Behavior of Water Vapor in the Surface Boundary Layer in Desert Areas

Tetsuo Kobayashi and Hideyuki Nagai

Faculty of Agriculture, Kyushu University
6-10-1 Hakozaki, Higasi-ku, Fukuoka 812-81, Japan
Fax: +81-92-642-2804, E-mail: kobayasi@agr.kyushu-u.ac.jp

Abstract

Observations of boundary-air-layer processes made in the daytime in desert areas show that the behavior of water vapor in the surface boundary layer is considerably different from that in moist areas; that is,

(a) latent heat flux is negative (downward);
(b) constant-flux layer of water vapor is not detected;
(c) mixing ratio of water vapor increases with height on fine days;
(d) counter-gradient flow of water vapor occurs.

These phenomena are shown to be resulted from the following processes.

(1) Hot, dry soil surfaces produce dry air or gradients of water vapor density by thermal diffusion.

(2) The gradients of water vapor density made at the surface are transported upward by micro-convection cells arising from the large difference in temperature between the surface and the air immediately above it.

1. Introduction

Air flows over changing surface conditions show that an internal boundary layer (IBL) develops over the new surface, growing in height with downwind distance. It is supposed, in general, that the lowest 10 % or the surface boundary layer has been achieved in equilibrium with the new surface and is often called the equilibrium layer or the constant-flux layer.

There are two kinds of IBLs, active IBL and non-active or passive IBL. The former develops over surface changes, smooth to rough, cold to hot, and dry to wet, while the latter is formed over changes, rough to smooth, hot to cold, and wet to dry. However, the data on the non-active IBL have scarcely been obtained so far. Especially, there is no evidence for supporting the formation of IBL for humidity when air flows from moist areas to dry areas. In other words, it is not clear to us what occurs when cool moist air conditioned in oases for example flows into deserts.

This paper reviews the behavior of water vapor observed recently in arid regions and describes a model constructed to explain the behavior of water vapor over dry soil surfaces.

2. Boundary-air-layer processes of humidity

Recently, many observations of boundary-air-layer processes in arid regions have been made and "peculiar" phenomena have been found. Wang and Mitsuta (1990) showed that the flux of latent heat or of water vapor over a gobi desert in the HEIFE (Sino-Japanese Cooporational Program on Atmosphere-Land Surface Processes in Heihe River Basin) area was negative (downward) in most of the daytime. Harazono et al. (1992) observed also humidity inversions or increases in humidity with increasing height over a sand dune in Hulunbuir sandy land, China, during the day. However, these observations do not mean that water vapor moves into the ground, because its gradient immediately below the surface in the dry surface layer (DSL) points downward; that is, soil water moves upward just beneath the surface (Kobayashi et al., 1993).

Hu et al. (1993) made observations of the profile of specific humidity in the 0.25 to 16 m surface air layer over a sand surface at the HEIFE desert station and found that there often existed a minimum value of specific humidity near the ground in the daytime, which seems to mean that the water vapor flux is not constant with height but even changes its vertical direction in the surface air layer. Teshima and Kobayashi (1997) took observations of boundary-air-layer processes in Kokosiri ranges of the Qinghai-Xizang plateau, China, and showed that the constant-flux layer of water vapor disappeared as the soil surface dried and unstable conditions prevailed in the air layer just above the surface. Tamagawa (1996) analyzed the data on wind, temperature and humidity obtained at the HEIFE desert station, and concluded that the Monin-Obukhov hypothesis was not supported.

Nagai et al. (1997) showed that monthly mean mixing ratio of water vapor on fine days at the HEIFE desert station increased with increasing height below 20 m throughout year, which means that humidity inversions always occur in the surface boundary layer at this station. Kobayashi and Nagai (1995) confirmed at the same station that evaporation was occurring under these humidity-inversion conditions, which means that water vapor was transported against its density gradient.

No explanation for these phenomena has not been offered till now.

