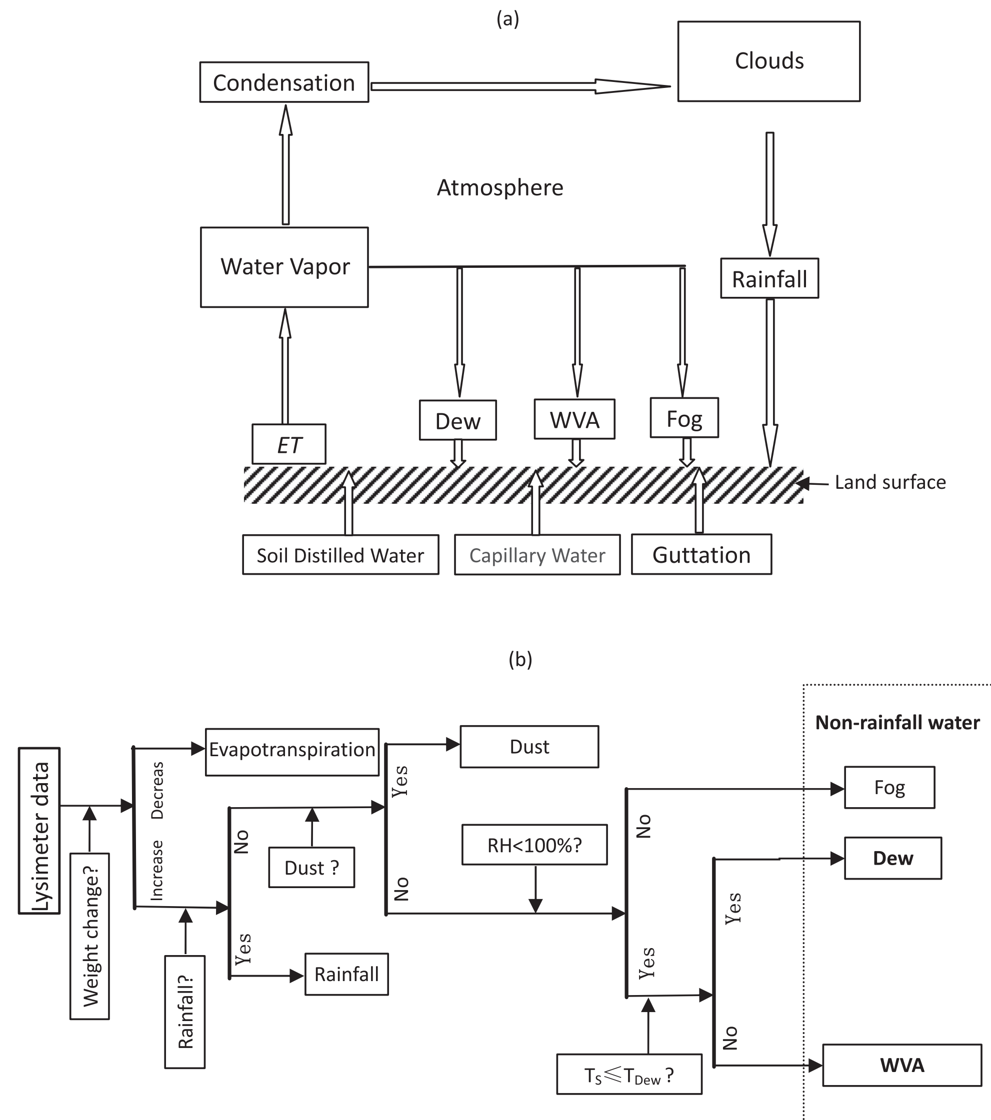

Fig. 2. (a) Schematic of land surface water (LSW) cycle. (b) Flowchart used to estimate NRW component (*ET* is evapotranspiration, *RH* is air relative humidity, *Ts* is surface temperature, T_{dew} is dew-point temperature).

expressed as

$$W_{nrw} = 1000 \times \sum_{i=0}^{i=T} \Delta w_i/(\rho_w \times S_p), \tag{1}$$

where W_{nrw} is the amount of dew or WVA [mm], ρ_w is the density of water [kg/m^3], w_i is weight value as NRW occurrence [kg], Δw_i is the instantaneous NRW value observed by the lysimeter [kg] (when there is no NRW, we have $\Delta w_i = 0$), i is the series number of the instantaneous value at each 60-min interval, S_p is the lysimeter surface area [m^2], and T is the length of time for each data sampling [s]; herein we assume $T = 3600$ s (i.e., 1 h).

Based on the above statement, it is easy to calculate the various statistics of the NRW component. The average diurnal variation of the amount of NRW can be calculated as

$$w_{nrw}(j) = (\sum_{k=1}^{365} w_a(k, j))/365 \tag{2}$$

where j is the hour number of each day (ranked from 1 to 24), $w_{nrw}(j)$ is the dew amount or WVA amount at hour j [mm], k is the sequence of days from 1 to 365, and $w_a(k, j)$ is the dew amount and WVA amount of hour j on day k. The frequency of occurrence of the NRW's average diurnal variation can be calculated as

$$f_{nrw}(j) = (N_d(\text{j})/365) \times 100\% \tag{3}$$

where $f_{nrw}(j)$ is the frequency of occurrence of NRW at hour j as a percentage. N_d(j) is the number of days with the formation of NRW at hour j in the whole year, i.e., fewer than 365. Similarly, the monthly amount of NRW in one year can be calculated as

$$w_{nrw}(s) = \sum_{k=1}^{H(s)} w_a(s, k) \tag{4}$$

where $w_{nrw}(s)$ is the amount of NRW in month s [mm], k is the sequence of the hour number of month s, $H(S)$ is the number of hours in month s (which differs each month but is never greater than 24 × 31), and $w_a(s, k)$ is the amount of NRW in hour k of month s. The frequency of occurrence of monthly NRW in one year can be calculated as

$$f_{nrw}(s) = (M_m(s)/M_0(s)) \times 100\% \tag{5}$$

where $f_{nrw}(s)$ is the frequency of occurrence of NRW in month s as a percentage, $M_m(s)$ is the day number for the occurrence of NRW in month s [which is less than $M_0(s)$], and $M_0(s)$ is the number of days in month s (which differs each month but never exceeds 31). Finally, The rate of NRW occurrence is calculated as:

$$R_{NRW}(s) = A_m(s)/M_0(s), \tag{6}$$

where $R_{NRW}(s)$ is the rate of NRW occurrence (mm/d), $A_m(s)$ is the daily average amount of NRW in a month, $M_0(s)$ is the number of days in month s.

