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The daily evaporation characteristics of deeply buried phreatic water in an extremely arid region

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SUMMARY

Measurements of the daily evaporation characteristics of deeply buried phreatic water in an extremely arid area are reported. The results are used to analyze the mechanism responsible for water movement in the groundwater–soil–plant–atmosphere continuum. A closed PVC greenhouse was set up on Gobi land at the top of the Mogao Grottoes where phreatic water is more than 200 m deep. An air-conditioning unit and an automatic weighing scale were placed inside the greenhouse to condense and monitor phreatic evaporation and soil water changes in this extremely arid region. Soil temperature and humidity at various depths (0–40 cm) and other meteorological factors were also recorded on a sub-hourly basis. The relationship between evaporated water and soil water movement was analyzed by observing changes in soil weight, the condensate from the air-conditioning unit, and air moisture. The results show that phreatic water evaporation occurs from this deeply buried source in this extremely arid zone. The daily characteristics are consistent with the variation in the Sun's radiation intensity (i.e. both show a sinusoidal behavior). In the daytime, most of the soil water does not evaporate but moves to cooler sub-layers. In the afternoon, the shallow soil layer absorbs moisture as the temperature decreases. At night, an abundance of water vapor moves upwards from the sub-layers and supplements the evaporated and downward-moving moisture of the superstratum in the daytime, but there is no evaporation. The stable, upwardly migrating vapor and film water is supported by geothermy and comes from phreatic water, the daily evaporation characteristics of which changes according to soil temperature when it reaches the ground.

1. Introduction

An extremely arid region (EAR) generally refers to a place where rainfall is scarce and the climate very dry (Warner, 2004). However, strictly speaking, the effect of phreatic water should also be considered in defining an EAR (Tang et al., 2001). In a shallowly buried area, phreatic water is an important source of soil water. As a result of capillary action it can lead to high soil water content and strong phreatic water evaporation (Ninari et al., 2004; Shang and Mao, 2010). If the burial depth exceeds 6 m, the impact of phreatic water on soil water decreases sharply, resulting in very low water content in the soil layer (Shah et al., 2007). Therefore, a typical EAR should be a place which not only has an arid climate but also deep-buried phreatic water.

It is commonly believed that soil water in an EAR originates from the residues of precipitations and that there exists an "extinction depth" above which the phreatic water will stop evaporating (Gardner and Fireman, 1958; Warner, 2004). Investigations on the characteristics of unsaturated soil water (mostly based on the above premise or that of liquid-phase continuity, Shokri et al., 2010) have been carried out worldwide. Topics such as water evaporation, the coupling of water and heat, energy balance, and spatial and temporal changes have all been considered (Rose, 1968a,b; Milly, 1982; Cahill and Parlange, 1998; Shah et al., 2007; Bittelli et al., 2008). Rich accomplishments have been made using experiments simulating rainfall and irrigation. However, the influence of deep phreatic water has been generally ignored. Zhang et al. (2009) reported that the intensity of phreatic water decreases as a power function of the depth of the water table. According to this theory, there should be no depth limit for phreatic water evaporation. The phreatic water, therefore, may still be one of the most important sources of soil water in EARs.

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The water content in the soil in EARs is very low, usually lower than the wilting coefficient, and this causes a breakdown of the ecological chain. Thus, EARs can readily turn into sediment resources for sand storms. As protection of the ecology and environment in arid land has attracted increasing importance, the significance of water content near the wilting coefficient with regard to the restoration of desertified lands has been gradually realized. However, the accuracy of neutron moisture gauges, depressimeters, and thermoelectric methods are all insufficient to capture the minuscule changes in soil water content in EARs (Guo and Liu, 2005). In recent years, the microlysimeter has become accepted as a reliable and universal tool for studying this topic (Cahill and Parlange, 1998; Sun et al., 2004). However, such devices have limited monitoring space (about 10–15 cm in diameter and 20 cm in depth) which is hardly sufficient to reflect the dynamics of soil water in deep layers. Therefore, the determination of a suitable research method and measurement technique could play a crucial role in current and new studies on soil water sources in EARs.

The world-famous Dunhuang Mogao Grottoes heritage site, created about 1600 years ago, is located in northwest China in a typical inland EAR with a water table that is deeper than 200 m. As moisture can impact the salts hidden in mural plaster layers, it may be responsible for the formation of various kinds of diseases found in the wall paintings in the Mogao Grottoes. A survey found that about 50% of the wall paintings have suffered deteriorating diseases. Long-term studies on the diseases' mechanisms have shown that soil moisture is the most active factor in the deterioration of the murals. Following environmental surveys, data monitoring, and theoretical analysis, we believe that the soil moisture comes from phreatic water and that there is evaporation of the deeply-buried phreatic water in this arid Gobi location atop the grottoes (Li et al., 2009). Thus, on one hand, large phreatic evaporation is necessary for ecological restoration in this Gobi desert area but, on the other hand, soil moisture should be controlled at a low level in the grottoes. Study of the groundwater–soil-plant-atmospheric continuum (GSPAC) is important to reflect the cave's moisture sources and to facilitate preservation of the cultural relics therein.

