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Dynamic Behavior of the Moisture near the Soil-Atmosphere Boundary

Nobutaka MONJI, Ken HAMOTANI, and Yukio OMOTO

Laboratory of Agrometeorological Environment, College of Agriculture

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Abstract

Dynamic relations between the moisture in the atmosphere and the soil are studied based on a field experiment. Sensors to measure the moisture in the skin layer near the atmosphere-soil boundary were developed and applied to the bare soil surface. The amount of moisture change in a shallow soil layer (less than 4 cm depth) was observed to be related to the rate of evaporation from the surface on the basis of daily averages. On the hourly basis, however, the agreements are poor. The soil moisture even at the small depth (−1 cm) began to decrease around noon although the evaporation started immediately after the start of insolation. The hydraulic diffusivity obtained from the phase difference of diurnal moisture variation is shown to vary with the volumetric water content of the soil.

1. Introduction

The moisture content in the atmosphere and that in the soil are closely related to each other through the evaporation from the soil surface. The factors which control the evaporation are the solar radiation, the vertical distributions of wind, temperature and water vapor in the atmosphere, and those of moisture content and temperature in the soil. Other factors such as the surface roughness, albedo, fetch for the wind and soil structure may be important as well.

Many experimental works have been made in order to investigate the basic characteristics of the soil moisture (e.g. PHILIP[1]), HILLEL[2])), and that of the atmospheric surface layer (summarized by BRUTSAERT[3])). However, researches to search for the relation of the moisture in both atmosphere and soil have not been satisfactory.

The approaches to connect the evaporation and soil moisture have been made in the application to the general circulation model. The concept of the force restore developed for the heat budget was applied to the soil moisture by DEARDORFF[4]) and TOYA and YASUDA[5]). Although agreements between the developed model and the observations are attained, many uncertainties in generalizing the parameters still exist.

The dynamic response of the soil moisture near the surface has been investigated by numerical experiments by various workers (e.g. CAMILLO *et al.*[6]), KUZUHA *et al.*[7])). One of the difficulties in the modelling of the atmosphere-soil interaction may be attributed to the lack of knowledge about the unsaturated hydraulic conductivity and/or the diffusivity of water vapor in the soil. Although a considerable amount of field and laboratory experiments to obtain those coefficients have been carried out, there still remains many uncertainties to be cleared. Especially, the dynamic characteristics of the water vapor movement under temperature gradient, which may be important for the research of the field evaporation near the atmosphere-soil interface, has to be clarified. It is necessary to accumulate more experimental results under various field conditions.

In order to investigate the relation between the surface evaporation and the soil moisture content, it is necessary to know the moisture content and the temperature of the soil-atmosphere interface. The surface temperature may be measured with an infrared radiometer by assuming the emissivity of the surface. However, it is difficult to measure the moisture content at the boundary itself. In this research the sensors to approach considerably close to the surface boundary are developed and the relations between the moisture in both atmosphere and soil are investigated.

2. Field Observation

The observation field was located at the north end of the experimental farm of the University of Osaka Prefecture. The field was previously used as a rice field, and the soil was a fertile loam down to the depth of about 25 cm, below which the soil contain more clay. The soil was tilled about 4 months before the experiment. The surface of the soil during the observation was considerably smooth with the roughness length (z_0) determined from the wind profile being 0.058 cm.

Since the objective of this research is to find the characteristics of moisture in the layer very close to the surface boundary, the sensors were developed to located as close to the atmosphere-soil interface as possible. The thickness of the measured layer was 50 cm above and 20 cm below the soil surface.

The observation started on December 1 and ended on December 22, 1988. All the signals from the sensors were digitized by a data-logger (Etoh Thermodack-E) and transported into a micro-computer through RS-232-C interface. Mean values computed over 30 minutes were recorded on floppy disks.