In addition, when calculating the climatic factor gradient, it is expressed as (4 m–1 m) in our text if we calculated a variable gradient at 4 m minus that at 1 m. For example, the gradient of relative humidity between 4 m and 1 m was expressed “(4 m–1 m) relative humidity difference” in this manuscript. The same is applied to soil temperature and soil moisture. Then, these factors are average divided into 3–5 groups in principle. For example, the soil moisture range is about from 0.15 (m^3/m^3) to 0.5 (m^3/m^3). But few values are near 0.15 (m^3/m^3) or 0.42 (m^3/m^3), groups were set arbitrarily to 3 for soil moisture < 0.25, 0.25–0.35, and > 0.35. It is similar to other impact factors.

3. Results

3.1. Diurnal and annual characteristics of NRW

Variation characteristics of dew and WVA must differ because climatic and environmental factors produced different effect on dew and WVA. As shown in Fig. 10, the timings of the peak values of WVA and dew clearly differ, with the peak value of dew occurring at night and the peak value of WVA occurring at 14:00, while the mean NRW diurnal variation fluctuated very little (Fig. 3a). The maximum amount of dew occurred between 16:00 and 09:00 the following morning because dew can only occur when the surface temperature is below the dew-point temperature. The surface temperature cannot be below the dew-point temperature during the day, and consequently dew cannot occur from 09:00 to 16:00. The soil becomes relatively dry because of comparatively strong evaporation in the morning, and the attraction between soil particles and water molecules is strongest at that time. Consequently, this leads to WVA being easier to occur and a high level of adsorption in the afternoon. This indicates that diurnal variation of dew and WVA exists in a good complementarity which maintains a steady daily amount of NRW. The diurnal variations of occurrence frequency of dew, WVA, and their sum are consistent with the diurnal variations of their amounts (Fig. 3b), though the WVA occurrence frequency is greater than that of dew.

The maximum amount of dew (~7 mm) occurred in October of non-monsoon season and the minimum occurred in June of monsoon season, when no dew formed (Fig. 4a). This pattern occurred because in autumn, following the temperature decrease, the large diurnal temperature difference and sufficient water–vapor conditions created the most beneficial conditions for dew condensation. In June, it was unlikely that the surface temperature would decrease to below the dew-point temperature, which, together with the lack of water vapor in the semi-arid environment at this time, prevented the formation of dew. The peak WVA (4.8 mm) occurred in November while the minimum occurred in June. For most of the year except from June to September, the region with the highest WVA had the lowest formation of dew and vice versa. This reflects their different formation mechanisms and also indicates their mutually complementary relationship. The total amount of NRW was 52 mm during the whole year, which represented the effective water supply to the semi-arid climate region of the SMTZ, especially in the dry non-monsoon period.

The monthly WVA occurrence frequency was very high (Fig. 4b). The maximum value was 25 days for November, whereas the monthly

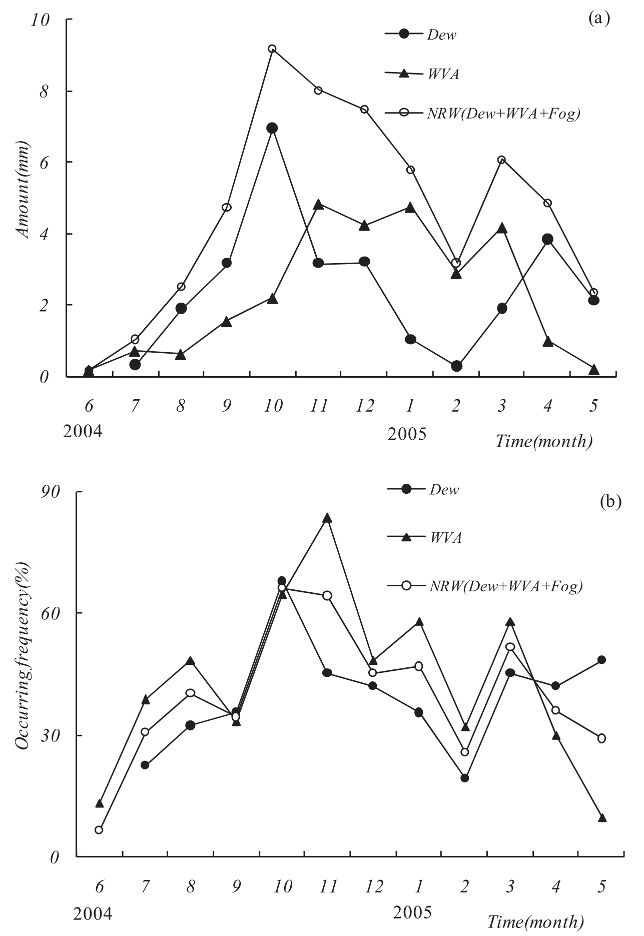

Fig. 4. (a) Annual variations of NRW components. (b) Annual variation of NRW occurrence frequency.

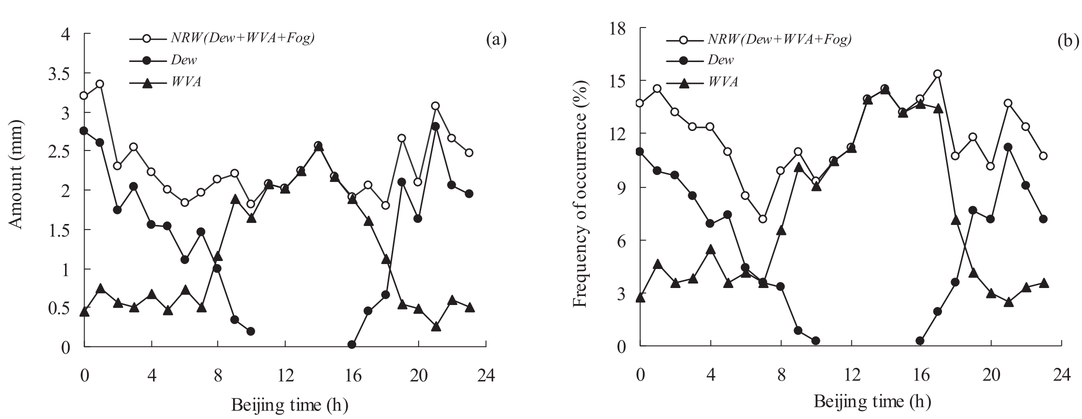

Fig. 3. Mean diurnal variations of NRW: (a) amount and (b) occurrence frequency.(note: amount of NRW is a sum amount of Dew, WVA and Fog; the frequency of NRW is the average frequency of Dew WVA and Fog).

