Why the Thickness of the Dry Surface Layer in Sand Dune Fields Exhibits a Diurnal Variation?

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A dry surface layer usually forms in a sand dune field and it has an effect on the micro-climate. The thickness of the layer exhibits a diurnal variation with a maximum in the late afternoon and a minimum in the early morning. The thickness is a measure of the degree of dryness in the upper layers in sand dune fields; thus, the diurnal variation in the thickness suggests that there are large diurnal as well as irregular variations in the moisture conditions of the upper layers. The reason for the diurnal variation is that the rate of evaporation from the ground changes during the course of the day, while the upward water flux in the moist underlayer remains nearly constant throughout the day.

Key words: Dry surface layer, Evaporation, Sand dune field, Soil water movement.

1. Introduction

Considerably dry surface layers are formed in sand dune fields except during short periods immediately following rainfall or irrigation and they have an effect on the micro-climate. This surface layer of dry sand is customarily called a “Kan-Sha-So” in Japanese, which means a “dry sand layer”, so we shall often use this expression hereafter (Kobayashi et al., 1986).

The dry surface layer grows thicker under conditions of no rain or irrigation, but the thickness does not change in a monotone. We know from observation that it also exhibits a diurnal variation with a maximum in the late afternoon and a minimum in the early morning. In some cases the dry surface layer moistens and dies out during the night.

The purposes of the present paper are to describe the diurnal variation in the thickness of the dry sand layer by a simple evaporation model and to present the experimental demonstration of this model.

2. Model

The phenomenon of evaporation from bare soil surfaces is generally classified into three stages (Kobayashi, 1990). During the first stage with much soil water, vaporization occurs at the surface, or within the thin top layer in the strict sense of the word. With decreasing water content the location of vaporization spreads downward and vaporization takes place not only at the surface but also within the ground. This stage is called the second stage of evaporation. In the third stage complete vaporization takes place within the ground, when a dry surface layer exists in which the water movement occurs exclusively in the vapor phase.

The evaporation phenomenon in the last stage
is schematically presented in Fig. 1. Under a dry surface layer (henceforth called the D-layer) a moist layer where the water movement occurs in two phases, liquid and vapor, exists. This layer will be referred to as the M-layer.

![Schematic model of the third stage of evaporation from bare soil surfaces.](image)

Furthermore, it is useful to partition the M-layer into two sublayers; one is the upper part (M1-layer) where most vaporization occurs and the water content profile changes notably with time, and the other is the lower part (M2-layer) in which the rupture of capillary bonds arising from drying occurs and the water content profile scarcely changes throughout the day.

Unsaturated layer with relatively plentiful soil water (US-layer) exist under the M-layer, where water movement occurs in the liquid phase. Thus almost all vaporization takes place in the M-layer. Let us assume that water moves only vertically, upward or downward, and refer to the water fluxes in the surface air layer, D-layer, and M-layer as $q_a$, $q_d$, and $q_m$ (cm h$^{-1}$, positive upward), respectively. It is supposed that the driving forces of $q_m$ are the vertical gradients of water content and temperature. In the third stage of evaporation, however, the M2-layer is generally located deeper than several centimeters; thus $q_m$ is mainly controlled by the gradient of water content. Since the time variation of the water content profile in the M2-layer is small, we can assume that the change in $q_m$ with time is also small.

When applying the present model to evaporation from a sand dune field, the D-layer is the dry sand layer. Thus $q_d$ is the vapor flux in the dry sand layer, which increases with increasing temperature and also with decreasing thickness (Kobayashi et al., 1989). As long as the layer grows thicker there exists the relation $q_a = q_d > q_m$. However, if the flux $q_d$ decreases through an increase in thickness and/or a decrease in temperature and comes into equilibrium with the flux $q_m$, that is, if the relation $q_a = q_d = q_m$ holds, then the development of the dry sand layer ceases.

The time variation of $q_m$ is not so great that the rate of evaporation $q_a$ becomes smaller than $q_m$ in the evening, when the destruction of the dry sand layer begins, that is, an increase in moisture content and a decrease in thickness of the D-layer results. The next morning, $q_a$ becomes larger than $q_m$ again and the same process with a somewhat smaller $q_m$ recurs.