2.1 Measurements in the Air

Dry and wet bulb temperatures were measured at three heights. Copper-constantan

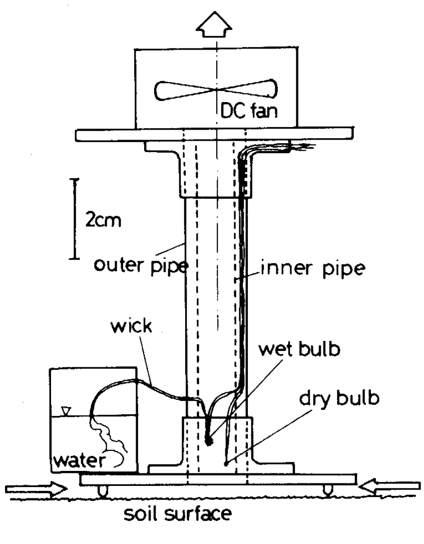

Fig. 1 Schematic of the psychrometer to measure the temperature and humidity close to the soil surface.

thermocouples of 0.1 mm in diameter were used for the upper two heights, 50 and 2.5 cm. In order to measure the air very close to the ground surface, a psychrometer shown in Fig. 1 was developed. A transparent plexiglas plate was placed near the ground and the air was sucked into the pipe at the center through the layer between the plate and the soil surface. At the lowest end of the pipe a thermocouple psychrometer was located. The thickness of the layer between the plate and the ground surface was chosen to be about 0.2 cm in the present experiment.

Wind speed was measured at two heights, 50 and 2.5 cm above the ground with hot-wire anemometers (KANOMAX Model-6071). The signals of the dry and wet bulb temperatures and the wind speeds were averaged by analog mean meters with a cut off frequency of 0.1 Hz before digitizing. The solar radiation, net radiation and rainfall were also recorded.

Estimation of the evaporation into the atmosphere and the sensible heat flux are made according to Businger-Dyer representation for unstable conditions and log-linear law for stable conditions[8]. Applicability of the similarity law in this field was examined by profile measurement near the ground 2 month before the start of the experiment[9].

2.2 Measurements in the Soil

Soil moisture was measured at 1.0, 4.0, 10.0 and 20.0 cm below the ground surface. Heat conductivity sensors were selected among many types of soil moisture instruments[10] since it may be the best to reach the layer close to the boundary. The outline of the sensor is shown in Fig. 2 (a). The principle of this instrument is to make use of the nature of the soil that the heat conductivity varies with soil moisture[11),12]. The sensor consists of brass pipe of 0.4 cm in diameter and 10 cm in length. A manganin wire of 15 ohms in resistance was put in the form of a coil in the pipe. The raise of the temperature was detected by a thermocouple located at the center of the pipe. The reference

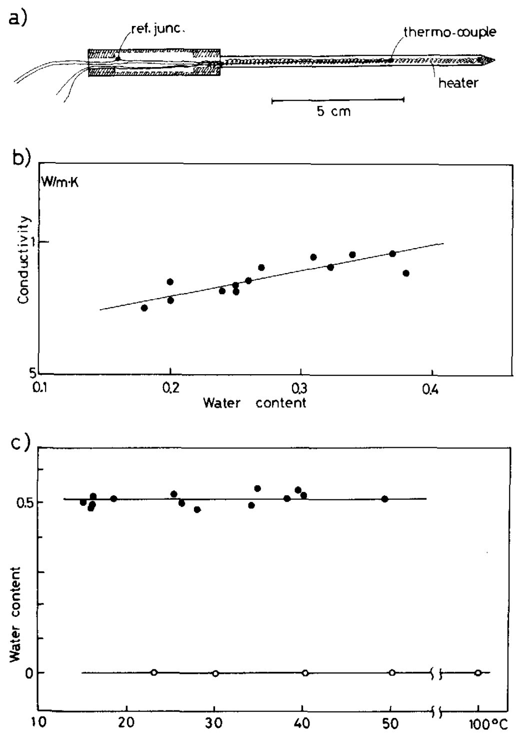

Fig. 2 a) Schematic of the soil moisture instrument.
b) Calibration curve. Heat conductivity expressed as a function of volumetric water content.
c) Dependency of the moisture sensor output on the soil temperature. The upper curve is for the wet soil, and the lower for the dry soil.

thermocouple junction was located at the end of the sensor being isolated from the heater. The sensors were installed in the experimental field 3 months ahead of the observation period. The heat conductivity was measured by supplying the heat to the pipe in a step function and by sampling the temperature rise. A steeper temperature rise implies a smaller heat conductivity thus smaller water content. Measurements were made every 30 minutes. The temperature sampling was made every 10 seconds between 1 min. and 3 min. after the heater was turned on. The computation of heat conductivity was made in real time by a micro-computer and stored on a floppy disk together with other outputs.

