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A Phenomenon of Inverse Humidity Gradient and Negative Vapor Flux Over the Desert in the Daytime as Observed from Mast Profile

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Abstract

A phenomenon of inverse humidity gradient and negative or downward vapor flux over the desert in the daytime as observed in the HEIFE has been analyzed from the results of preliminary observations over the sand desert. Water is transported downward at the rate of about 1 mm/day on a fine day as estimated from a profile of between 4–8 m in the surface layer.

1. Introduction

The hydrological processes have a great influence on the world climate and general circulation of the atmosphere. The First Hydrologic Atmospheric Pilot Experiment (HAPEX-MOBILHY) program (Andre et al., 1986)[1] is carried out in southwest France aimed at studying the hydrological budget and evaporation at the scale of a GCM (General Circulation Model) grid. Sino-Japanese Cooperative Program on the Atmosphere Land Surface Processes Experiment (HEIFE) peformed at the Heihe River Basin in the western China is to study the hydrological budget within an arid region, as the Third HAPEX.

The evaporation or the water vapor flux from ground surface is the most important component in the hydrological budget. The latent heat flux may dominate in the energy budget in moist areas. Plenty of researches on evaporation in moist areas have been executed, but those in arid areas are relatively rare.

A pilot observation of HEIFE had been conducted during September, 1988. The results obtained by the Energy Balance Method (Hu and Qi, 1990)[2] and the Eddy Correlation Method (Wang and Mitsuta, 1990)[3] show that there is a phenomenon of inverse humidity gradient on the Gobi (Gravel Desert), which means that water vapor flux is downward in the surface layer in the daytime under the condition of settled fine weather.

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This paper attempts to study the characteristics of water vapor transport and the energy budget on the ground surface of the desert in the Heihe River Basin, Gansu Province of China by analyzing the profile data obtained in the surface layer at the Desert Station of the HEIFE from July to September, 1990.

2. Observation Site and Instrumentation

The Field Observation Period (FOP) of the HEIFE started on 26 June 1990. Five fundamental stations in the FOP were set up at Zhangye(001), Linze(002), Pingchuan(003), Huayin(004) and Desert(005) (see Fig. 1). Stations 001 and 002 are located in an oasis, 004 in the Gobi, 005 in a desert, 003 in an oasis bounded on the north by a desert. A Mobile Station of LIPAP was set up in the desert at the 005 point during the period from June 26 to September 28, 1990 as the instruments at Station 005 had not yet been installed.

The Desert Station(005) is located in the northern region of the experimental area, and to the northeast of the oasis. Air flow from the northwest, north, northeast or east is from the Gobi or desert, so the underlying surface at this station is a representative one of the desert experimental area. The desert is formed by the encroachiment of the Badanjuran Desert upon the northern part of Gansu Province, and it is a tongue shaped belt. The desert belt is about 20 km long and 8 km wide, lying approximately north to south. Both sides of the desert belt are Gobi, the southern tip of the belt being connected to an oasis.

The terrain of the Desert Station is fairly even, and is somewhat higher to the north with a slope of 0.05 percent. Elevation of the station is about 1400 m. Daqin Mountain, the main peak of which is 2084 m, is 25 km to the northwest of the station. Because of the effect of this mountain, air flow at the station is mostly from the northwest and that from north is rare.

A tower with 6 observation levels of 0.5, 1, 2, 4, 8 and 16 m was set up at the station. The sensors for wind speed, temperature and humidity were mounted at each level, and a wind vane was set at a height of 10 m. In addition, radiometers used for measureing incoming shortwave and infrared radiation as well as outgoing radiation were mounted on a separate mast of about 2 m high. Four thermometers were mounted in various directions on the ground surface to measure its temperature. Sensors for soil temperature were set at the depths of 5, 10, 20, 40, 80, and 160 cm, and two heat flux plates were set at depths of 5, 10 cm separately.