The foregoing is a schematic description of the mechanism for generating a diurnal variation in thickness of the dry surface layer in a sand dune field. This model must be verified on the basis of observations and experiments, which will be presented next.

### 3. Verifications

#### 3.1 Vaporization depths

Evaporation is the phenomenon in which water vaporizes and disappears. In the third stage, therefore, it is closely related to the thermal conditions within the ground. According to the present model, vaporization occurs mostly in the M-layer which consists of two sublayers with distinctive features, the M1- and M2-layers. We will first of all substantiate this point by analyzing the soil temperature profile.

Fig. 2 shows a part of the soil temperature profile observed at 14:00 on July 28, 1983 in the Tottori Sand Dune (Sand Dune Research Institute, Tottori University). The weather on that day was clear from morning and the surface temperature reached about 333 K (60°F) at 14:00. The thickness of the dry sand layer measured by visual observation was 4.6 cm (indicated by a dotted line).

We can see a temperature drop in the shape of the profile around the boundary between the dry sand layer and the moist underlayer, which suggests that intensive vaporization takes place within these depths.
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The dash-dotted curve in the figure depicts the profile which would appear if the concentrated vaporization did not occur. This profile was estimated by reference to the temperature variation in soil consisting of two layers (Wijk, 1966). Since the heat of vaporization is added from the upper layers at higher temperatures, our attention should be given to the downward heat flux in the lower part of the dry sand layer.

A comparison of the observed and the estimated vaporization-free profiles in the layer 3 cm to 4 cm deep given in Fig. 2 reveals that the observed temperature gradient is about 1.5 K cm⁻¹ in excess of the estimated one. Since the volumetric water content ranges from 1.5% to 2% in the lower depths of a dry sand layer in the Tottori Sand Dune, the thermal conductivity can be estimated to be about 1 x 10⁻³ cal cm⁻¹ s⁻¹ K⁻¹ according to Wijk (1966).

Thus, if this condition persists, the excess gradient causes excess heat flow of about 5.4 cal cm⁻² h⁻¹, which corresponds to the heat consumed for vaporization occurring at a rate of about 0.009 cm h⁻¹.

By using the simple theory of vapor transfer (Philip and de Vries, 1957), Adachi (1984) calculated the vapor flux through the same layer at the same time and obtained the value of 0.008 cm h⁻¹ on the basis of the temperature (Fig. 2) and water content profiles (Fig. 3). The vapor flux $q_d$ through the entire dry sand layer calculated using the dry surface layer method (Kobayashi et al., 1989) and letting the water content at the surface ($\theta_0$) be 0.3% and the mean temperature in the layer ($T_m$) be 323 K is 0.007 cm h⁻¹.

The excess heat flowing downward through the layer 3 cm to 4 cm deep seems to be consumed mainly for vaporization, though a small part of the heat may be used for increasing the soil water temperature which rises from the lower depths at lower temperatures. The thermal phenomena within the ground are complicated, but the above results show that vaporization takes place mostly in the upper depths of the moist underlayer ($M$-layer). Ishihara et al. (1989) took the depth of the minimum temperature to be the depth of vaporization, which is reasonable with the understanding that it refers to the depth at which vaporization occurs most intensively. In reality, however, vaporization also takes place in the lower layers.

The time variation of the volume of water contained within the layer 3.5 cm to 5.5 cm deep was estimated from the water content observations made at the depths of 4 cm and 5 cm in the sand dune field. The decreasing rate of soil water at 14:00 corresponds to the evaporation rate of 0.005 cm h⁻¹, which is of course not equal to the real rate of vaporization within the layer. The upward water flux into this layer, which is nearly equal to $q_m$ of the present model, consists of two components, liquid flux and vapor flux, but the upward flux from this layer occurs only in the vapor phase. Therefore the real rate of vaporization in this layer must have been greater than 0.005 cm h⁻¹. This is related to the ratio of the liquid flux and the vapor flux making up the upward water flux in the $M$-layer of this model, though the actual conditions are not clear. However, we can estimate the magnitude of $q_m$ at 14:00 to be in the range of 0.002 cm h⁻¹ to 0.003 cm h⁻¹ which is about one-third of the evaporation rate $q_a (= q_d)$.

