Characteristics of Hydrologic Transfer between Soil and Atmosphere over Gobi near Oasis at the End of Summer

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ABSTRACT

By utilizing the data observed at Dunhuang during August and September 2000 in the "Field Experiment on Interaction between Land and Atmosphere in the Arid Region of Northwest China (FEILARNC)", the characteristics of the soil moisture, temperature, and atmospheric humidity are analyzed. It is found that the thickness of the soil temperature active layer is about 5 cm and much thinner than is typical, that not only the atmospheric humidity gradient is often inverted but also the soil moisture gradient in the shallow layer in the Gobi near oasis, that the diurnal variation of soil moisture can be divided into the four stages that are called the wet stage, the losing-water stage, the dry stage, and the attaining-water stage. It is shown that in soil moisture profiles, the depth of the soil moisture active layer is about 10 cm and soil moisture inversion is the main feature in the shallow layer during the wet stage. Such a feature as soil moisture inversion indicates that soil in the shallow layer can inhale moisture from the air through condensation in the nighttime and exhale moisture to the air through evaporation in the daytime. The condensation and evaporation constitute together the full respiration process of moisture on the ground. The formation of soil moisture inversion is related with the state of soil temperature and moisture, the intensity of atmospheric humidity inversion, and the atmospheric thermodynamic stability.

Key words: Gobi, soil active layer, atmosphere specific humidity inversion, soil moisture inversion, respiration

1. Introduction

Such a wide desert or Gobi interspersed with many small oases of different shapes is the main geomorphologic feature in the arid region of Northwest China (Cheng et al., 1999). Its land surface process is much more complex than in other regions (Lin et al., 2002). Though oasis and desert are two extreme opposite ecosystems, they forever remain a pair of coexisting ecosystems. The effect of the antagonism and interaction between them not only forms a balanced ecological distribution but also reflects a dynamic tendency of desertification and oasisification in the natural world. In interaction between oasis and desert, exchange of energy and matter, especially heat and water, is dominant. In a word, the mian effect of desert on oasis is thermodynamic forcing, but the main effect of oasis on desert is to influence and modify soil moisture and atmospheric humidity (Zhang and Wang, 1994). Thermodynamic forcing by the desert forms the "Cold Island Effect" whose key characteristic is the existence of an inversion in the atmosphere over the oasis (Su and Hu, 1987; Hu, 1987; Zhang et al., 1992) and the influence of oasis on desert or Gobi near it results in the frequent occurrence of a specific humidity inversion in the atmospheric surface layer over desert or Gobi (Hu et al., 1992; Wang Yasushi, 1991; Zhang and Zhao, 1999).

At present, it has been found that the oasis's "Gold Island Effect" can restrain surface evaporation and decrease moisture dissipation caused by atmospheric turbulent mixing (Zhang et al., 1998; Zhang et al., 2000). But it has not been clear how humidity specific inversion in the atmospheric surface layer over desert

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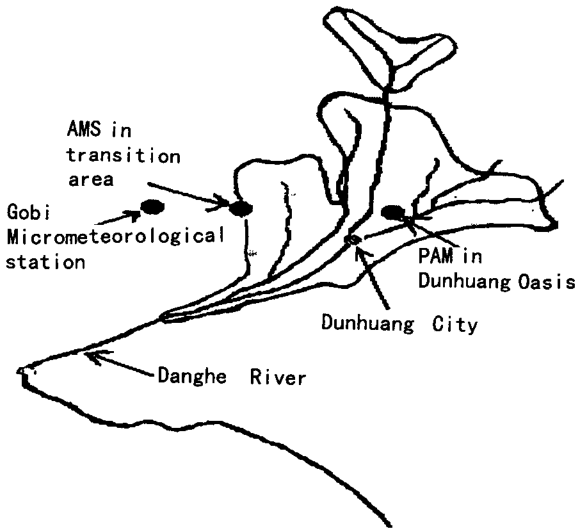

Fig. 1. The sketch map of geographic location and environment of Dunhuang Gobi observational station.

or Gobi near oasis modifies soil moisture and temperature structure, affects further the hydrological cycle between land and atmosphere, or contributes to ecological processes. It has been continually inferred by these authors that there might be a process of "respiration" of moisture on the ground, namely inhaling moisture from the air through condensation in the nighttime and exhaling moisture to the air through evaporation in the daytime, on soil in the desert or Gobi near oasis (Zhang and Zhao, 1999; Zhang et al., 1998). But the inference has not been confirmed and on some key aspects such as essential characteristics of the respiration process and conditions to form it we are still lacking a thorough understanding.

It is not only an issue of land surface processes in the general sense but also an issue of the influences on the microclimate and ecological maintenance mechanism in the Gobi or desert areas near oasis in the especially important sense that the atmospheric humidity, soil moisture, and moisture transfer process are modified by the Oasis Effect. And this is closely related with the maintenance and degeneration of the oasis system and has a widely ecological and economical importance.

2. Field experiment and research method

The data were observed in one of the three stations in Dunhuang County in Gansu Province, which fall into observational stations in the "Field Observational Experiment on Land-Atmosphere Interaction in the Arid Region of Northwestern China" (Zhang et al., 2002a, b). The micrometeorological and soil physical variables observed in Gobi are mainly analyzed. Considering the representation and quality of the data, the data that are observed after adding soil moisture sensors and during August and September 2000 are intentionally selected for this study.

The micrometeorological station in which the data analyzed in this paper were observed is situated at 40°10′N and 94°31′E with an elevation of 1150 m above sea level, in the Shuangdunzi Gobi to the west of Dunhuang oasis, with the nearest distance of about 7 km to the edge of Dunhuang oasis. Its field is even and pebbly Gobi. The sketch map of its geographic location and environment is shown in Fig. 1.