3. Humidity inversion across the soil surface

Figure 1 shows the vertical profiles of water vapor density obtained at about 1500 JST on fine days in a 3 m by 3 m dune sand field at Kyushu University, Fukuoka, Japan (Kobayashi et al., 1996). The water vapor density in DSL where water moves only in the vapor phase was estimated from the soil temperature and moisture content assuming the vapor to be in equilibrium uniquely with the liquid in the same pore. The DSL thickness was in the range of 1.5 cm to 4 cm. Humidity in the air was measured with an Assmann ventilated psychrometer. The vertical profiles took a jump discontinuity at the hot, dry soil surface and increased from under to above the surface; that is, the humidity inversion developed across the soil surface.

Humidity inversion across the surface were measured also with HUMICAP humidity sensors (VAISALA). The sensors were covered with a metal filter of 1.2 cm diameter and installed at depths of 0.6 cm, 2.6 cm and 10 cm, and at a height of 2.6 cm in the same sand field that was covered with a vinyl house to keep dry conditions, natural ventilation of the air being allowed through openings in the wall. Thus, the top of the sensor at 0.6 cm deep was just exposed to the air, and it was dusted with sand. Figure 2 shows the diurnal variation of water vapor density on fine day (June 26, 1994), the DSL thickness being about 4.5 cm in the daytime (Kobayashi et al., 1996). The difference in temperature between the soil surface and the air in the vinyl house amounted to about 15 °C. The water vapor density at 0.6 cm deep was often smaller than that at 2.6 cm high during the period 1100 JST and 1500 JST when the soil surface temperature was much higher than the air temperature immediately above the surface.

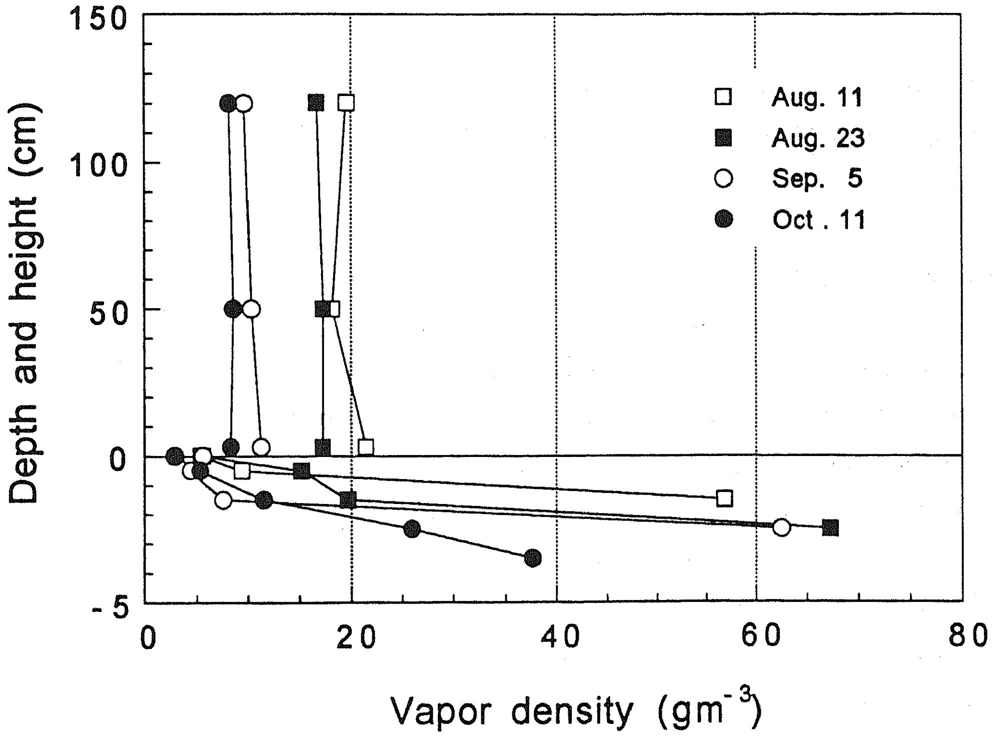

Fig. 1. Vertical profiles of water vapor density measured at about 1500 JST on fine days in a dune sand field at Kyushu University, Fukuoka, Japan in 1993.