3.2 Diurnal variation of the water content profile

In the present model the upward water flux in the $M_2$-layer, $q_m$, is supposed to change little throughout the day. It is taken as the basis for this supposition that the water content profile in the $M_2$-layer hardly changes with time.
Fig. 3 shows the diurnal sequence of water content profiles in the upper 10 cm, which were observed on two successive days (July 27-28, 1983) in the Tottori Sand Dune. The open circles on the curves denote the boundary between the dry surface layer and the moist underlayer measured by visual observation.

In the layers ranging from about 6 cm to 10 cm in depth where the volumetric water content is larger than about 3%, the water content profile hardly changed throughout the day. These layers seem to make up the $M_2$-layer of the present model. In the case of the Tottori Dune Sand, the volumetric water content at the boundary between a dry sand layer ($D$-layer) and the moist underlayer ($M$-layer) is 1.5–2%, so that the volumetric water content in the $M_1$-layer seems to be in the range of about 2% to 3%.

The dry sand layer, i.e., the $D$-layer, and the $M_1$-layer exhibit diurnal changes in water content. It can be seen from the water content profiles that the water content at the surface was increasing with decreasing temperature in the late afternoon (18:00 July 27, solid curve); during the night the water content in the $D$- and $M_1$-layers increased (4:00 July 28, dashed curve), and after sunrise the top layer started to dry again (6:00, dash-dotted curve). The thickness of the $D$-layer reached a maximum of 4.8 cm at 16:00 (Fig. 5).

The moisture condensed in the $D$-layer during the night was thought to come from the moist underlayer. To verify this expectation an experiment was conducted.

Fourteen sample containers 30 cm long were constructed from 14 sets of transparent acrylic resin tubes having an inside diameter of 5 cm; each set consisting of five tubes 1 cm long, two 2.5 cm long, two 5 cm long, and one 10 cm long. The Tottori Dune Sand was packed into each container by water binding, the bulk density being about 1.5 g cm$^{-3}$ (Kobayashi et al., 1986). Each sample container was laid in a vertical position under the ground in a sand field set up in an experimental farm at Shimane University (Matsue); the top surfaces of the sample columns were set at the same level as the ground and the bottom surfaces were brought into intimate contact with the surrounding sand. These samples were allowed to stand for about a week so that the soil water contained in them might be in equilibrium with that in the field.

On a cloudless night (September 1–2, 1984), we dug the sample containers from the ground and measured the water content by breaking up the containers according to the following schedule. At 16:00 on September 1, two sample containers were dug out; at 18:00, half the remainder, i.e., six containers were covered with acrylic resin disks to prevent vapor movement through the top surfaces; at 20:00, 24:00, and at 6:00 September 2, two sample containers with lids and two without were dug out simultaneously. Thus the water content observations used for this analysis are the
average of two samples.

Fig. 4 shows the time variations of the water content profiles for two cases, (a) with a lid and (b) without a lid. The numbers by the curves represent volumetric water contents (%). The dashed curves depict the depth of the volumetric water content of 1.5%, which is a criterion of the interface between the dry sand layer and the moist underlayer. During the night the dry sand layer moistened and decreased in thickness; in particular, the dry layer in the sample containers with lids almost disappeared. These results show that, although there was a lot of condensation on the plant surfaces, the moisture condensed in the dry sand layer came from the moist underlayer and evaporation also occurred slightly during the night.

In the lower depths where the volumetric water content is larger than 3%, water content is subject to much smaller variations than in the upper depths; furthermore, the effect of the lid, that is, the influence of vapor movement through the top surface on the appearance of isopleths cannot be detected. This suggests that the lower depths correspond to the $M_2$- and US-layers of the present model. The results of this experiment also show that the water content profile in the $M_2$-layer scarcely changes through the night.