Concerning the characteristics of climate, the Dunhuang region is arid and it rarely rains: its mean annual precipitation is about 39 mm but the mean annual potential evaporation is about 3400 mm, and its soil is extremely dry. In the region, the diurnal surface temperature range is very large (the maximum daily range is close to 60°C, and the recorded maximum surface temperature is 43.6°C and the minimum is −28.5°C. Also, cloud is rare, and solar radiation and sunshine are strong enough to keep such a long frost-free period as 178 days. There, strong wind and dust storms occur frequently. On account of the basin terrain there, the prevailing large-scale west wind is barred and returns in Anxi county to the west of this region, so its main wind direction is east, generally occuring with a frequency of more than 50%. These properties make the atmosphere over the observational site greatly affected by the Dunhuang oasis.

At the station, wind, temperature, and humidity of the atmosphere are observed at the four levels of 1, 2, 8, and 18 m high on a tower, soil temperatures are observed at the six levels of 5, 10, 20, 40, 80, and 180 cm deep, and soil moistures are observed at the four levels of 5, 10, 20, and 80 cm deep. The soil moisture is measured by a TDT soil moisture hygrometer made in America, whose calibrated accuracy is about 1%. The observational accuracy of the gradients of wind, temperature, and humidity of the atmosphere is under 0.01% after correction through a comparison with observation in the field. The accuracy of other instruments is introduced in the references (Zhang and Hu, 1992; Wang et al., 1992). The times reported in this study are in the local time of Dunhuang city.

3. Analyses of results

3.1 *Evidence on "Respiration" of moisture on the surface*

In Fig. 2, profiles of atmospheric and soil temperature and a magnified profile of soil temperature 0–20 cm deep on a typical clear August day over the

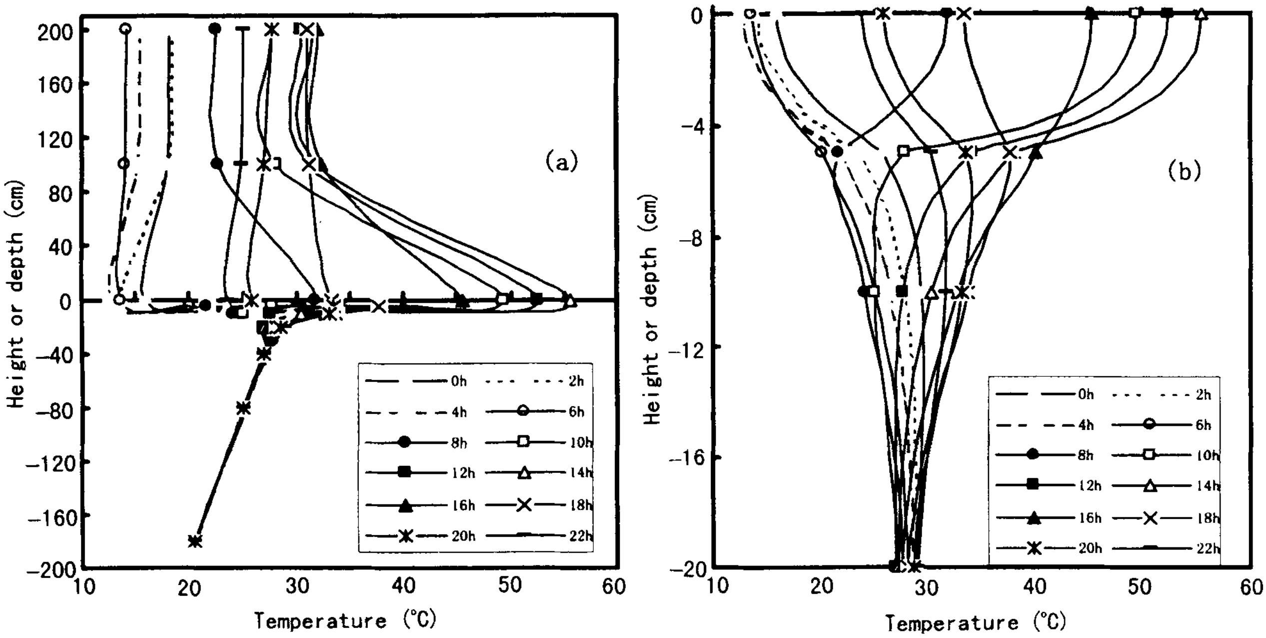

Fig. 2. (a) Characteristics of profiles of the atmospheric and soil temperature and (b) the magnified profiles of soil temperature 0–20 cm deep on 20 Augst 2000 (a typical clear day) in the Dunhuang Gobi.

Dunhuang Gobi are given. Panel (a) shows that there is almost no signal of the daily temperature cycle in the soil deeper than 40 cm, and the depth is much thinner than that of damp soil (Stull, 1991). The shapes of the temperature profiles are basically in accord with those of the general soil, except for a more protrusion towards high temperature in the soil surface in the daytime. Panel (b) shows more clearly that vertical variation of soil temperature occurs mainly in the layer shallower than 5 cm and the temperature variation of soil deeper than 5 cm is very small. This indicates that the thickness of the soil temperature active layer is about 5 cm, only about one fourth of the general one (Stull, 1991). The thinner soil temperature active layer relies on a smaller soil heat diffusivity in desert or Gobi (Stull, 1991). The heat diffusivity in the Dunhuang Gobi is less than one third of that of sandy clay with 15% moisture (Hu et al., 1990), so it is no wonder that the thickness of the soil heat active layer in the Dunhuang Gobi is only one quarter of the general one.