The relation between the heat conductivity and soil moisture for the present field is shown in Fig. 2 (b). The volumetric water content of the soil was measured by the oven dry method. The calibration was made during the observation period. In order to examine the temperature dependency of the moisture sensor an oven test was made by changing the temperature from about 15°C to 100°C for 2 kinds of water content (see Fig. 2 (c)). No temperature dependecies are seen in the dry soil. Although a considerable scatter is seen under wet conditions, systematic trend were not recognized.

Soil temperature was measured at the same depth as the soil moisture sensors by copper-constantan thermocouples.

3. Variations of Water and Water Vapor near the Surface

The time changes of the volumetric water content in the soil, specific humidity in the

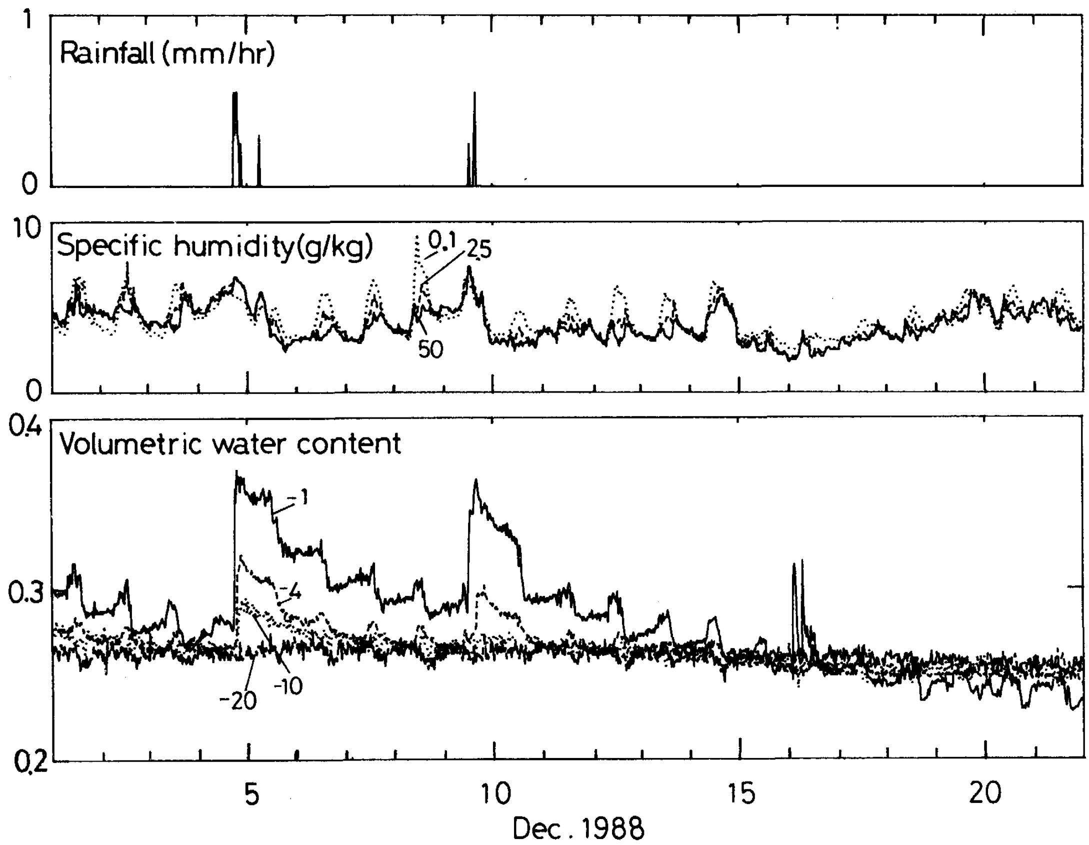

Fig. 3 Variations of the specific humidity in the air and the moisture in the soil for the whole observation period. The numbers in the figure indicate the distance from the surface in cm. At the top is the houry rainfall during the period.