The systematic experiments reported in previous works have confirmed the existence of phreatic water evaporation from the deeply-buried areas. In 2008, a hemispherical greenhouse was built (long after the last rainfall to eliminate the influence of precipitation) and used to collect water which had evaporated from the soil and condensed on the film of the greenhouse. The results of 235 days of monitoring demonstrated that there was stable phreatic evaporation. However, the amount collected was only 2.1 $g\,m^{-2}\,d^{-1}$ due to the 'closeness' effect of the greenhouse, which made the inner air humidity higher than that outside and restrained the evaporation rate (Li et al., 2010a, 2011a).

In 2009, an air-conditioning unit was installed in the greenhouse to restrain the 'greenhouse effect' and reduce air humidity. By doing so, the internal environmental conditions became similar to those of the open air. The quantity of water from the air-conditioning unit can be used to determine the amount of evaporated phreatic water. These improved results showed that the measured water evaporation, 21.9 $g\,m^{-2}\,d^{-1}$, was much larger than that obtained earlier (Li et al., 2010b). This value is, in fact, eight times greater than that obtained from the same greenhouse in 2008 without the air-conditioning unit.

Later, the authors became concerned that the rainwater may not evaporate into the atmosphere but instead penetrate the earth and form deep soil moisture. Based on this hypothesis, a closed greenhouse with an air-conditioning system was constructed to simulate the recycling of precipitation (Li et al., 2014a). At the same time, a new experiment using an isolation method was conducted to study soil water sources in the area (Li et al., 2013). The results of the two experiments eliminated the possibility that the evaporation comes from residual precipitation. Furthermore, other precipitation recycling experiments found that the precipitation can increase the content of dry soil water, strengthen phreatic evaporation, and finally result in a total evaporation amount that is much larger than the precipitation in the area.

The daily evaporation is the basal manner of evaporation of the phreatic water. It is clearly important to investigate the characteristics of the phreatic evaporation and the mechanisms involved. The results of these investigations will also have a profound effect on the possibility of utilizing phreatic water for ecological restoration. In 2009, besides measuring the evaporation quality in the air-conditioned greenhouse (Li et al., 2010b), the characteristics of the daily evaporation were also measured and studied. In this paper, the environmental factors recorded inside and outside the greenhouse, including the temperature, humidity, and solar radiation, are analyzed to describe the daily characteristics of the phreatic water evaporation.

2. Study area

The experiments were carried out in the Gobi area at the top of the Mogao Grottoes (40°02′14″N, 94°47′38″E) from May 22 to July 5, 2009. The closed polyvinylchloride (PVC) greenhouse with its indoor air-conditioning unit was located about 1 km away from the Grottoes (Fig. 1). The salinity and water content of the top 60 cm of the soil layer in the Gobi land are shown in Table 1. The salt content in shallow soil significantly affects phreatic evaporation (Li et al., 2010c; Li and Wang, 2014b). The soil water content was measured using an oven drying method during the dry season. A major part of the soil water originates from the crystallization moisture associated with Na_2SO_4. Another part is composed of hygroscopic soil moisture. The hydraulic potential was very low with no free moisture. Phase changes (decomposition and combination) in the soil-bound water were affected by the daily temperature variation which leads to a daily change in soil water content (Li et al., 2011b).

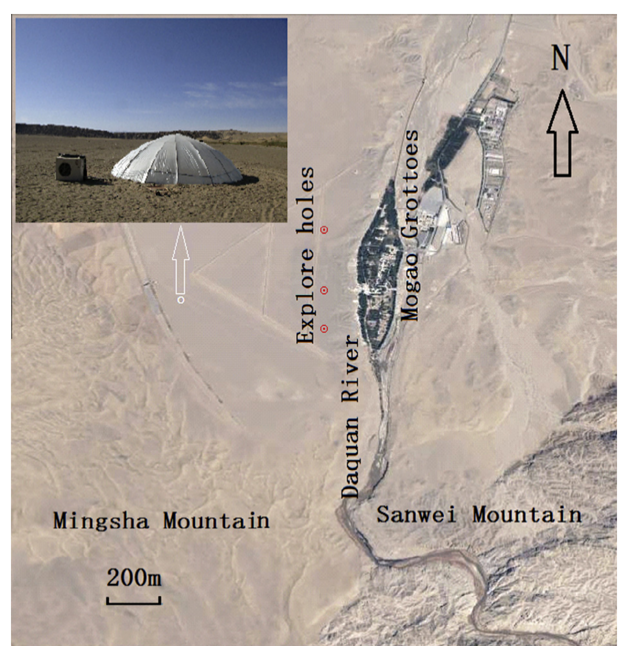

Fig. 1. Location of the greenhouse and air conditioning condensation system.