All sensors had been calibrated before observation. The wind speed sensors were supplied by the BELFORT Company, U.S.A. (Model 1022S), and the platinum film temperature sensor by Mathey Electronic Company, U.K. (Model Thermafilm 100 W 30). Two platinum films were joined as twin arms of an electronic bridge, and mounted on adjacent layers of the tower to measure air temperature difference between the two layers to improve the precision of air-temperature gradient measurement. The humidity sensors were supplied by Vaisala Company, Fin-

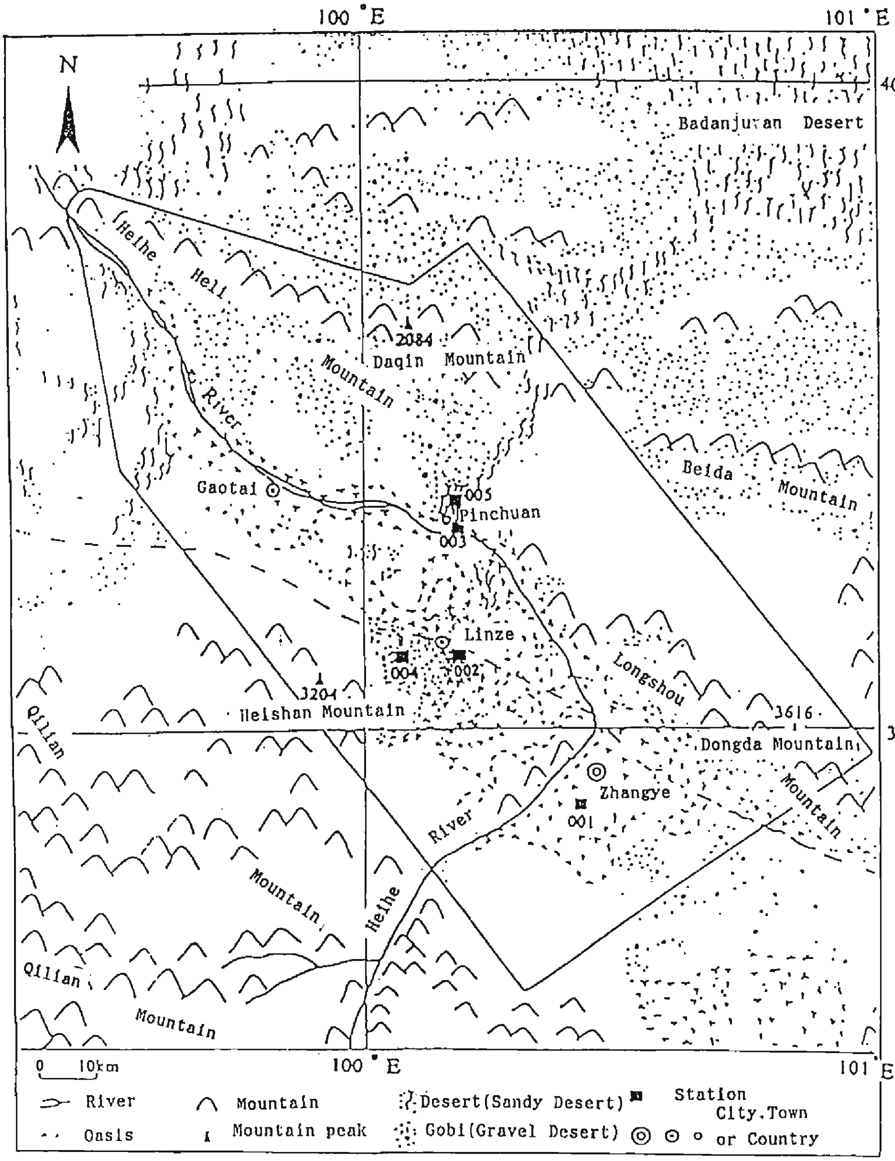


Fig. 1 Location of the HEIFE Prcgram net work.

land (Model HMP 35A), the shortwave incoming and reflected radiometers (Model MR-21) and the soil heat flux plates (Model CN-81) were supplied by the EKO Company, Japan, and the infrared radiometers (Model PIR) by the Eppley Company, U.S.A. The thermal conductivity of the soil heat flux plates was 0.22 $wm^{-1}\,k^{-1}$.

In order to research the characteristics of water vapor transport, we must know the consistency among the sensors or their in precision gradient. For this reason we made strict comparison experiments two times at the same height of 2 m. The first one conducted from May 30 to June 2, 1990; in this experiment 6 temperature sensors and 6 humidity sensors had been tested. The average standard errors of those sensors were 0.05°C for temperature and 0.06 g/kg for specific humidity. The second one, in which 10 temperature sensors and 10 humidity sensors were tested, had been performed from July 4 to July 8, 1991. The average standard errors gained in the experiment were 0.10°C for temperature and 0.08 g/kg for specific humidity. Therefore, we can consider actual precision of gradient to be better than 0.10°C for temperature and 0.08 g/kg for specific humidity from June to October in 1990.