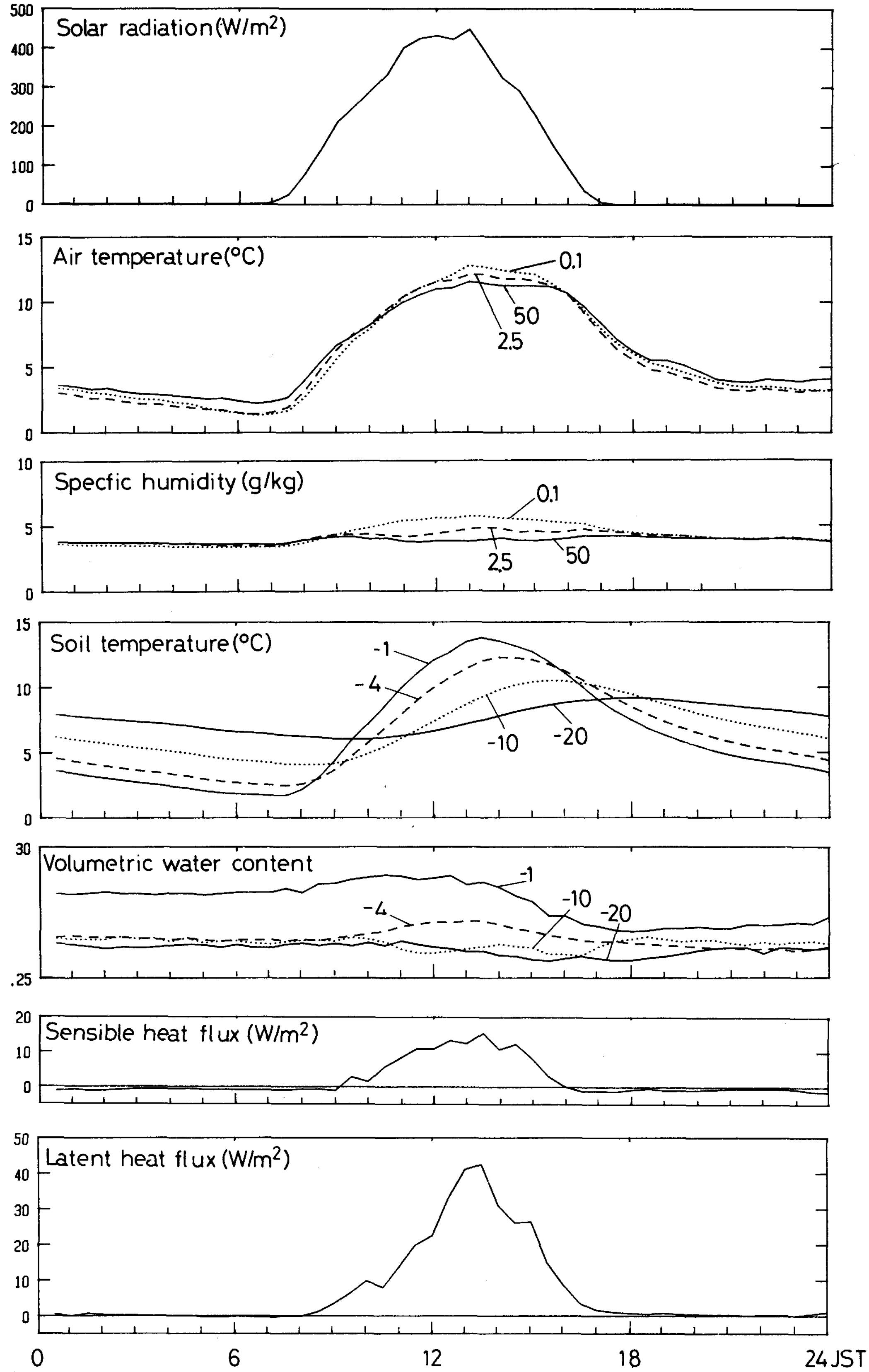

Fig. 4 Superpositions of the diurnal variations. The total number of days is 18. The days of rain and snow are omitted. The number indicating the curves are the distance from the soil surface in cm.

air during the whole observation period are indicated with the rainfall in Fig. 3. There were considerable amount of rainfall before the start of the observation and the soil in the upper layer was wetter than below at the beginning. During the period of the observation, there were precipitations on the 4th and the 9th day. Sharp increases occurred in the water content corresponding to each rainfall. Toward the end of the observation period, the upper layers became dryer than the lower layers. There was a snowfall on December 16. The amount was so small that it was sensed only by the moisture sensor at 1 cm depth. The amplitude of the diurnal moisture variations decreased steeply as the depth. Only small changes were recorded at the depth of 20 cm.