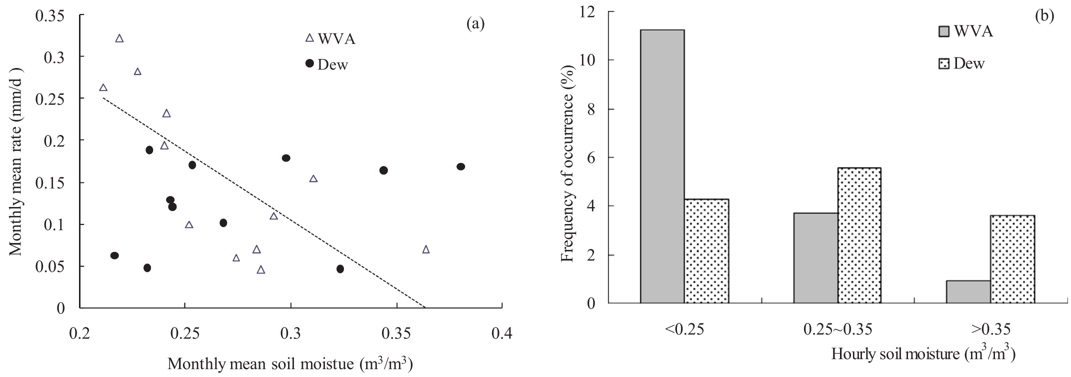

Fig. 5. (a) Relationship between monthly mean rate and monthly mean soil moisture at 5 cm (note: Mean rates represent daily average rates per month, the same is true in other Figures. The dotted line illustrates the trend line of WVA's mean rate. Dew's trend line is not drawn as correlation coefficient is less than 0.5) and (b) distribution of NRW occurrence frequency with soil moisture at the depth of 5 cm.

frequency of occurrence of dew was relatively low. The annual number of days on which absorption occurred was 152, whereas it was 135 days for the occurrence of dew; thus, WVA was more likely to occur than was dew. Although their phases are asymmetric, some complementarity exists.

3.2. Relationship between NRW and climatic and environmental factors

The mean rate of WVA shows an obvious decrease when the soil moisture increases (correlation coefficient r = 0.74) (Fig. 5a), which is consistent with that frequency. There is no clear trend from mean rates of dew when the soil moisture increases. Fig. 5b also shows this. The WVA occurrence frequency was greater when the soil was drier, less than 0.25 (m^3/m^3), with the maximum value being close to 12%. The dew occurrence frequency was highest when the soil moisture ranged from 0.25 to 0.35 (m^3/m^3) with the maximum being just 5.6%. There were small differences between the different soil moisture intervals.

With regard to the thermodynamic state, mean rate variation of dew with surface temperature does not show obvious an trend, whereas that of WVA with surface temperature decreases and their correlation coefficient is 0.82 (Fig. 6a). It indicated that the rate does not reflect the relationship between NRW and surface temperature. From Fig. 6b, it can be seen that WVA occurrence frequency did not change significantly with surface temperature, but there was an obvious change in the dew occurrence frequency. The dew occurrence frequency was highest at 10% when the surface temperature ranged from 0 °C to 10 °C, but this decreased when the surface temperature exceeded 10 °C. It is a remarkable fact that frequency of frost occurrence is also about 5%, which exceeds the frequency of dew in summer.

The available energy (difference between net radiation (R_n) and soil heat flux (G)) on the land as the main source of energy for water molecules on the soil surface determines the energy state of WVA or evaporation (condensation) processes to some extent, and is the most important condition influencing WVA or evaporation (condensation) processes. The rate of dew is evidently different from that of WVA, the former occurs mainly below 0 W/m^2, and the latter is mainly above 0 W/m^2. It shows that energy required for dew and WVA to occur are completely different (Fig. 7a). This just reflects the complementary characteristics of dew and WVA. It seems completely different from Fig. 7b. In fact, their trend is consistent if Fig. 7b is divided into two intervals: less than 0 W/m^2 and greater than 0 W/m^2. Phase change in the condensation process releases heat, and the adsorption process converts the internal energy of molecules into heat energy and then releases it. Thus, when the available energy was negative, the amount of dew reached the maximum of 24.8 mm. When the range of available energy was 0–150 W/m^2, evaporation was likely to occur and the amount of WVA evidently decreased. By contrast, the decrease in the amount of dew was more rapid in this range, when the energy was 0–150 W/m^2, evaporation was likely to occur and the amount of WVA evidently decreased. On the other hand, the quantity of dew decreased rapidly in this range, with the quantity of dew being less than 1 mm, which was almost negligible. This range of 0–150 W/m^2 in fact represents the alternating stage of WVA occurrence and evaporation

processes, in which the strength or weakness of the attraction between soil particles and water molecules, compared to the counter-attraction provided by the available energy to water molecules, was the key factor in the occurrence of evaporation or WVA (or condensation).

WVA predominantly occurs when the soil moisture gradient is small. The rate of WVA drops sharply when the soil moisture gradient increases. Both Fig. 8a and 8b show an increase after decreasing while dew occurs with the increase of soil moisture gradient. WVA occurred mainly where the soil moisture difference was less than 0.05 (m^3/m^3)

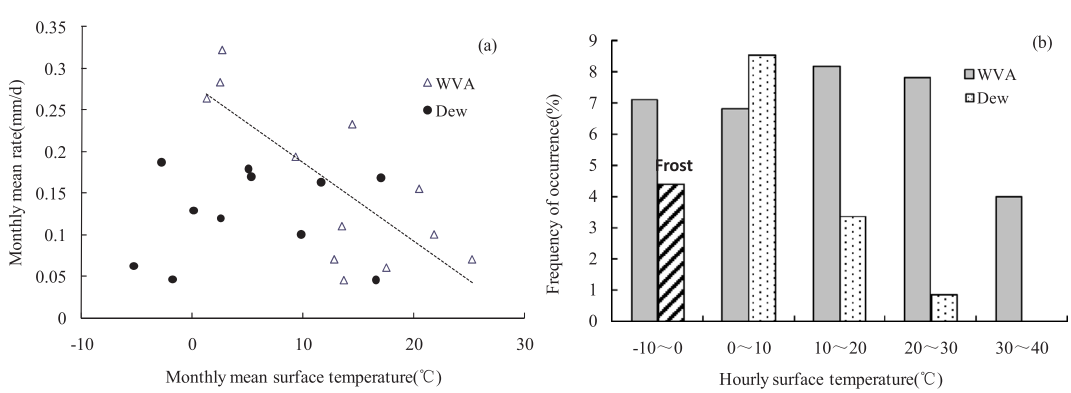

Fig. 6. (a) Relationship between monthly mean rate and monthly mean surface temperature (The dotted line shows the trend line of WVA's mean rate. Dew's trend line is not drawn as correlation coefficient is less than 0.5) and (b) distribution of NRW occurrence frequency with hourly surface temperature.