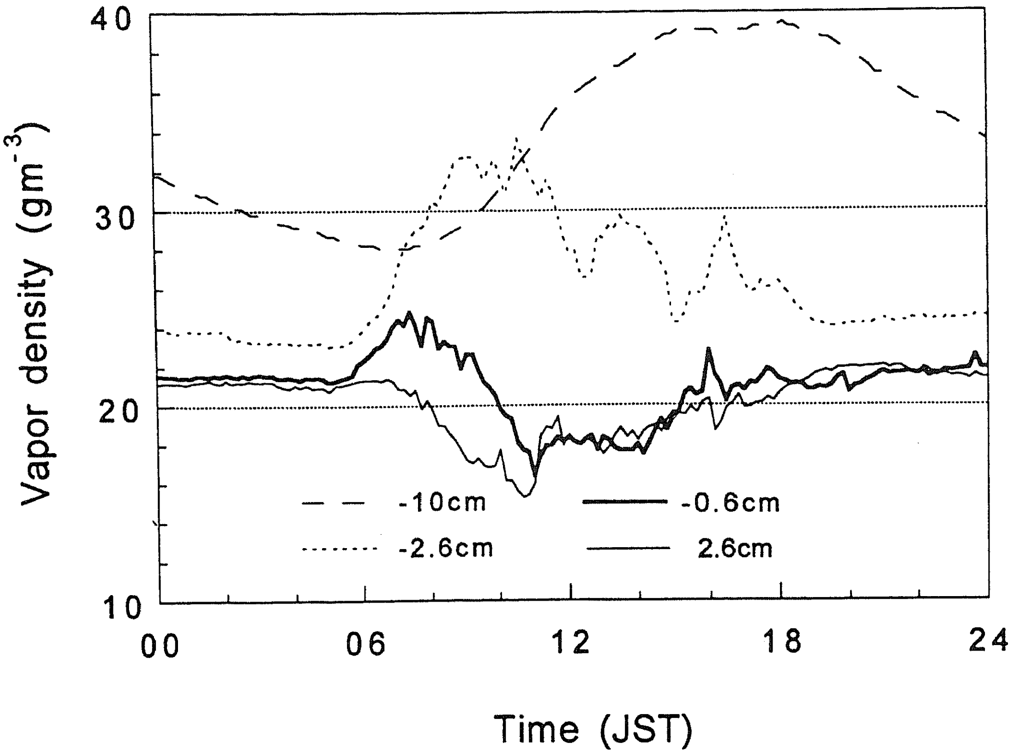

Fig.2. Diurnal variations of water vapor density measured with HUMICAP sensors in the same field as in Fig.1 at a height of 2.6 cm and at depths of 0.6 cm, 2.6 cm and 10 cm on June 26, 1994.

4. Production of dry air

The humidity inversion seems to be related to another peculiar phenomenon which is also seen in Fig.2. After the sunrise at about 0150 JST, the water vapor density near the surface increased owing to the temperature rise. However, it started decreasing drastically at about 0700 JST at 0.6 cm deep and 2.6 cm high, and also at 2.6 cm deep delayed in time about one hour.

The minimum density at 2.6 cm high was below 17.0 gm^{-3}, while the daily mean and minimum values of water vapor density observed at Fukuoka Meteorological Observatory about five kilometers away from the sand field was 20.5 gm^{-3} and 19.7 gm^{-3}, respectively. These results mean that the small sand field with a dry surface layer in vinyl plastic house with openings in the wall produced dry air during the day and this process was activated suddenly in the morning when the surface temperature exceeded a critical value.

If hot, dry soil surfaces make dry air, the discontinuity at the surface in the vertical profile of water vapor density, or the humidity inversion across the surface can be explained in the same way as in the case of temperature discontinuity at the surface in which sensible heat generated there plays an essential role.