The superpositions of the diurnal changes except for the rainy and snowy days are presented in Fig. 4. The time that the soil moisture at 1 cm depth started to decrease was around noon, which is a few hours after the start of the evaporation. This delay is larger in deeper soil, i.e., about 1300 JST at the depth of 4 cm and about 1430 JST at 10 cm. At the depth of 20 cm, although it is difficult to determine, the time of decrease seems to occur approximately at 1600 JST. The mechanism that the moisture increases in the soil even when the surface evaporation is going on may be attributed to the water movement due to the temperature gradient in the soil. The moisture kept near the soil surface during the night may start being transported down into the soil as well as into the atmosphere when the solar radiation hits the surface. Large enhancements of the water vapor transport are known to occur when temperature gradients exist in the soil. A number of investigations have been made concerning this enhancement mechanism (e.g. CASS *et al.*[13]), PHILIP and deVRIES[14])). However no reliable relations have been formulated.

The variations of the water vapor content in the air adjacent to the soil surface is also presented in Fig. 4. There are a few points to be noted in the diurnal variation of the atmospheric moisture near the ground. Compared to the moisture variation in the soil, the response of moisture in the atmosphere to the insolation is fast. The humidity in the surface skin layer (between 0 and 0.2 cm) responds to the intensity of the solar radiation and varies in similar way to the temperature variations. The humidities in the upper layers (2.5 and 50 cm) start to increase similar to those in the skin layer in the early morning, but they stop increasing around 0900 JST and even tend to decrease in later hours at 50 cm height. This is a remarkable difference from the reguler sinusoidal changes observed in the air temperature. This may be caused by the difference in the transport mechanism of the sensible heat and latent heat, i.e., the divergence of the moisture flux is larger than that of the sensible heat flux in this shallow layer. This difference is yet to be explained.

4. Response of the Soil Moisture

One of the measures to indicate the mobility of the moisture in the soil is the hydraulic conductivity. The hydraulic diffusivity is also used to indicate the transport of moisture in the soil. The hydraulic diffusivity is defined as the coefficient when the flux of water is proportional to the gradient of water content. If it is assumed that the water content varies periodically, then we may determine the diffusivity from the phase difference of the moisture variation at two depth in the soil. The relation between the phase difference in the moisture at 1 and 4 cm depths computed by the harmonic analysis for the component of the 24 hour period and the volumeteric water content of the soil at these depths is shown in Fig. 5. In order to convert the phase difference for the com-

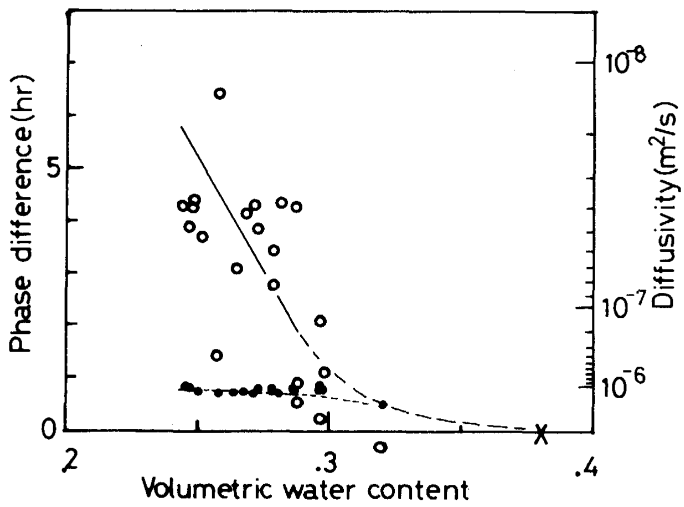

Fig. 5 Phase shift or derived diffusivity of the moisture content (circle) and temperature (dot) as functions of volumetric water content.

ponent of 24 hours ϕ (hours) between -1 and -4 cm into the diffusivity, D (m^2/s), the relation $D = (86400/4\pi)\,(0.04 - 0.01)^2/(3600\phi)^2$ is used. The phase difference in the soil temperature is also shown for comparison. It is seen that the diffusivity of the moisture is more than an order of magnitude smaller (about 1/20) than that of the temperature. The phase difference seen in the downward advance of the wetting front on rainy days (Fig. 3) is less than half an hour between -1 and -4 cm. This is plotted as the value for the saturated condition (about 0.38 for this soil) by the simbol X in Fig. 5.