In Fig. 3, the diurnal variation of soil moisture at four levels and atmospheric specific humidity at four levels are given for the period from 22–23 August 2000. The figure shows that an evident daily cycle of soil moisture occurs only at the level of 5 cm deep, that soil moisture at 10 cm deep decreases slightly but continuously and its diurnal cycle is not obvious, and that change of soil moisture at the deeper two levels is invisible. They indicate together that the upper boundary of soil is affected both by solar heating and by atmospheric processes. In general, in case of no precipitation, soil moisture in the active layer should decrease gradually hour by hour due to evaporation, but the change of soil moisture at the level of 5 cm deep still shows a distinct diurnal cycle. This means that soil water in the shallow layer may be supplied by some systematic sources other than precipitation. Thus, it is probable that soil in the shallow layer obtains moisture from the air by condensation or by transfer from the deeper soil layer (Zhang and Hu, 1997a; Zhang et al., 2002c). And the fact that the supplement of soil water at 5 cm deep is still maintained even if its moisture is bigger than that of the deeper soil layer further shows that the water supplement in the shallow layer mainly comes by inhaling atmospheric moisture through the upper soil boundary. The slight but continuous decrease of soil moisture at the levels of 10 cm deep and 5 cm deep shows the water complemented by inhalation from air cannot fully offset the water loss caused by evaporation. Hence, to be exact, were there no supplement of precipitation, the variation of soil moisture in the shallow layer should actually exhibit a diurnal cycle with a gradually decreasing amplitude.

Furthermore, the diurnal variation of soil moisture at a depth of 5 cm shows that the diurnal variation of soil in the shallow layer can be divided into four stages that are respectively called a wet stage (0100–0600 LST), a losing-water stage (0700–1100 LST), a

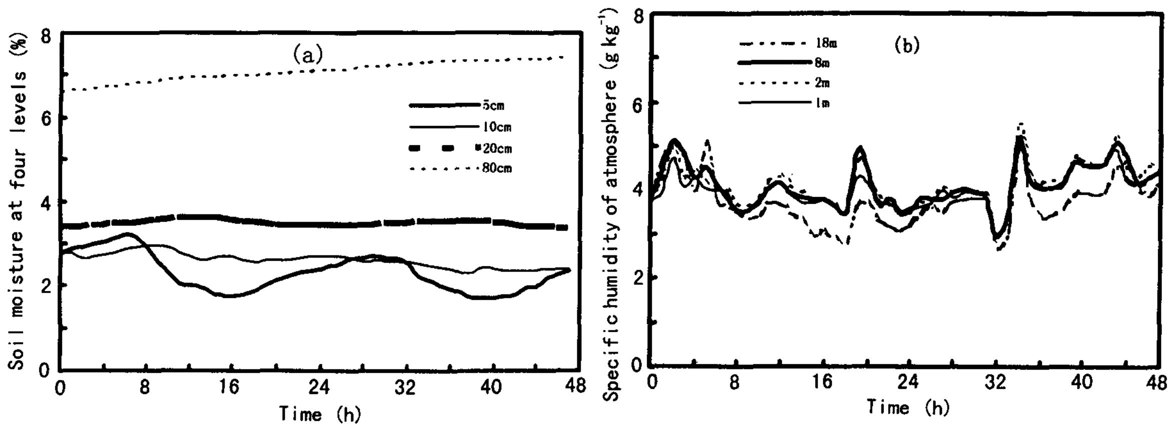

Fig. 3. (a) The diurnal variation of soil moisture at four levels and (b) atmospheric specific humidity at four levels during the period 22–23 August 2003.

dry stage (1200–1800 LST), and an attaining-water stage (1900–2400 LST). During the first stage soil is always wetter, during the second stage soil moisture falls obviously, during the third stage soil is often drier, and during the fourth stage soil moisture gradually rises. The diurnal variation of atmospheric specific humidity, which is given in Fig. 3b, however, is not the same as that of soil moisture and its fluctuation is weaker. This shows that atmospheric humidity is affected by some factors more complicated than those affecting soil moisture, namely many factors without a clear diurnal cycle such as the atmospheric dynamic field.

The four stages constitute a full diurnal cyclic process. If the process in which soil attains moisture from the air through condensation during the wet stage is called "inhalation" the process in which soil releases vapor to the air through evaporation during the dry stage is called "exhalation", and the other two stages are called transitional periods between "inhalation" and "exhalation", then a full diurnal cycle of soil moisture is equivalent to a full respiration process of moisture between the active soil layer and the atmospheric surface layer. Such a respiration process was initially guessed at with insufficient evidence (Zhang and Zhao, 1999; Zhang and Hu, 1997b). The guess is preliminarily confirmed by the diurnal variation process of soil moisture given in this paper.

In Fig. 4, four groups of soil moisture profiles in the Dunhuang Gobi on a typical clear August day respectively in the four stages are given. During the four stages, clearly, the four groups of soil moisture profiles have respectively different characteristics:

(1) During the wet stage, the shapes of the soil moisture profiles are similar to each other and there is soil moisture inversion in the shallow layer. The cause of the soil moisture inversion must be that the soil obtains moisture from the atmospheric surface layer, namely the atmospheric surface layer is one of the sources of soil moisture. Under the conditions of a clear sky, no irrigation, and no surface runoff, inhaling moisture from air by condensation at night is the exclusive way that Gobi or desert soil obtains moisture and makes soil wetter in the shallow layer.

(2) During the losing-water stage, soil moisture inversion gradually disappears and changes into an upward decrease of soil moisture. In this stage, soil moisture is mainly controlled through evaporation, and the disappearance of soil moisture inversion is just caused by exhaling moisture in the shallow layer through evaporation.

(3) During the dry stage, soil moisture profiles change very little and basically keep an upward decrease of soil moisture. This means that soil neither loses nor attains moisture and that no moisture in the shallow layer can be provided for evaporation.

