NOTES AND CORRESPONDENCE

Another Comment on "Peculiar Downward Water Vapor Flux
over Gobi Desert in the Daytime"

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Abstract

The downward water vapor flux over deserts in the daytime has been observed by many scientists including Wang and Mitsuta (1990). Tsukamoto (1993) pointed out the importance of density correction to flux measurements and showed that the magnitude of the water vapor flux measurements made by Wang and Mitsuta should be reduced by about 22 %, but the direction was still downward. The present authors discuss this problem from the viewpoint of the behavior of water vapor near the ground surface and arrive at the conclusion that the analysis of the problem must take into consideration water vapor advection if correct conclusions are to be drawn.

1. Introduction

Wang and Mitsuta (1990, henceforth WM) observed humidity inversions in the surface air layer (SAL) and took downward water vapor flux measurements at the HEIFE Gobi station, China, in the daytime. Harazono *et al.* (1992) also obtained similar downward fluxes over a sand dune in the eastern part of Inner Mongolia, China. Some scientists think these results mean that the water vapor moving downward was absorbed through the dry soil surface, and others hesitate to think that way.

The soil surface temperature in a desert may rise greatly during the day; consequently, a rather large temperature gradient along the vertical can exist in the SAL. Therefore, when fluxes of atmospheric minor constituents such as water vapor are measured by gradient method or eddy correlation it is necessary to take into account the simultaneous flux of heat (Webb *et al.*, 1980).

Tsukamoto (1993) re-examined the measurements

made by WM with the eddy correlation technique by taking the density effect due to heat transfer into account. His results show that the magnitude of their flux measurements should be reduced by about 22 %, but the direction is downward, all the same.

In this paper, the downward-flux phenomenon is discussed from the viewpoint of the behavior of water vapor near the ground surface. The gradients of temperature and water vapor density in the vertical right above and under the ground surface are examined and the direction in which water vapor moves is discussed.

2. Soil surface humidity

It is usually believed that the rate of evaporation from bare soil is directly proportional to the difference in water vapor density between the soil surface and the SAL. Thus many investigations have been undertaken to estimate the soil surface humidity. However, there are a few important points which remained unsettled; one of them is what is meant by the "surface" and another is how we measure the humidity at the soil surface.

Lee and Pielke (1992) made a review of the for-

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Fig. 1. Temporal variations of the water vapor density at the surface on a sand dune (solid lines) and at a height of 1.2 m above the dune surface (dashed lines) (HEIFE desert station, China, 1992).

Fig. 2. Same as in Fig. 1, but for the temperature.

mulae for estimating the soil surface humidity and proposed an empirical formula to be used in numerical models on the basis of data by Kondo *et al.* (1990). They asserted that it is not accurate to use the Kelvin Eq. (1) to represent the air humidity at the soil surface, because the surface humidity estimated by Eq. (1) is almost always saturated and is not be able to account for the decrease in evaporation rate as the soil surface dries.

$$\rho_v(\psi, T) = \rho_{vs}(T) \exp(\psi g / R_w T) \quad (1)$$

where ρ_v is the water vapor density, $\rho_{vs}(T)$ the saturation vapor density at absolute temperature T , ψ the soil water potential, g the acceleration of gravity and R_w the gas constant for water vapor. However, Milly (1982) showed that the law (1) is exactly correct except for artificially high infiltration rates into coarse soils. The moisture content in the surface layer varies greatly with depth, so the surface humidity varies depending on the thickness of the top layer defined as the "surface". Kondo *et al.* (1990) defined the surface water content as the average content over the 2 cm-thick top layer, which seems to be too thick because the surface layer in which water vapor transfer by eddy diffusion prevails and water content is almost constant with depth is of the order of 1 mm thick (Kobayashi *et al.*, 1989).

Figure 1 shows the temporal variations of the water vapor density at the surface on a sand dune (solid lines) and at the height of 1.2 m above the dune surface (dashed lines) in the HEIFE desert station. The water vapor density at the surface was obtained from the soil surface temperature (solid lines in Fig. 2) and the soil water potential using the law (1). The sand surface temperature was measured with a thermister thermometer. The soil water potential was estimated from the moisture ratio in the top

Fig. 3. Temporal variation of the moisture ratio in the top layer about 2 mm thick on a sand dune (HEIFE desert station, 1992).

layer of about 2mm thick (Fig. 3) on the basis of the soil moisture characteristic curve (2) for the dune sand obtained by indoor experiment. The moisture ratio, which is defined as the ratio of the weight of water to the weight of dry soil grains in the mass, was measured by the oven dry method.

$$pF = \log_{10} |\psi| = -0.805\theta + 7.0 \quad (0 < \theta < 5.1 \%) \quad (2)$$

where θ is the volumetric water content (in percent), which is obtained by multiplying the moisture ratio by the bulk density (=1.59) (Inoue and Nomura, 1983); the water potential ψ is expressed in head, cm. Thus, for example, $pF=3$ corresponds to $\psi=-1,000$ cm.

As we can see in Fig. 1, the surface humidity was lower than the air humidity in the surface air layer (SAL) for most periods of observation time, which means humidity inversions often developed just above the ground. Figure 4 shows the temporal variations of the thickness of a dry layer of sand at the dune surface (DSL, dashed lines) and of the latent heat flux estimated by the DSL method (solid

Fig. 4. Temporal variation of the thickness of the dry surface layer (DSL) on a sand dune (dashed lines) and the latent heat flux (solid lines) (HEIFE desert station, 1992).