5. Mechanism for producing dry air

Dry air can be made by separating water vapor from moist air. There are two processes by which water vapor can be removed from moist air, condensation and thermal diffusion. Although the former is very common, the latter may be unfamiliar to us.

A flow of matter caused by a temperature gradient in a fluid mixture is called thermal diffusion (de Groot and Mazur, 1984). If moist air, which is a mixture of dry air and water vapor, is kept under a strong temperature gradient, water vapor moves toward regions with lower temperatures. As a result, since the air in regions with higher temperatures becomes dry, thermal diffusion makes dry air with leaving moist air as a by-product. Thus, it may be more relevant to say that thermal diffusion produces the gradient of water vapor density in the air.

Kobayashi et al. (1997) discussed this subject and concluded that temperature gradients in close proximity to soil particles forming the ground surface can be large enough to develop humidity inversions across dry, soil surfaces.

6. A micro-convection model

A model that describes the way the gradient of water vapor density is transported upward is presented in Fig.3 (Kobayashi et al., 1997). The stippled area shows dry air made at hot, dry soil surfaces. The dry air made at the surface is mixed with moist air above and below, part of which is the by-product of thermal diffusion, resulting the convergence of water vapor toward the surface. Thus, if only mixing by eddy diffusion or forced convection were in action, the dry air could not efficiently be transported upward. Consequently, free convection which occurs as a result of the density gradients should be responsible for the transport.

A convection cell consists of the core where the updraft is fast and the environment where the downdraft is slow. The hot, dry air made just above the ground surface is easily entrained into the cell. However, if it is made and trapped in soil pores being opened to the atmosphere, the mass movement of hot, dry air may be complicated, because hot air is small in density and is laid under cool heavier air; that is, unstable conditions prevail there. This phenomenon can be solved as a problem of the Kelvin-Helmholtz instability (Kobayashi et al., 1997).

The results obtained are as follows:

The instability develops when (a) the difference in temperature between the two gases, hot and cool, is large, (b) the surface wind is strong, (c) soil pores are large, and (d) the wave number of disturbances is large; that is, the size of convection cell is small.

From these results, we can imagine that lots of small convection cells develop here and there, and hot, dry air is sent up from the surface through the thin core like a jet (micro convection jet, MCJ). In the wide environment rather moist air moves downward and part of it taken into the soil pores, and under strong temperature gradients the dry air layer is reformed there. It is essential to realize that MCJs send up not only dry air but also gradients of water vapor density or humidity inversions produced at the surface, which means that the air masses moving up from the surface are rather small parcels composed of two kinds of gases, dry air in the lower part and moist air in the upper part (Fig.3).

One type of experimental evidence in support of this model is also seen in Fig.2. The phenomenon that water vapor density near the dry surface started decreasing suddenly in the morning can be explained on the basis of this model; that is, the instability near the surface develops with a rise in the surface temperature and when a critical state is reached MCJs burst and dry air confined within the thin, dry air layer spreads to the surroundings. Nagai et al. (1997) showed another example of such a phenomenon in which a sudden increase in the surface wind speed caused a sudden decrease in water vapor density in DSL as well as in the surface boundary layer, which suggests that the strong wind triggers the burst of MCJ as is expected from the result (b) shown above.