(4) During the attaining-water stage, on account of inhaling moisture into the soil from the atmosphere through condensation, soil moisture in the shallow layer gradually increases and the more shallow the soil layer is the greater increase is, and the upward decreases of soil moisture gradually change into a moisture inversion in the shallow layer.

According to synthetic characteristics of soil moisture profiles during the four stages, it can be deduced that the vertical variation of soil moisture is great mainly in the shallow layer thinner than 10 cm and that soil moisture in the deeper soil layer basically does not vary. This clearly show that the soil moisture active layer is about 10 cm thick.

In Fig. 5, four groups of profiles of atmospheric

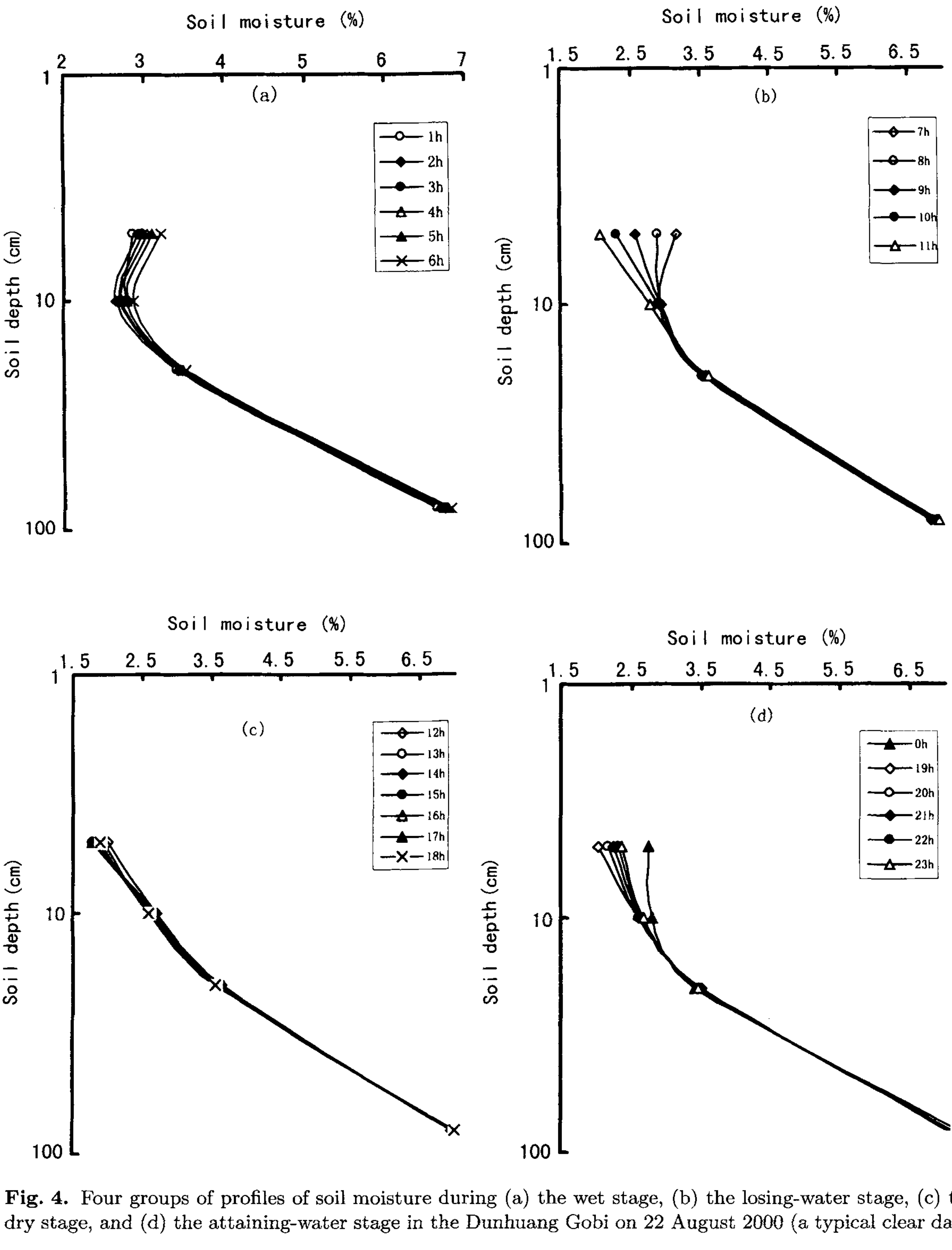

Fig. 4. Four groups of profiles of soil moisture during (a) the wet stage, (b) the losing-water stage, (c) the dry stage, and (d) the attaining-water stage in the Dunhuang Gobi on 22 August 2000 (a typical clear day).

specific humidity respectively, during four different stages in a diurnal cycle of soil moisture over Dunhuang Gobi on 22 August 2000 (a typical clear day) are given. Although the four groups of profiles always keep a specific humidity inversion, there are some differences among their characteristics. In past studies (Zhang and Zhao, 1999; Zhang et al., 1998), it is preliminarily shown that transport and diffusion of moist air over oasis will result in the formation of an atmospheric humidity inversion over Gobi or desert near