3. A Phenomenon of Inverse Humidity Gradient

A phenomenon of inverse humidity gradient arises in the daytime over the desert on dry clear days. The temperature and specific humidity profiles in the daytime at the Desert Station are given in Figure 2 for three days, August 30, and September 4 and 29, 1990.

The three days were fair, but the wind directions were different. The wind directions were from south in the daytime on August 30, from east on September 4 and from northeast on September 29. The airflow was mainly from the oasis in the daytime on August 30, from Gobi or a little oasis on September 4, and from the desert and Gobi on September 29, so the wind directions of the three days are representative for all cases.

It is observed that the temperature profiles are unstable but the specific humidity profiles present an inverse humidity gradient state. We can see from these figures that specific humidity at 16 m is 0.4–1.0 g/kg more than that at 0.5 m. Because the gradient precision is better than 0.08 g/kg, this phenomenon of inverse humidity gradient is credible. The profiles in the daytime on clear days from June 26 to October 7 are generally quite similar to each other.

An observation over the desert near Pinchuan by a Japanese group also testified to the phenomenon of inverse humidity gradient (Sahashi et al., 1990)[4]. Harazono et al. (1991)[5] also reported downward turbulent flux of water vapor in the daytime from profile measurement within 5 m from the ground over the desert of Inner Mongolia.

4. Calculating Method of Fluxes

The Combination Method (Hu, 1990[6], Hu et al., 1991[7], Thom et al., 1975[8]) has been used to determine water vapor flux, the sensible heat flux and latent heat flux. This method combines the Aerodynamic Method with the Energy Method to calculate the turbulent fluxes.

Under a diabatic condition, the flux to gradient relationship can be written from aerodynamic considerations as follows,

$$\frac{kz}{u_*}\frac{\partial u}{\partial z} = \phi_M \tag{1}$$

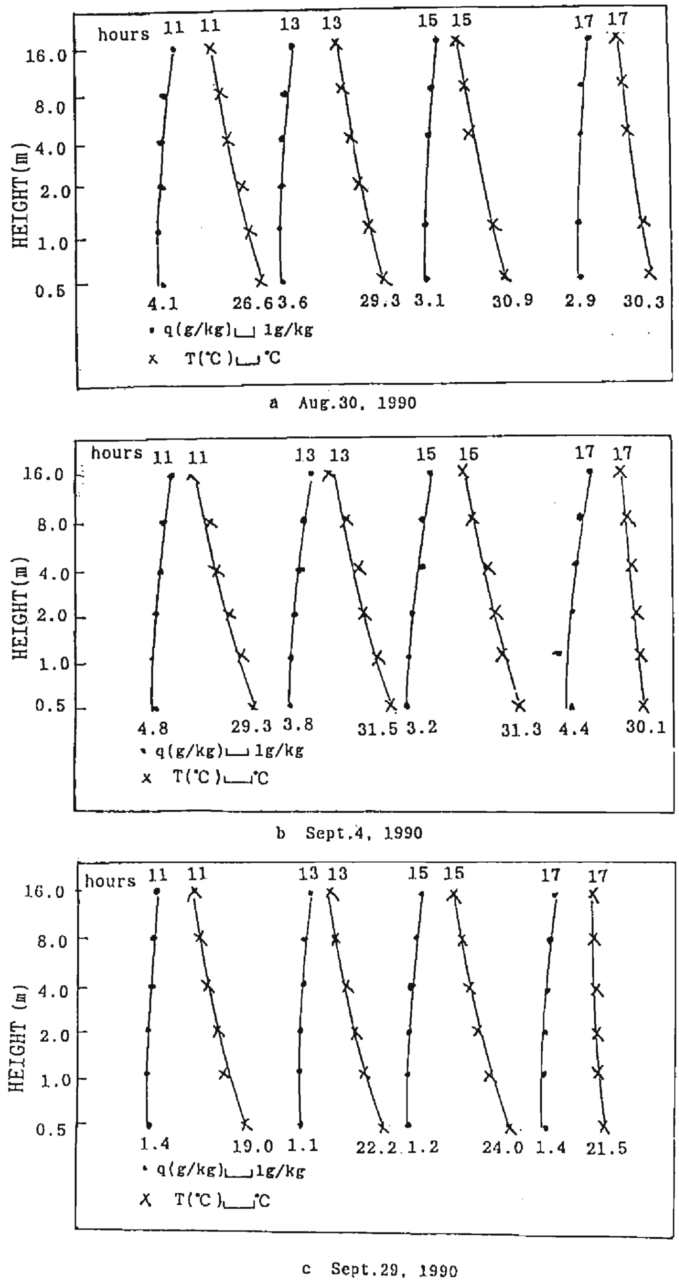


Fig. 2 The profiles of air temperature (cross) and specific humidity (dot) in the daytime at Mobile Station at Desert (005);
a: August 30, 1990. b: September 4, 1990 and c: September 29, 1990.
The values at the bottom of profiles show specific humidity and air temperature at 0.5 m at the time shown above.