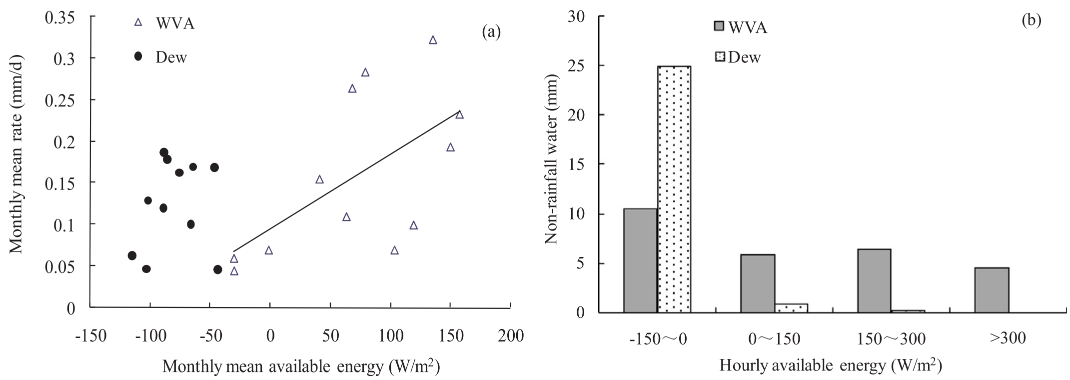

Fig. 7. (a) Relationship between monthly mean rate and monthly mean available energy (The dotted line shows the trend line of WVA's mean rate. Dew's trend line is not drawn as the correlation coefficient is less than 0.5) and (b) distribution of NRW's amount with hourly available energy.

and occurrence frequency exceeded 8%, which was mainly due to the low soil moisture of the surface soil. Over the range of soil moisture investigated, the dew occurrence frequency was low in the middle part of the range. When the difference in soil moisture was 0.025–0.05 (m^3/m^3), the dew occurrence frequency was minimal. However, it increased gradually with soil moisture, with the maximum occurrence frequency (almost 8%) in the range 0.075–0.1 (m^3/m^3). The influences of environmental factors on each NRW component differ, overall showing complementary characteristics; that is to say, the high value area of dew matches the low value area of WVA, and vice versa.

There are different soil temperature gradients as WVA and dew occur, and the boundary gradient is at about 2 °C (Fig. 8c). The occurrence frequency also indicates the characteristic (Fig. 8d). That of WVA was highest when the gradient of (10 cm-0 cm) soil temperature ranged from − 15 °C to −10 °C, reaching 17.4%. However, the frequency was very low when the gradient was colder than −15 °C or warmer than 0 °C. In short, the rate of dew and WVA is controlled by different soil hydrothermal conditions.

Atmospheric wind, the temperature, humidity of the surface layer and their vertical gradients determine the water-vapor source and transmission of NRW. Of these parameters, the relative humidity has a very significant influence on NRW. The rate of WVA decreases, but dew increases with the increase of RH (Fig. 9a). WVA occurs mainly when the relative humidity is 6–50%, with occurrence frequency of over 10% (Fig. 9b). WVA decreases significantly at higher RH, with an occurrence frequency of less than 4%. It is consistent with Fig. 7a. This indicates that it would be difficult to meet the necessary water–vapor conditions for the occurrence of adsorption if the atmosphere was too dry. If, on the other hand, the atmosphere was too wet, fog and dew would form easily, which would restrain the adsorption of water vapor. Dew occurs

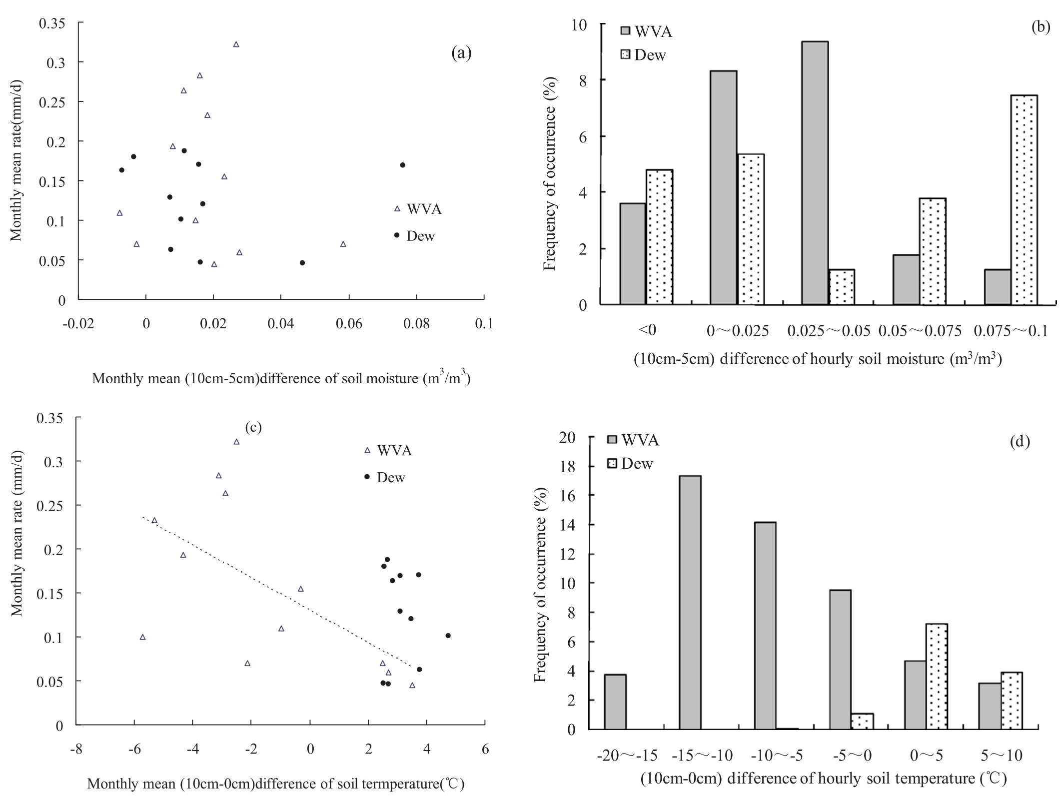

Fig. 8. (a) Relationship between monthly mean rate and monthly mean difference of soil moisture in 5–10 cm layer (No trend line is drawn as correlation coefficients of WVA and dew are less than 0.5) and (c) monthly mean difference of soil temperature in the 0–10 cm layer (The dotted line shows the trend line of WVA's mean rate. Dew's trend line is not drawn as correlation coefficient is less than 0.5); Distribution of NRW occurrence frequency with difference of hourly soil moisture in the 5–10 cm layer (b) , and difference of hourly soil temperature in the 0–10 cm layer(d).