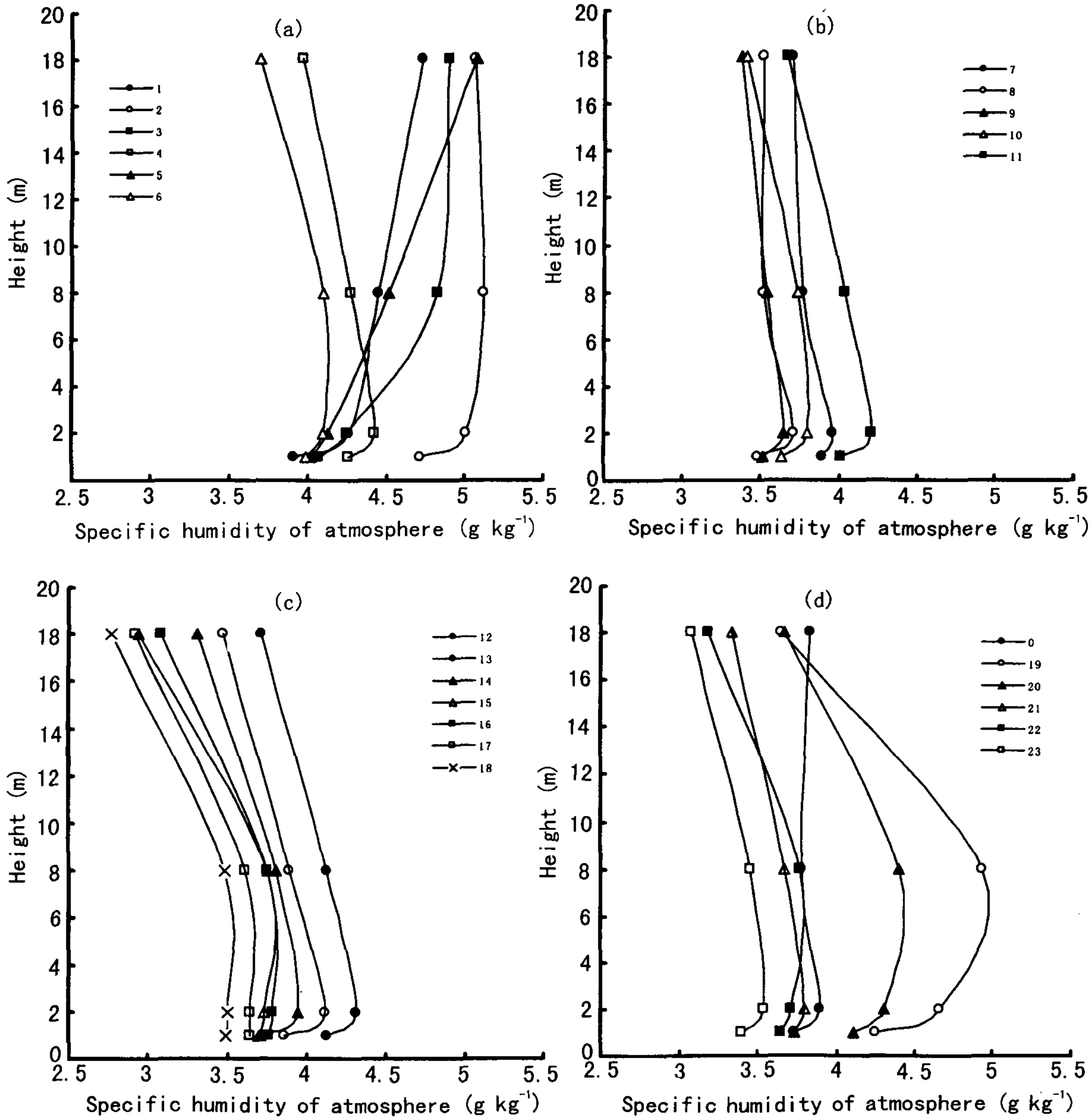

Fig. 5. Four groups of profiles of atmospheric specific humidity respectively during (a) the wet stage, (b) the losing-water stage, (c) dry stage, and (d) the attaining-water stage over the Dunhuang Gobi on 22 August 2000 (a typical clear day).

the oasis. During the wet stage and the attaining-water stage, evaporation is weak and atmospheric humidity in the surface layer is chiefly affected by vapor advection from the oasis, so the specific humidity inversion of the atmosphere is stronger and thicker. During the losing-water stage and the dry stage, evaporation is outstanding, and air humidity in the surface layer is jointly controlled by evaporation and vapor advection, so the specific humidity inversion of the atmosphere is weaker and thinner, and even disappears. Thus, it can be affirmed that a very strong downward water potential gradient is formed because the specific humidity inversion of the atmosphere during the wet stage and the attaining-water stage is stable and deep. This is an important physical base to support the inhalation of moisture by the soil from the atmosphere through condensation during the stages.