$$-\frac{kz}{q_*}\frac{\partial\theta}{\partial z}=\phi_H \tag{2}$$

$$-\frac{kz}{q_*}\frac{\partial q}{\partial z}=\phi_v \tag{3}$$

where k is von Karman's constant, z height from the ground, u_* friction velocity, θ_* friction potential temperature defined by $H/\rho C_p u_*$ and q_* friction specific humidity defined by $E/\rho\, u_*$, ϕ stability function, and subscripts M, H and v being for momentum, sensible heat and water vapor exchange respectively.

From Eqs(1) and (2), we can define H_0 and influence function F as follows

$$H_0(\phi_H\,\phi_M)^{-1}=H=F_H\,H_0\,, \tag{4}$$

where $H_0=-\rho C_p k^2 z^2\dfrac{\partial u}{\partial z}\dfrac{\partial\theta}{\partial z}$ and $(\phi_H\,\phi_M)^{-1}=F_H$. And from

Eqs(1) and (3), we can also define $(LE)_0$, as

$$LE=(\phi_v\,\phi_M)^{-1}(LE)_0=F_v(LE)_0 \tag{5}$$

where $(LE)_0=-\rho Lk^2 z^2\dfrac{\partial u}{\partial z}\dfrac{\partial q}{\partial z}$ and $(\phi_v\,\phi_M)^{-1}=Fv$.

Various form of the stability functions have been reported by many investigators, but their results are not so greatly different from each other. The results of Businger et al., (1971)[9] are as follows,

$$\phi_M=\begin{cases}(1+15\,Z/L)^{-1/4} & Z/L\leqq 0\\ 1+4.7\,Z/L & Z/L>0\end{cases} \tag{6}$$

$$\phi_H=\phi_v=\begin{cases}0.74(1-9Z/L)^{-1/2} & Z/L\leqq 0\\ 0.74+4.7\,Z/L & Z/L>0\end{cases} \tag{7}$$

where L is the Monin-Obukhov stability length. Z/L can be related to Richarson Number, Ri in near neutral conditions following Businger, (1966)[10], (1988)[11] and Pandolfo, (1966)[12],

$$\begin{cases}Z/L\fallingdotseq R_i & R_i\leqq 0\\ Z/L=R_i/(1-5\,R_i) & 0<R_i<0.2\end{cases} \tag{8}$$

where $R_i=(g\partial\theta/\partial z)/\{T(\partial u/\partial z)^2\}$. Thus we can compute these parameters, and consequently turbulent fluxes from profile observations by the aerodynamic method. However, in this relation ϕ_V is supposed to be equal to ϕ_H or $F_V=F_H$. This is somewhat doubtful in the arid area from the results of direct measurement of turbulent fluxes (Wang and Mitsuta, 1991)[13]. The detailed discussion will be made in a coming paper.

The influence function is also defined from energy balance considerations to be (Thom et al., 1975[8], Hu, 1990[14]):

$$F=(\phi_{v,H}\,\phi_M)^{-1}=\frac{A}{H_0+LE_0} \tag{9}$$

where A is the available energy on the ground surface, defined as:

$$A = R_n - G - S \tag{10}$$

where R_n, G and S are repsectively, net radiation, soil heat flux at a depth and rate of heat stored within soil layer between ground surface and a layer on which soil heat flux is measured. The formula used for calculating the stored soil heat in the unit time is given by:

$$S = C \frac{\partial T_S}{\partial t} \delta z \tag{11}$$

T_s is the mean temperature of the soil layer between ground surface and a depth of the heat flux plate, t time, with C being the soil thermal capacity, taken as $1.28 \times 10^{-6}\,\mathrm{Jm^{-3}K^{-1}}$ for sandy soil (Oke, 1981)[14].