Fig. 5. Schematic representation of the profiles of temperature (T) and water vapor density (ρ_v) near the ground surface.

lines) (Kobayashi *et al.*, 1989). These results imply that the evaporation from a sand dune occurs under humidity inversions. Kobayashi (1993) showed that the rate of evaporation is not necessarily negative under humidity inversions when a large temperature gradient from the air to the soil surface exists. The temperature gradient produces molecular thermal diffusion in a thin surface air layer immediately above the ground (TSAL), the thickness of which is less than 1 mm, and drives the water vapor in the layer upward (Fig. 5). When the soil surface temperature is much higher than the air temperature above the surface (Fig. 2) and the capacity of water vapor transport of the SAL is not sufficiently large, vapor inversions usually seem to prevail in the TSAL (Fig. 5). However, this inversion due to thermal gradients is of a different nature from that observed by WM in the SAL which does not arise from thermal gradients as was confirmed by Tsukamoto (1993).

During the day, when the difference in temperature between the soil surface and the SAL is great,

Fig. 6. Soil moisture profiles at the HEIFE Gobi station. The abscissa shows the ratio of the volume of liquid water to the volume of the soil finer than 2 mm in diameter.

there exists a molecular thermal diffusion which pushes water vapor upward against the gradient of water vapor density of the order of, at the greatest, 1 kg m^{-4} in the TSAL (Kobayashi, 1993). Therefore, it may be concluded that the water vapor moving downward in the SAL hardly reaches the surfaces of soil particles forming the ground surface at high temperatures.

3. Soil moisture profile

In areas of no rain, soil moisture would steadily increase with depth to the groundwater level. However, in real deserts with a little rain, we can see a characteristic form for the soil moisture profile. Figure 6 shows the soil moisture profiles at the HEIFE Gobi station where WM made the flux measurements. The moisture measurements were made by sampling the soil finer than a No. 10 sieve (2 mm) from test holes, thus the volumetric water content (abscissa) means the ratio of the volume of liquid water to the volume of the soil finer than 2 mm in diameter. The fractional percentage of the volume of the finer part changes at random with depth and is in the range of about 20 % to 80 % of the total soil volume.

The water content in the shallow surface layer reflects the weather conditions of the past few days. However, the moisture profiles developing through the underlying layer have a characteristic form common to these two measured profiles; that is, the moist layers are located at the depths between about 10 cm and 50 cm, and the water content decreases with depth beyond about 60 cm deep. The soil moisture characteristic curve differs from soil to soil, and the curve for this soil finer than 2 mm in diameter is

$$pF = -0.196\theta + 7.0 \quad (0 < \theta < 19.2 \%). \quad (3)$$

Thus the volumetric water contents of 8 % to 10 % correspond to the pF values of about 5.4 to 5.0 which are much greater than the value of rupture of capillary bonds of about 3.0 (Inoue and Nomura, 1983). Consequently, it can be said that soil water, at least in the upper 1 m, moves only in the vapor phase, because it can move in the liquid phase only if the pF value is less than the value of rupture of the capillary bond, *i.e.* 3.0. Incidentally, the groundwater table is located at a depth of about 18 m in this area. Rain water infiltrated into the soil in deserts seems to remain in layers near the surface for a long time, because, once the soil surface dries, soil water moves in both the vertical directions only in the vapor phase; thus, both the upward and downward soil water fluxes from rather moist layers are very small.

The pF values in the range of 5.0 to 5.4 correspond to relative humidities ranging from about 84 % to 93 %, as we can calculate with ease from Eq. (1). Therefore, in general, since the humidity in soil pores near the surface is almost saturated and the temperature is higher than that in the SAL, the gradient of water vapor density immediately below the surface is much greater in magnitude than that in the SAL. This implies that the water vapor moving downward in the SAL cannot get into the pores under the ground.

4. Water vapor advection

A temperature gradient of the order of 10^4 to 10^5 K m^{-1} can exist across the TSAL in the daytime (Kobayashi, 1993), when water vapor is strongly accelerated upward by thermal gradients. Under such conditions, the upward transportability of water vapor in the lower part of the SAL is usually smaller than that in the TSAL; consequently, water vapor accumulates around the boundary between the TSAL and the SAL and humidity inversions occur in the TSAL (Fig. 5). Therefore, the surface humidity is almost independent of the humidity conditions in the SAL. Thus air masses conditioned in moist regions do not easily adjust to dry soil surfaces, which means that advective effects of water vapor generated in oases will not be eliminated for a long distance over deserts.

Some methods of measuring the evaporation rate, such as the eddy correlation technique and the aerodynamic method, are based on the assumption that advective effects can be neglected. Therefore, such methods should be applied to evaporation measurements in deserts under conditions with sufficiently long fetches.

5. Concluding remarks

From the present discussion it can be concluded that: On a clear day, (1) the dry soil surface does not absorb (or adsorb) the water vapor in the surface

air layer (SAL) in the daytime; (2) the water vapor density in the pores immediately below the soil surface is larger than that in the SAL all through the day.

No answer to the question "Where does the water vapor moving downward in the SAL over deserts reach?" has been found by the present discussion. However, we can say at least that the water vapor cannot arrive at the surfaces of soil particles forming the ground surface at very high temperatures, and that the water vapor does not go into the soil pores near the surface.

Water vapor moves downward in the SAL, while it moves upward in the dry surface layer of soil. There also constantly exist water vapor inversions in the thin air layer immediately overlying the dry surface at high temperatures. Thus we have two possible answers to the question of where the water vapor goes. One is that the water vapor coming from both the vertical directions accumulates in the lower part of the SAL. The other is that advective effects play an important rôle in the phenomena under consideration. The authors believe that the latter is more realistic than the former, but further investigations must be made before getting a definite answer.

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「ゴビ砂漠において昼間に観測された下向きの水蒸気輸送について」
に対するもう一つのコメント

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