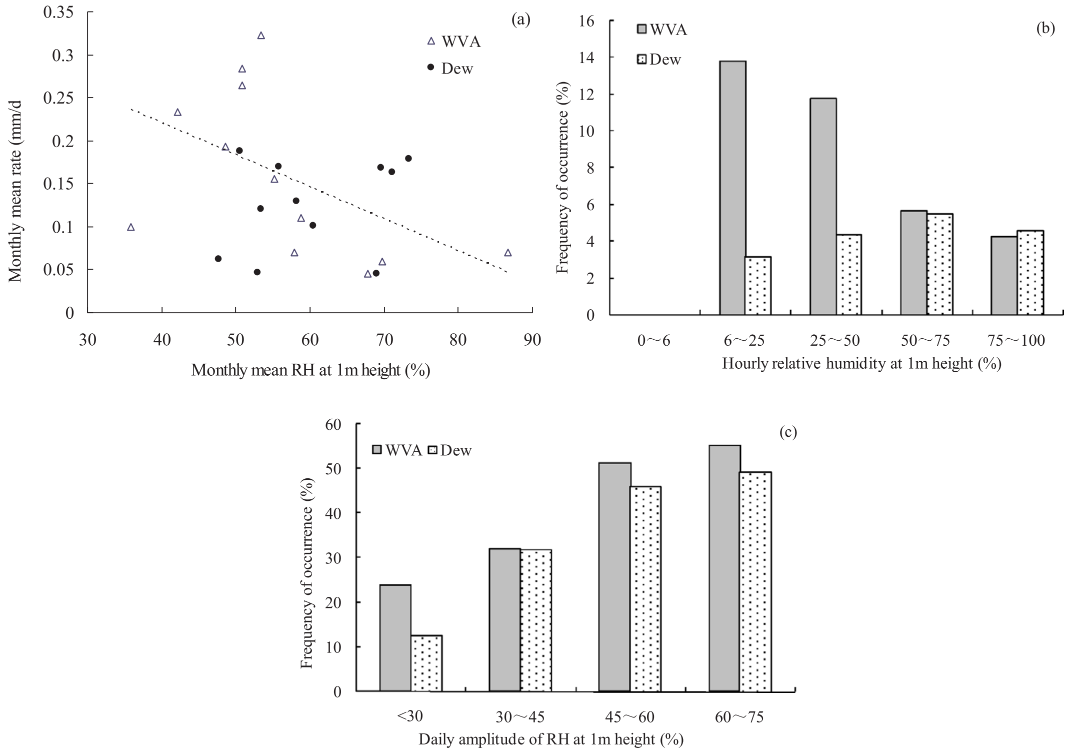

Fig. 9. (a) Relationship between monthly mean rate and monthly mean RH (The dotted line illustrates the trend line of WVA's mean rate. Dew's trend line is not drawn as correlation coefficient is less than 0.5), distribution of NRW occurrence frequency with hourly RH (b) and (c) daily amplitude of RH at the height of 1 m.

mainly when the relative humidity exceeds 50%, but the dew occurrence frequency is lower than that of WVA. It also shows the complementary characteristics which is similar to that in Fig. 8.

NRW is also related to the daily amplitude of relative humidity in the surface layer (Fig. 9c). The adsorption rate of water vapor and the condensation rate both raise with an increased daily amplitude of relative humidity, and therefore daily amplitude of relative humidity has an effect on the generation of WVA and dew. For WVA, an increased daily amplitude of relative humidity means that the minimum daily relative humidity decreases. For dew, increased daily amplitude of relative humidity means that the maximum daily relative humidity increases, thereby facilitating the condensation process.

The variation of the RH gradient of the surface layer had a complex influence on NRW. It is shown that WVA increases with the increase of RH gradient in Fig. 10a and 10b. When RH at the heights of 1 m was greater than that of 4 m, both the rate and occurrence frequency of WVA were very low, the converse was high, at approximately 12% of the frequency. This indicated that a weak humidity inversion in the surface layer favored the process of soil WVA. For condensation, the frequency of dew in Fig. 10b shows the trend of first increasing and then decreasing. It seems that this trend also exists in Fig. 10a, but the dispersion is too large to draw the trend line effectively. When the RH gradient was negative, the dew occurrence frequency was higher than that under a positive humidity gradient. A weak humidity inversion results in dew occurrence frequency being decreased. This is also consistent with the temperature-gradient relationship.

Fig. 10c shows a good complementary relationship between dew and WVA, wherein WVA mainly occurs in the interval where the temperature gradient is less than 0, and dew mainly occurs in an interval of that > 0. When the temperature gradient in the surface layer ranged from −1 °C to 0 °C, the occurrence frequency of WVA reached a maximum of 12% (Fig. 10d). This indicates that the temperature gradient of the surface layer facilitates adsorption simultaneously. However, adsorption still occurs and condensation increases when there is a weak temperature inversion in the surface layer of the atmosphere. It indicates that a weak temperature inversion is more important for dew than that for WVA. When the temperature gradient ranged from 0 °C to 2 °C, the dew occurrence frequency was high (> 6%) and that of WVA became weaker, thereby enabling dew and WVA to occur simultaneously. It is more common for the two processes to supplement each other.

Wind speed is another important factor that was found to influence NRW. The influence of wind speed on dew and WVA also shows complementary characteristics (Fig. 11). An adequate wind speed facilitates the transmission of water vapor in the surface layer towards the surface, and increasing the wind speed also increases the downward heat flux, keeping the surface warmer. It is beneficial to forming dew; however, But an excessive wind speed will increase evapotranspiration and water–vapor loss from the surface layer, resulting in decreased dew, and then low soil moisture increased WVA. It is shown that negative feedback exists between wind speed and dew occurrence but positive feedback exists between wind speed and WVA occurrence.