5. Relation between the Evaporation and the Moisture Change

Since the time scales of the moisture variation in the air and the soil are entirely different as discussed in Section 3, it is not possible to obtain the agreement between the amount of evaporation and the rate of change in the soil moisture on the basis of short period averages. For example, the soil moisture at -1 cm continued to increase even the surface evaporation started in the morning as seen in Fig. 4. In order to obtain an instantaneous agreements between both quantities, better knowledges of the water transport mechanism in the liquid and vapor phase under the existence of moisture and temperature gradients are required. Under ideal conditions, however, the agreement in both quantities should be attained if the sampling duration is large enough. Nevertheless, it is usually difficult because of the inhomogeneity of the soil at the measuring point and/or the percolation of water into the deeper layers. In Fig. 6, the evaporation into the atmosphere is compared with the time change of the moisture for various depth on the basis of daily average. The data on the rainy days are omitted from the analysis. For the layer between the surface and -20 cm, the rate of the moisture decrease always larger than the evaporation in this observation. If we consider only the layer between -1 and -4 cm, the magnitude of these quantities agrees, although there are scatters. The situation does not change much even when the layer only between 0 to -2 cm (i.e., -1 ± 1 cm) is taken into account. This may suggest the possibility to parameterize the rate of the surface evaporation in terms of the moisture change near the surface.

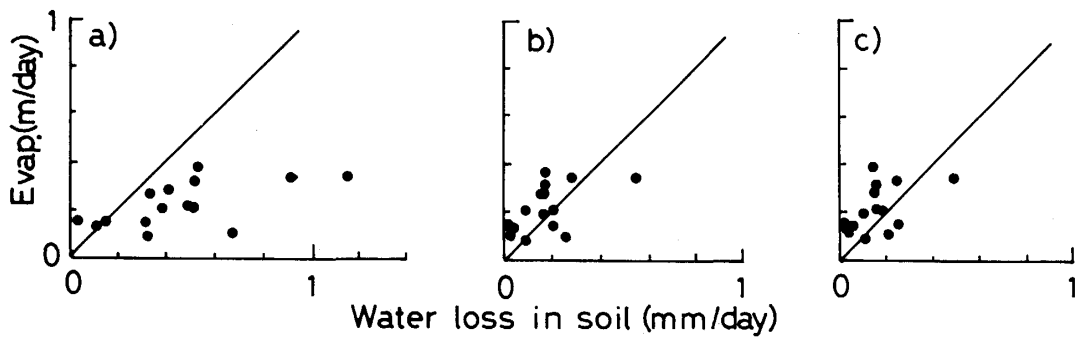

Fig. 6 Comparison of the daily evaporation and changes in the soil water content.
a) Changes of the soil moisture in the layer 1 – 20 cm,
b) Same but for the layer 1 – 4 cm,
c) Only 1 cm moisture is used.

6. Summary and Conclusion

The dynamic characteristics of moisture in the thin layers of atmosphere and soil near the boundary are studied based on a field experiment. Sensors to approach the soil-atmosphere interface were developed and applied to bare soil surface. The experiment was carried out in winter and following results were obtained:

1) In the air, the diurnal moisture changes are not simple compared to those in temperature. The moisture at the height of 50 cm above the soil surface does not continue to increase after the start of insolation. It even tends to decrease before noon in most of the fine days.
2) In the soil, the moisture variations are not simple either, compared to those in temperature. Components of the longer term variations than diurnal period are more predominant.
3) The diurnal variations are also well recognized in the soil moisture and it is possible to derive the moisture diffusivity from the variations. The hydraulic diffusivity derived from the harmonic analysis increases as the soil moisture content. Its values are an order of magnitude smaller compared to the thermal diffusivity.
4) Moisture in the shallow layer starts to decrease daily at around noon although the surface evaporation starts right after the insolation first hit the ground.
5) The amount of evaporation is related to the soil moisture changes only for the shallow soil layer.

Although the very thin layer was investigated by locating the sensors close to the surface boundary in both atmosphere and the soil, it is concluded that phenomena which occur even in a shallower layers, i.e., the layers less than 1 cm thick, may be playing important rolls in evaporation.

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