### 3.3 An estimate of $q_m$ during the night

We have found that the $M_2$-layer for the Tottori Dune Sand is equivalent to the depths where the volumetric water content ranges from about 3% to 5%, and the main characteristic of the water content profile within this layer is its small variation in time and space.

The upward water flux in the $M_2$-layer, $q_m$, is controlled mainly by the gradient of water content in the layer, so the time variation of $q_m$ must also be small. The flux $q_m$ at 14:00 on July 28 was estimated to be 0.002 cm h$^{-1}$ to 0.003 cm h$^{-1}$, as mentioned in section 3.1, and an attempt will be made to estimate the $q_m$ of the previous night.

Fig. 5 shows the diurnal variation of the total volume of water contained in the upper 10 cm per unit surface area for the period from July 27 to 28. The water content measurements were made every hour at the depths of 0, 1, 2, 3, 4, 5, 7.5, and 10 cm. The sampling location was shifted each time within a limited field, hence the total volume estimates (solid circles) are also subjected to local variations. To eliminate these variations the 4-hour running means (averages of 3 consecutive estimates) were taken (open circles). The dotted curve in the figure shows the thickness of the dry sand layer measured by visual observation.

![Fig. 4 Time variation of the water content profiles for two cases, (a) with a lid and (b) without a lid (September 1–2, 1984). The numbers by the isolines represent the volumetric water content (%).](image1)

![Fig. 5 Diurnal variations of the total volume of water in the upper 10 cm per unit surface area (solid circles) and the thickness of the dry sand layer (dotted curve) in the Tottori Sand Dune (July 27–28, 1983). The water content measurements made at 22:00 and 10:00 are excluded because their validity was judged as doubtful. The open circles show the 4-hour running means.](image2)
Since the water content at the depth of 10 cm is about 5% (Fig. 3), this depth is located almost at the lower end of the $M_2$-layer. Thus, the rate of change with time of the volume of water contained in the upper 10 cm can be regarded as the difference, $q_m - q_a$, where $q_a$ is the water flux in the surface air layer, or the evaporation rate from the surface.

From evening to the next morning the thickness of the dry sand layer decreased steadily, and, at the same time, the volume of water contained in the upper 10 cm increased. The increase in the volume during the night (within about ten hours) can be estimated from the results shown in Fig. 5 to be larger than 0.02 cm$^3$ cm$^{-2}$, which corresponds to the vertical convergence of water flux of about 0.002 cm h$^{-1}$; consequently, the time averaged $q_m$ for this night is 0.002 cm h$^{-1}$ plus the rate of evaporation from the surface. The evaporation rate during the night is much smaller than $q_m$, so we can say that this estimate of $q_m$ is in fair agreement with that made at 14:00 mentioned above, 0.002 cm h$^{-1}$ $\sim$ 0.003 cm h$^{-1}$. This means that the value of $q_m$ during the night is almost equal to the value in the daytime.

4. Conclusions

In the third stage of evaporation, the upward water flux in the $M_2$-layer, $q_m$, hardly changes throughout the day, though the rate of evaporation from the ground, $q_a$, varies obviously during the course of the day. When $q_a$ is larger than $q_m$ the upper layers ($D$- and $M_1$-layers) dry, while when $q_a$ is smaller than $q_m$ these layers moisten.

A dry sand layer corresponds to the $D$-layer of the present model, which is the dry surface layer where the water movement occurs exclusively in the vapor phase. Thus, the thickness of the dry surface layer can be regarded as a measure of dryness of the upper layers. The reason why the thickness is subject to a diurnal variation is that there are large diurnal, as well as irregular variations in the moisture conditions of the upper layers.

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References


乾砂層厚の日変化の機構について

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要 約

砂丘地に形成される乾燥表層は一般に乾砂層と呼ばれ、砂丘地特有の微気象をもたらす要因となっている。乾砂層の厚さは日変化し、朝に最も薄く夕方に最も厚い。乾砂層厚は地表部の乾燥度を表す一つの指標であり、厚層の日変化は地表部の乾燥状態が日変化することを意味する。これは蒸発速度が大きな日変化を示すのに対し、湿潤下層内の水分蒸発フラークスが時間的にはほとんど変化しないことに起因する。

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