Therefore, the respiration process of moisture on

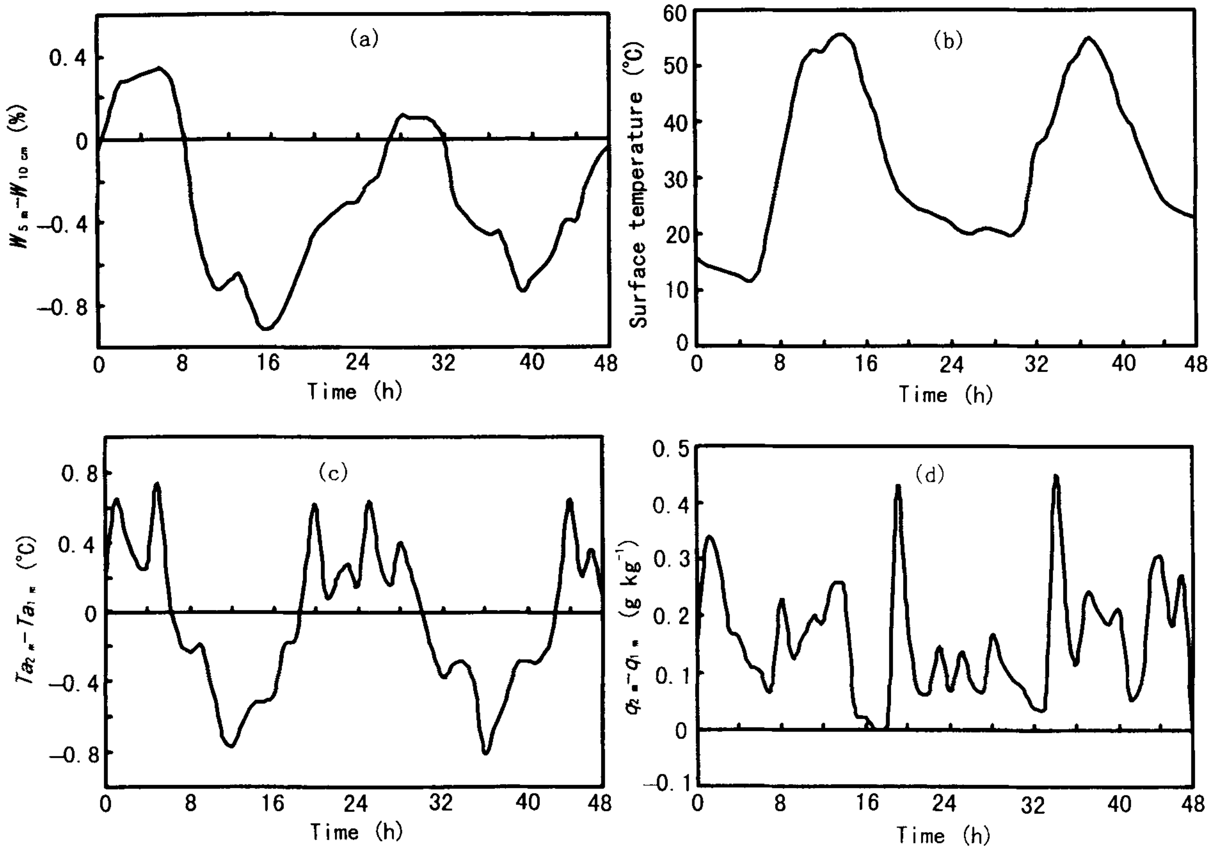

Fig. 6. Comparison of diurnal variations of (a) soil moisture inversion (b), soil surface temperature, (c) temperature gradient in the surface layer, and (d) moisture gradient in the surface layer over the Dunhuang Gobi on 22–23 August 2000.

the ground in desert and Gobi near oasis is an efficient way of reutilizing water vapor transferred from oasis and it can support a much stronger maintenance capability of the ecological community and microclimatic state than under the condition of natural precipitation, and forms an ecological protection zone of the oasis system. That is to say, the respiration process of moisture on the ground may have significant ecological value.

3.2 *Conditions for "respiration" of moisture*

The formation of "respiration" of moisture on the ground in Gobi or desert near oasis depends on some objective conditions. A downward water potential of atmosphere in the surface layer, namely a ground-hugging specific humidity inversion of the atmosphere, is indispensable for "respiration" of moisture on the surface. At the same time, a low enough surface soil temperature to reach the condition of condensation is required while inhaling moisture. In addition, stable atmospheric stratification is required to maintain the state that water vapor masses near the ground rather than diffuses into the upper atmosphere. In Fig. 6, a comparison of diurnal variations of (a) soil moisture inversion, (b) soil surface temperature (c), temperature gradient in the atmospheric surface layer (denoting stability) and (d) moisture gradient in the atmospheric surface layer (denoting atmospheric humidity inversion) over the Dunhuang Gobi on 22–23 August 2000 is given. It shows that the strongest soil moisture inversion and the lowest surface temperature occur almost at one time. This means that temperature is a critical factor in the condensation of water vapor. And the stronger soil moisture inversion and the most stable atmospheric stratification occur almost at one time. This means that atmospheric stratification is also very important for condensation because it makes for high air moisture content near the ground. Atmospheric humidity inversion can last a long time and it provides a source of moisture for inhalation, but it cannot ensure the occurrence of the "inhaling" process. Atmospheric humidity inversion without the occurrence of condensation cannot affect the soil moisture. In other words, the occurrence of atmospheric humidity inversion is not completely in phase with that of the soil moisture inversion. It should be concluded that a lower soil temperature is a necessary physical condition for the formation of soil moisture inversion or "inhaling" process, that atmospheric humidity inversion is a necessary material condition for the formation of soil moisture inversion, and that atmospheric stability is only an influencing factor in the formation of soil moisture inversion.

Figure 7 gives the correlation of soil moisture inversion in the shallow layer with (a) soil surface temperature, (b) the temperature gradient in the atmospheric surface layer, and (c) the specific humidity gradient in the atmospheric surface layer. By statistical analysis, it is shown that the correlation of the soil moisture inversion in the shallow layer is the best with the soil surface temperature and its correlation coefficient reaches 0.934, the next is with the temperature gradient in the atmospheric surface layer and its correlation coefficient is 0.50, and the poorest is with the moisture gradient in the atmospheric surface layer and its correlation coefficient is only 0.21. In the figure, it is noteworthy that soil moisture inversion in the shallow layer occurs only when the soil surface temperature is lower than 20°C.

Soil moisture inversion in the shallow layer just occurs after the soil moisture inhaled from the atmosphere through condensation comes to a critical value, rather than occurring offhandedly once the soil inhales moisture. But the soil moisture rate can reflect offhandedly the effect of the soil inhaling moisture. Figure 8 shows the correlation of the rate of change of soil moisture at 5 cm deep with (a) soil surface temperature, (b) temperature gradient in the atmospheric surface layer (c) and specific humidity gradient in the atmospheric surface layer. As seen in the figure, the soil surface temperature and temperature gradient in the atmospheric surface layer, have a good relation with the rate of change of soil moisture at 5 cm deep, and their correlation coefficients are 0.66 and 0.65 respectively. The correlation with atmospheric humidity inversion is poor with a correlation coefficient of less than 0.3. Soil moisture in the shallow layer just begins to increase when the surface temperature is lower than