3.3. *Contribution of NRW to water balance and role of NRW in non-monsoon period*

As can be seen from the contribution of NRW to LSW balance (Fig. 12a), Rainfall remains the leading component of the annual LSW balance in SMTZ, accounting for 85% of the evapotranspiration (ET, which is calculated by lysimeter data). The amounts of dew and WVA are of the same order, accounting for approximately 10% of evaporation, with fog making the lowest contribution to the water balance of just 1.3 mm, which is completely negligible. Additionally, there is still a 4.6% difference, which is called “Others” (Fig. 12b). The possible main factors covered by the category “Others” are (i) the LSW deficit caused by climate warming and drying, thereby leading to water imbalance; (ii) instrumental error. However, it should be noted, this category accounts for only 4% of evaporation which meets the needs of the overall water balance. NRW accounts for approximately 10% of the overall contribution to evapotranspiration. This also shows that the role of

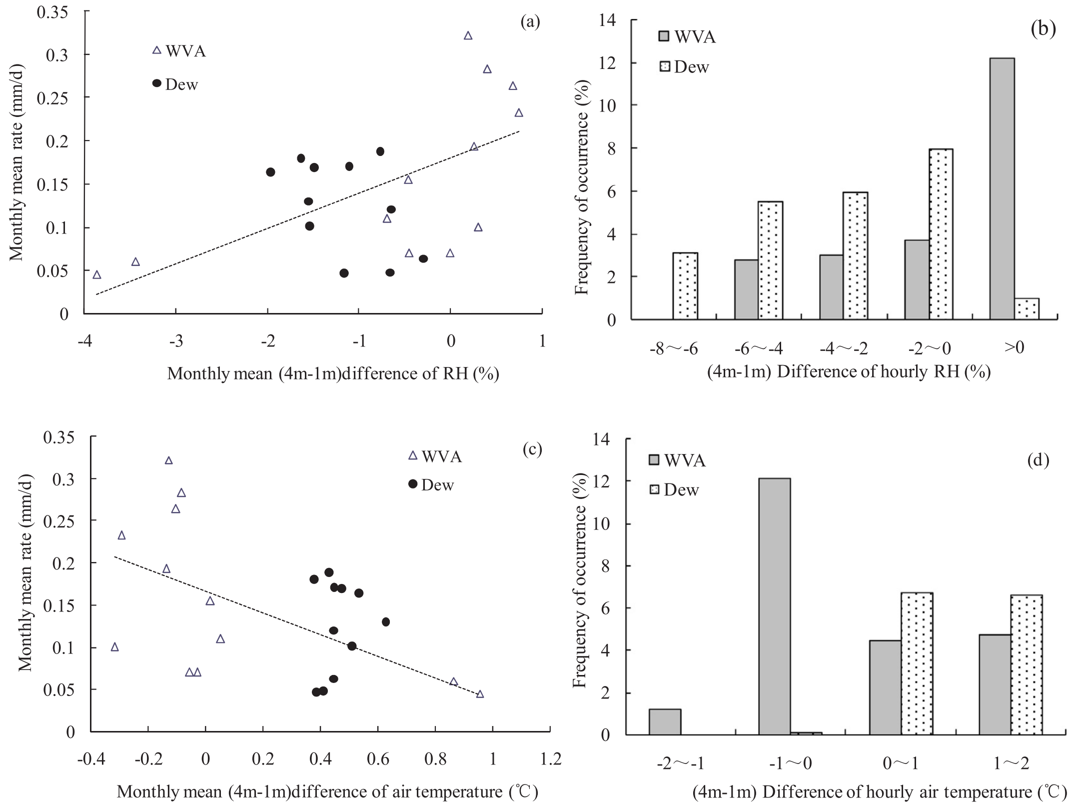

Fig. 10. Relationship between monthly mean rate and monthly mean difference of (a) RH of 4 m-1 m, and (c) monthly mean difference of air temperature (The dotted line illustrates the trend line of WVA's mean rate. Dew's trend line is not drawn as correlation coefficient is less than 0.5); Distribution of NRW occurrence frequency with (b) hourly relative humidity difference of (4 m-1 m), and (d) hourly air temperature difference of (4 m-1 m).

NRW in the water balance cannot be ignored in the SMTZ of China.

Although NRW is not dominant in LSW, it plays a special role in the SMTZ of China. Its ratio relative to rainfall was high in the non-monsoon period (October–March), exceeding 2 and rising to 3.7 in November (Fig. 13), whereas the ratio was much lower in the monsoon period (May–September). The ratio of WVA to rainfall was also high in the non-monsoon period, exceeding 2, and the ratio for dew was also high in that period.

Moreover, spring wheat and winter wheat are the main grain crops in the SMTZ of China. Precipitation is very low, mostly close to zero, during the sowing and emergence of winter wheat in the non-monsoon period, which is not conducive to the emergence of winter wheat under dry soil. At this time, NRW alone provides the moisture required by crops, thereby reducing crop mortality at least. Even if during the greening period, which is the water requirement stage, NRW supplies water and is beneficial to the growth of winter wheat as the amount of NRW exceeds that of precipitation. In other words, NRW supplied the predominant water source in the highest growth period of winter wheat and partial growth stage of the spring wheat in non-monsoon period. Therefore, NRW plays an important and even decisive role in maintaining the survival of spring wheat and winter wheat in the non-monsoon period over the SMTZ of China.

The contribution of NRW to LSW can also be reflected from evapotranspiration (Fig. 14). Large ratios of NRW to evapotranspiration also occurred in the non-monsoon period, with all ratios being greater than 0.1 and rising to 0.51 in December. Consequently, large amount of NRW and weak evapotranspiration in the non-monsoon season resulted in the contribution of NRW to the LSW balance being more significant.

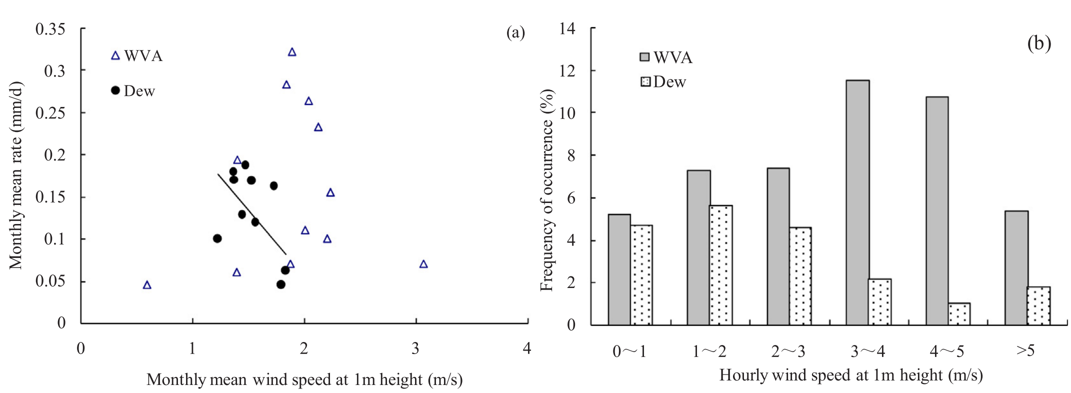

Fig. 11. (a) Relationship between monthly mean rate and monthly mean speed (The solid line is trend line of dew's mean rate. WVA's trend line is not drawn as correlation coefficient is less than 0.5) and (b) distribution of NRW occurrence frequency with hourly wind speed at the height of 1 m.