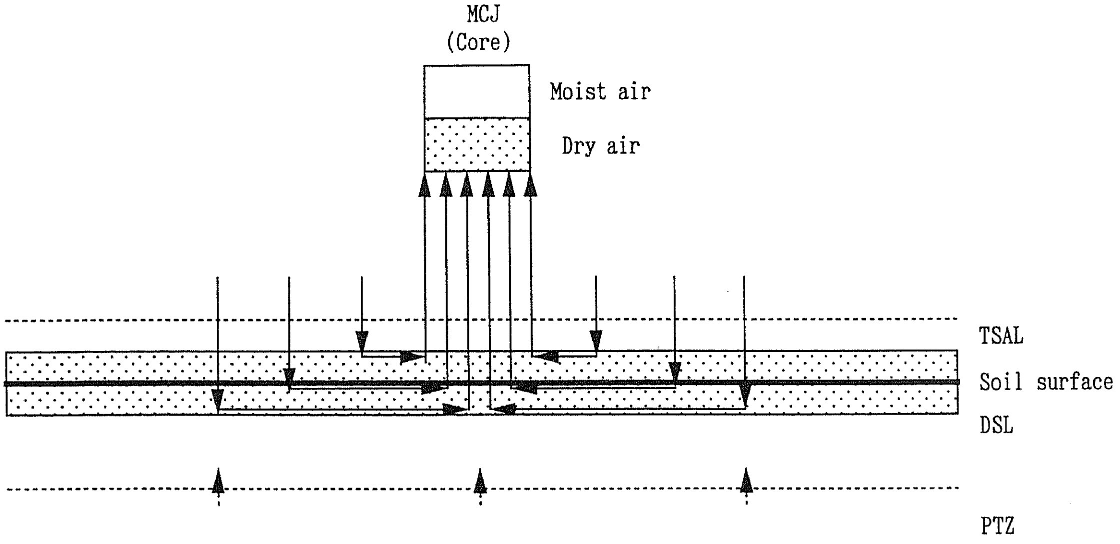

Fig.3. Schematic representation of a micro-convection model that describes the way dry air and humidity inversions made at the surface are transported up into the surface boundary layer.

7. Cause and effect of water vapor advection over deserts

Even if air masses conditioned in moist regions flow into areas with dry surfaces in the daytime, the humidity at the surface is scarcely influenced by them, because thermal diffusion arising from temperature gradients resists the flow of water vapor driven by its density gradient in TSAL and it is determined by the moisture conditions in the uppermost soil layers and the soil surface temperature (He and Kobayashi, 1997). Thus, the air masses do not easily adjust to dry soil surfaces, which means that advective effects of water vapor generated in moist-surface areas (e.g., oases) will not be eliminated for a long distance over dry-surface areas (e.g., deserts) (Kobayashi et al., 1993). This may be the main reason why the formation of IBL for humidity has not been confirmed when air flows from moist areas to dry areas. On the contrary, since humidity just above the surface is increased by the advection and hence humidity inversions across the surface are strengthened, the humidity inversion in the surface boundary layer will be strengthened as well.

8. Concluding remarks

In desert areas, in the daytime when the surface temperature is much higher than the air temperature, humidity at the surface is smaller than that in the surface boundary layer. However, water vapor is transported against its density gradient by MCJs, which means that there is another driving force for the water vapor transport besides the gradient of water vapor density; that is, the temperature gradient. Therefore, the rate of evaporation from hot, dry soil surfaces can not be expressed by the Ohm's analogy or the bulk aerodynamic formulations, because these techniques are explicitly based on the assumption that the process is isothermal. Consequently, it may be said that the rate of evaporation from hot, dry soil surfaces can not be estimated by observing boundary-air-layer processes. He and Kobayashi (1997) proposed to use a bulk formulation of the water vapor transport in DSL where the temperature gradient is tens to hundreds times less than in TSAL and its effects can be neglected (Kobayashi, 1993).

In desert areas, soil surfaces are usually dry and hence high temperatures are developed in the daytime. Thus, we come to a conclusion of great interest that deserts produce dry air. It may be said that dry air makes deserts and deserts themselves make dry air, which means that deserts have another self-induction effect in addition to that suggested by Charney (1975).

When moist air flows into desert areas, water vapor may be absorbed by dry soil surfaces in the nighttime. However, in the daytime, it keeps flowing over hot, dry surfaces for a long distance and humidity inversions will be developed in the surface boundary layer. The humidity structure in the surface boundary layer in desert areas is very complicated and further study is needed to clarify the details of the behavior of water vapor there.

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