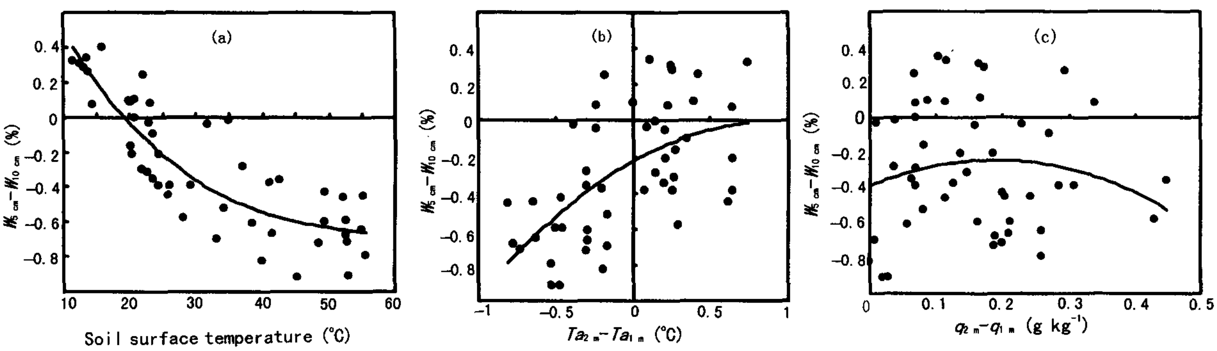

Fig. 7. Correlation of soil moisture inversion in the shallow layer with (a) soil surface temperature, (b) temperature gradient in the surface layer, and (c) specific humidity gradient in the surface layer.

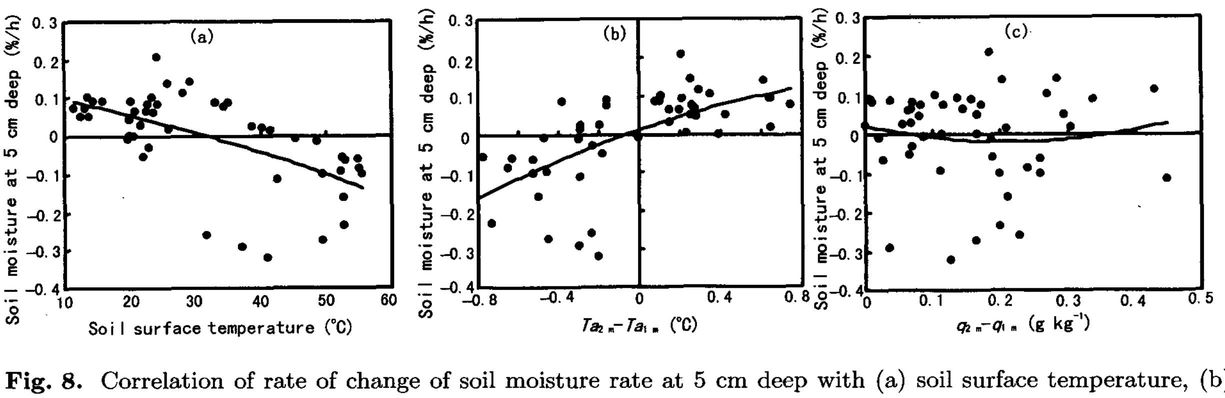

Fig. 8. Correlation of rate of change of soil moisture rate at 5 cm deep with (a) soil surface temperature, (b) temperature gradient in the surface layer, and (c) specific humidity gradient in the surface layer.

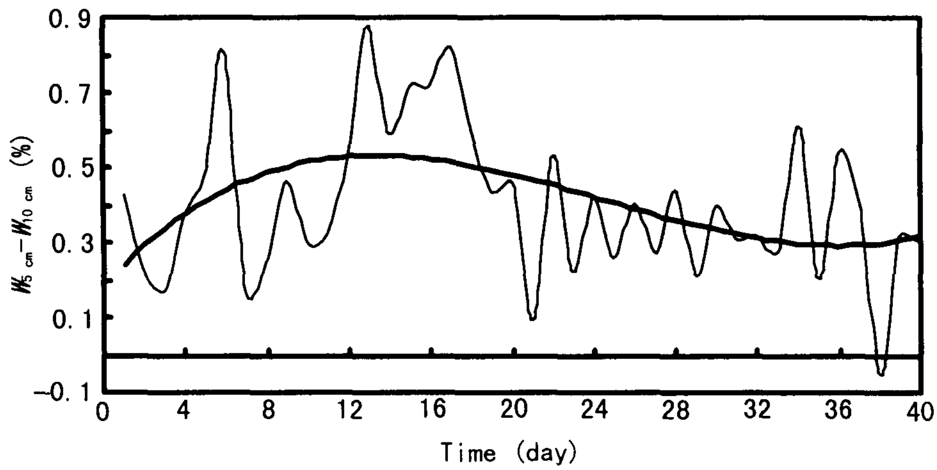

Fig. 9. Interdiurnal variation of daily maximum intensity of soil moisture inversion in the shallow layer during 22 August–30 September 2000 in the Dunhuang Gobi.

about 32°C and the atmosphere is inverted (stable stratification), but in other cases it often decreases.

Atmospheric humidity inversion is the material condition rather than a necessary and sufficient condition in the formation of soil moisture inversion and increase of soil moisture with time. In the general climatic state, as a result of the influence of the nearby oasis, the condition of specific humidity inversion can always be met, so its correlations with both the soil moisture inversion and soil moisture rate in the active layer are not very good.

Some critical values in the above fitted relationships can be considered for use in the parameterization schemes of land-surface processes over arid regions in atmospheric numerical models. This may be of great significance.