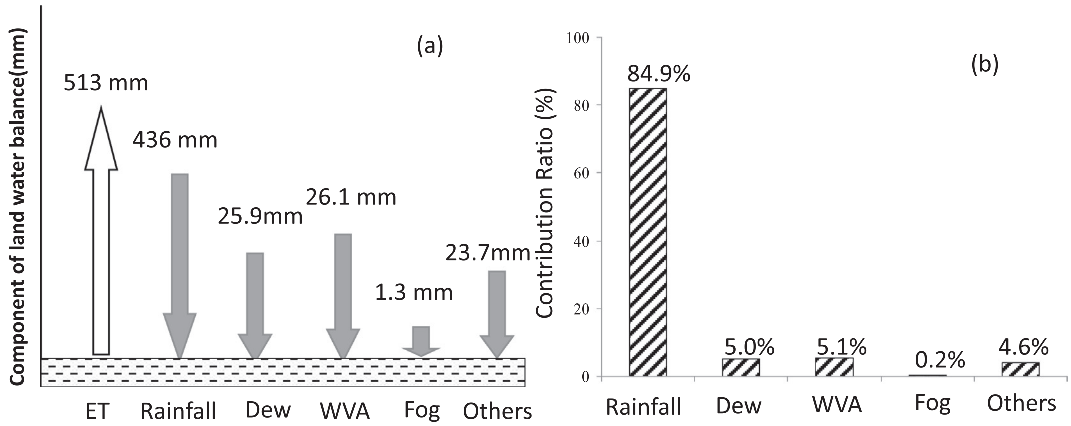

Fig. 12. (a) Amount of annual LSW balance component. (b) Ratio of NRW components and rainfall to evapotranspiration (ET).

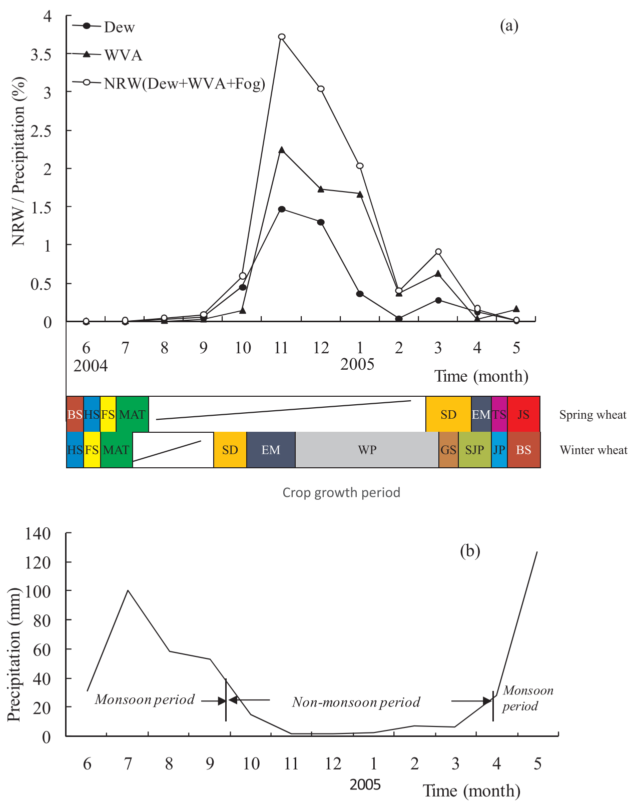

Fig. 13. (a) Variation of ratio of NRW to precipitation with crop growth period and (b) Precipitation during monsoon and non-monsoon period.

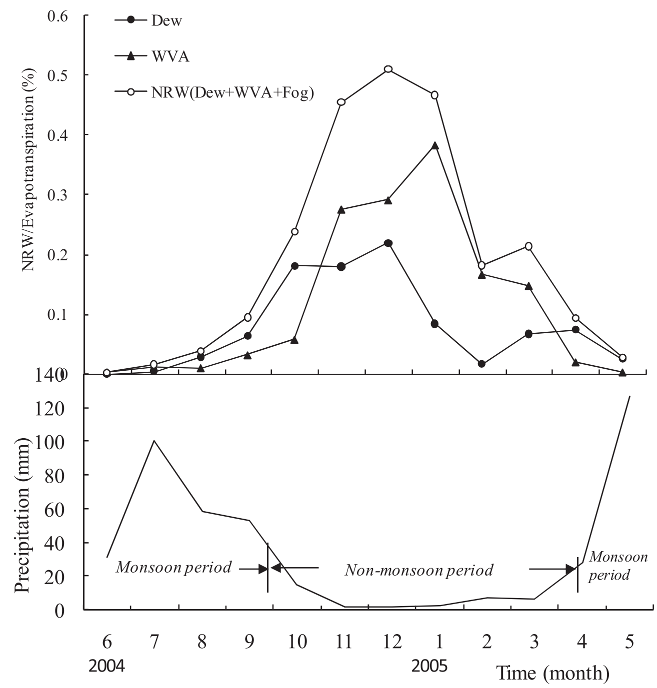

Fig. 14. Annual ratio of NRW to ET and precipitation during monsoon and non-monsoon period.

4. Discussion

4.1. Formation conditions of NRW component

Generally speaking, NRW is influenced mainly by local climate factors and environmental factors such as air temperature, relative humidity, wind speed, soil temperature and soil moisture et al. (Kosmas et al., 2001; Xiao et al., 2013). The present study makes it clear that different NRW components have different relationships with climatic and environmental factors. In particular, micro-meteorological elements such as wind speed, relative humidity, and moisture gradient have almost opposite effects on dew and WVA, which is reflected by their different formation mechanisms. Adsorption occurs readily which is consistent with the results (Agam and Berliner, 2006; Florentin and Agam, 2017). The occurrence of dew clearly depends on both humidity and temperature. Several authors has shown these factors effect on dew (Garratt and Segal, 1988; Xiao et al., 2013; Liu et al., 2018). The vertical gradients of soil moisture and temperature effect the transmission of water and energy as well as the dynamic characteristics of soil moisture and temperature (Gao et al., 2007). When the surface soil was warmer than the subsoil, the transmission of water from the subsoil to the surface soil was restrained, thereby facilitating the occurrence of WVA. An increase in the vertical gradient of soil temperature decreased WVA but increased dew formation. We attribute this to the increased vertical gradient of soil temperature as the surface cooled (Agam and Berliner, 2006).