The occurrence of soil moisture inversion in the shallow layer is the necessary effect of "respiration" of moisture on the ground. To verify the universality of the above conclusion in summer, data observed from 22 August–30 September 2000 (about 40 days in all) over the Dunhuang Gobi, which can basically represent the characteristics of the atmosphere and soil in summer, are analyzed systematically. It is found that for soil to respire, moisture is a universal process in the active layer. In Fig. 9, the interdiurnal variation of daily maximum intensity of soil moisture inversion in the active layer is given. Clearly, the soil moisture gradient in the shallow layer is inverted almost everyday. It shows that although the temporal-lengths of the "inhaling" and "exhaling" processes are to some extent different a day, the "respiring" process on the soil surface occurs almost everyday. The daily maximum intensity of soil moisture inversion is often 0.4% or so. The precision of the soil moisture gradient measured by the soil moisture sensor can basically meet the demand of this study.

4. Conclusion and discussion

From diurnal variations of soil temperature and moisture over desert or Gobi, it can be inferred that the soil thermal conduction coefficient is much smaller there, so the thickness of the soil temperature active layer is just about 5 cm, the depth of diurnal signal variation is just about 40 cm, and both are at most half of those values in damper soil. And according to the structure of the soil temperature profiles, it can be concluded roughly that the thickness of the soil moisture active layer in Gobi or desert is about 5 cm deep.

The obvious diurnal variation of soil moisture is mainly in the soil moisture active layer and its characteristics show that the upper boundary of soil is affected by both solar radiation and atmospheric processes. The characteristics of the diurnal cycle of soil moisture in the shallow layer show that soil moisture is jointly controlled by the evaporation of water to the atmosphere through solar heating and by the absorption of moisture from the atmosphere through condensation.

The diurnal variation of soil moisture in the shallow layer can be clearly divided into four stages which are called the wet stage, the losing-water stage, the dry stage, and the attaining-water stage. There are great differences among the four groups of vertical profiles of soil moisture respectively during the four stages. It is noteworthy that soil moisture inversion in the wet stage is rarely found before. And the changes of soil moisture profiles match very well with the changes of atmospheric specific humidity profiles in the surface layer from one stage to another. This shows that there is strong interaction between the soil shallow layer and the atmospheric surface layer.

Inhaling moisture from the atmosphere through condensation in the wet stage and exhaling moisture to the atmosphere through evaporation as a result of solar heating constitute a full process of "respiration" of moisture on the ground during a day. The occurrence of moisture inversion and moisture increasing with time in the shallow layer are necessary effects of the "respiration" process. However, water absorbed by the soil through condensation is not enough to offset that lost from soil through evaporation.

Key factors in the formation of the "respiration" process of moisture on the ground include the structure of atmospheric specific humidity and soil surface temperature, and the stability of atmospheric stratification. Lower soil temperature and atmospheric humidity inversion are a precondition to form soil moisture inversion, namely a necessary condition to the occurrence of the process in which soil "inhales" moisture, and the intensity of the atmospheric temperature inversion is an influencing factor in the formation of soil moisture inversion. Special attention should be paid to the effects of the following important critical temperature values. The "respiration" process and soil moisture inversion in the soil active layer occurs only when surface temperature is less than 20°C, and soil moisture in the soil active layer just begins to increase when surface temperature is smaller than 32°C and the atmospheric stratification in the surface layer is stable.

In a usual climate state, the correlation of surface temperature with soil moisture inversion in the shallow layer in Gobi or desert is highest, the correlation with atmospheric stability in the surface layer is second, and the correlation with the atmospheric humidity gradient in the surface layer is next. However, both the surface temperature and atmospheric stability in the surface layer have higher correlations, but the atmospheric humidity gradient in surface layer has a poor correlation, with the soil moisture rate in the active layer. Theoretically, atmospheric humidity inversion is a material condition that soil attains moisture from the atmosphere through condensation, lower surface temperature is an necessary physical condition, and stable atmospheric stratification is a influencing condition. The reasen why the relationships of soil moisture inversion and soil moisture rate with the atmospheric humidity gradient in the surface layer are not close is that the atmospheric humidity gradient over Gobi or desert near oasis is always in the state of humidity specific inversion which is necessary for the formation of soil moisture inversion.

The "respiration" process of moisture on the ground in desert or Gobi near oasis is an efficient reutilization of water vapor transferred from the oasis and it can support a much stronger maintenance capability of the ecological community and microclimatic state than under the condition of natural precipitation.

At present, it is impossible to calculate quantitatively the hydrological transfer in many interactive processes between the atmosphere and land near Gobi or desert, because of the limit in the number of observational items and the observational precisions. Hope is placed on the creation of better observations or better simulations of land surface processes for future analyses and studies.

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绿洲周边荒漠戈壁夏末土壤—大气水分传输特征

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摘　要

利用“我国西北干旱区陆–气相互作用试验”2000年8–9月在甘肃敦煌地区戈壁滩上取得的野外观测资料，分析了临近绿洲的戈壁土壤湿度和温度特征以及相对应的大气湿度特征，发现土壤热量活动层约为5 cm厚，比一般土壤要薄得多；临近绿洲的荒漠戈壁上，不仅近地层大气多为逆湿，而且浅层土壤有时也出现逆湿。土壤湿度日变化能清楚地被区分为湿维持、水分损失、干维持和水分补充等四个阶段。土壤湿度廓线表明：土壤水分活动层厚度约为10 m；湿维持阶段的浅层土壤逆湿是土壤湿度廓线最主要的结构特征，这一土壤湿度结构预示着夜间土壤可能通过凝结吸收大气水分，它与白天的土壤水分蒸发共同构成土壤对大气水分的“呼吸”过程。土壤逆湿的形成与土壤温度状态、大气逆湿强度和大气稳定度都有关。

关键词：戈壁，活动层，逆湿，“呼吸”过程，土壤—大气水分传输