In particular, a moisture inversion in the surface layer promoted the occurrence of WVA, whereas the occurrence of dew was favored under the opposite conditions. Dew occurred frequently when the relative humidity gradient was negative, but far less so when the relative humidity gradient was positive. WVA and dew condensation are two completely different kinds of physical mechanisms: the former is determined by the characteristics of the soil particles and atmospheric humidity, whereas the latter is influenced mainly by microclimate. In addition to the provision of water vapor, dew formation is controlled by the thermal state of the surface. WVA occurrence was in favor of a temperature gradient from −1 °C to 0 °C in surface layer. Both the rate and occurrence frequency of NRW indicate that there is a good complementary relationship between WVA and dew.

Evapotranspiration and WVA are also two inverse processes on the diurnal time scale: WVA occurs more favorably when the soil is dry, though the evapotranspiration process is dominant at this time. WVA can compete with evapotranspiration during the daytime.

WVA is more likely to occur under the following conditions: when the relative humidity of the surface layer is 6–50%, the wind speed is 3–4 m/s, the diurnal variation of relative humidity is large, humidity inversion and weak instability occur, the soil water content is low, and the surface temperature is not very high. We attribute a more humid environment being more favorable to the generation of dew (Wang et al., 2016; Zhang et al., 2015) because a weak humidity inversion in the atmosphere causes a water–vapor divergence in the bottom layer (Garratt and Segal, 1988). De Vries (1958) reported that WVA is dominant only when the relative humidity of the air around soil particles is less than 60%; when the relative humidity exceeds 60%, condensation is dominant. Zhuang and Ratcliff (2012) reported that a relative humidity of the surface layer of more than 80% facilitates the generation of dew. Kosmas et al. (2001) also reported similar results. On the other hand, dew is more likely to occur when the relative humidity of the surface layer exceeds 50%, wind speed is 1–2 m/s, diurnal variation of relative humidity is large and a weak inversion of the air temperature. The occurrence condition of dew is a little more different than that in humid areas (Liu, et al., 2018). Dew and WVA display obvious annual to seasonal variations: WVA occurs mainly by day with an annual peak in December, whereas dew occurs mainly in the evening with an annual peak in October; the minimum values of both parameters occur in June.

It should be noted that the rate of NRW is nearly consistent with their occurrence frequency. Small differences between them may be caused by their own incomplete meanings.

4.2. NRW's contribution to LSW balance and crop water requirements

In terms of the LSW balance, the NRW in the present study is no more than 15% of the LSW but is an important supplement to the SMTZ, where precipitation is critical for crop and ecological water requirements. The ratio of NRW to precipitation is close to the results of a Mediterranean semiarid steppe ecosystem (Uclés et al., 2014), larger than that of Haarweg Station in a humid region (Jacobs et al., 2006), but smaller than that in rice fields in a subtropical monsoon climate (Liu et al., 2018). The amount of NRW can reach 3.5 times that of the precipitation during the dry non-monsoon season, which coincides with the sowing date and the emergence of winter wheat. A previous study (Uclés et al., 2016) also showed that the contribution of NRW to the water balance during a dry period was 94%. In fact, NRW during the non-monsoon period is very important until the standing and jointing period of winter wheat and the emergence of spring wheat because rainfall is rare, during non-monsoon periods. NRW has a more prominent influence at that time. Some studies have shown NRW has an important impact on the recovery of crops after water loss (Went, 1955; Agam and Berliner, 2006), the growth of lichens (Zhang et al., 2009; Kaseke, et al., 2012) and the increased total biomass of plants (Zhuang and Ratcliff, 2012), but there are few results in studying the effects of NRW on the growth period of crops. This may be a field worth studying in the future. So NRW should be considered as a water resource in drought-prone SMTZ areas. An excellent complementarity exists between NRW and rainfall, thereby helping to alleviate seasonal droughts. Contribution of WVA to water balance is almost equal to that of dew in the SMTZ. In the dry season, the amount of dew and WVA significantly exceeds the contribution of precipitation to the water budget. NRW is of great significance to water resource management, agriculture and ecological planning.

A standard rain gauge was used to quantify the annual rainfall amount in this study. We knew this kind of rain gauge underestimates the amount of rainfall in comparison to rainfall obtained from lysimeter observations (Gebler et al., 2015; Hoffmann et al., 2016; Herbrich et al., 2017; Groh et al., 2018b). That affects NRW on contribution to precipitation at the annual scale. Until now, the contribution of NRW on precipitation might be overestimated because rain gauges underestimate precipitation and thus also increase the ratio of NRW on precipitation. Increasing the measurement frequency of lysimeter (e.g. recording lysimeter mass changes each minute) is a potentially successful method. Perhaps precipitation may be estimated based on lysimeter mass changes or a weighing rain gauge (Colli et al., 2014) with more observation points, thus reducing the underestimation of precipitation.

Additionally, climate warming and drying also influences LSW balance as it will change soil water. When soil water increases during a period of time, the ratio of NRW to ET will increase and then will overestimate the ratio of NRW to ET. On the contrary, it underestimates. However, the impact on LSW balance is limited (cf. “others” in Fig. 12).

Finally, to appreciate the specificity of NRW in the SMTZ, we require more extensive observations to improve our understanding of NRW characteristics and formation mechanisms in non-SMTZ regions.

5. Conclusion

In this work, components of NRW were analyzed scientifically through a combination of lysimeter measurements and micro-meteorological data. The impacts of environmental and meteorological conditions on NRW were analyzed, and the contributions of NRW to water balance were also investigated. NRW plays an important role in alleviating drought during the critical period of crop growth in the semiarid region of the SMTZ.

The climatic and environmental conditions of dew and WVA occurrence vary considerably. In terms of diurnal variation, WVA can occur at almost any time of the day, whereas dew occurs normally overnight and not during the day, and the period with the highest WVA has the lowest formation of dew and vice versa. Thus, there is good complementarity between dew and WVA on the diurnal scale. In terms of annual variation, the NRW amount during the non-monsoon period is evidently higher than that during the monsoon period. The annual total amount of NRW is a considerable water input to a region with a semiarid climate. Among the total amount of NRW, dew and WVA are very close, which are 25.9 mm and 26.1 mm, respectively. That contribution to annual precipitation is 5.9% and 6%, respectively. WVA is more likely to occur than dew. Thus, complementarity exists additionally on the annual scale. Furthermore, NRW dominates LSW during the non-monsoon period, which is vital for crop growth during that period. That NRW is an important supplement of rainfall (especially in the non-monsoon period) improves our knowledge about the LSW cycle.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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