Inverse humidity gradient means that the water vapor flux is downward. However, it seems that it doesn't condense on the surface and that the downward water vapor in the air is possibly stored in the surface layer. Because it is so hot and dry in the daytime on clear summer days that it is impossible for water vapor to be condensed to liquid water on ground surface, as well as the fact that the water vapor deosn't change its phase, the latent heat has nothing to do with the energy budget on the surface. In this case the sensible heat flux H becomes,

$$FH_0 = H = R_n - G - S \tag{12}$$

and LE is zero. And in the normal or decreasing upward humidity gradient case,

$$\left\{\begin{aligned} H &= \left(\frac{A}{H_0 + LE_0}\right) H_0 \\ LE &= \left(\frac{A}{H_0 + LE_0}\right) LE_0 \end{aligned}\right\} \tag{13}$$

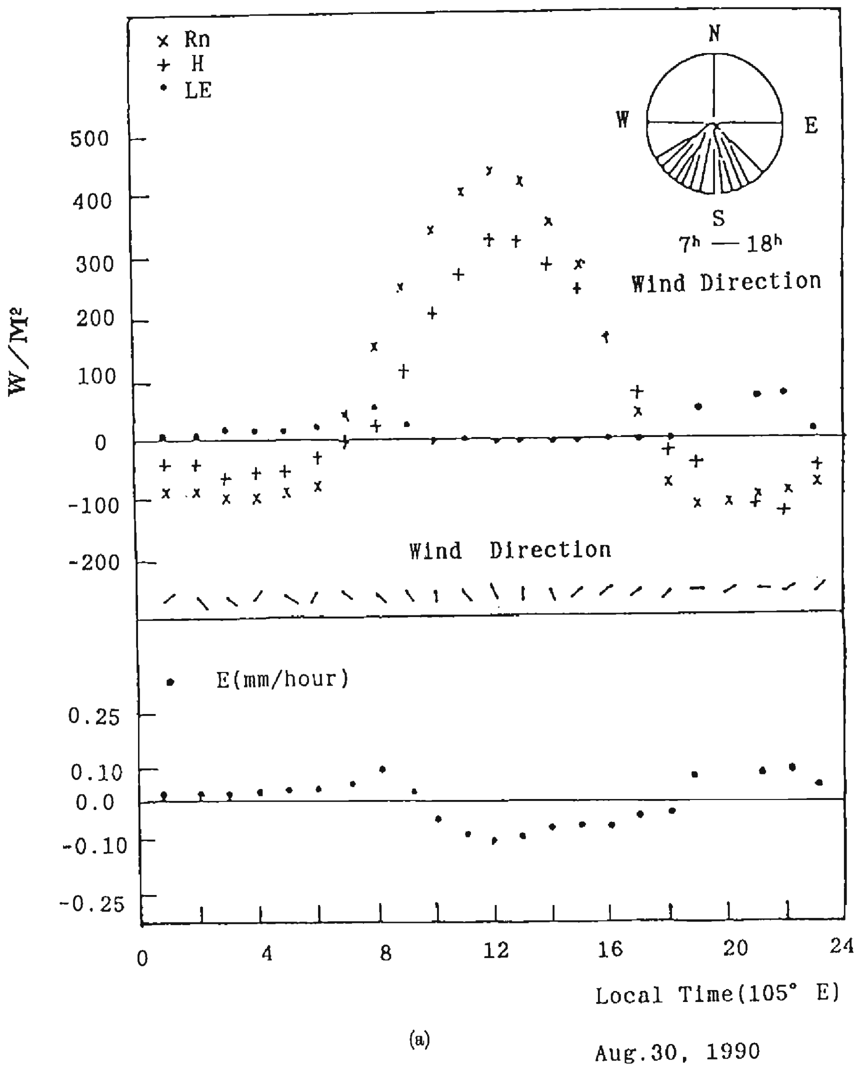
5. Negative Water Vapor Flux and Characteristics of Energy Budget on the Desert Surface

Fugure 3 shows diurnal variations of the components of energy budget on the surfcae and the turbulent fluxes of water vapor determined by the aerodynamic method with the mast profile of 4–8 m on August 30 (a), September 4(b) and September 29(c), 1990. Because the measurements of soil parameters at 5 cm depth were erroneous, the values were estimated by some empirical relations from the observations at 10 cm depth on September 29, 1990. The wind direction at every hour is marked below the figure of the energy budget, and the wind direction ranges from 07h to 18 h are shown in the upper right-hand corner.

In general, the vapor flux from the mast profile is negative in the daytime, i.e. downward, but latent heat flux at the surface is zero. Therefore, the sensible heat flux is dominant in the energy budget on the desert surface.

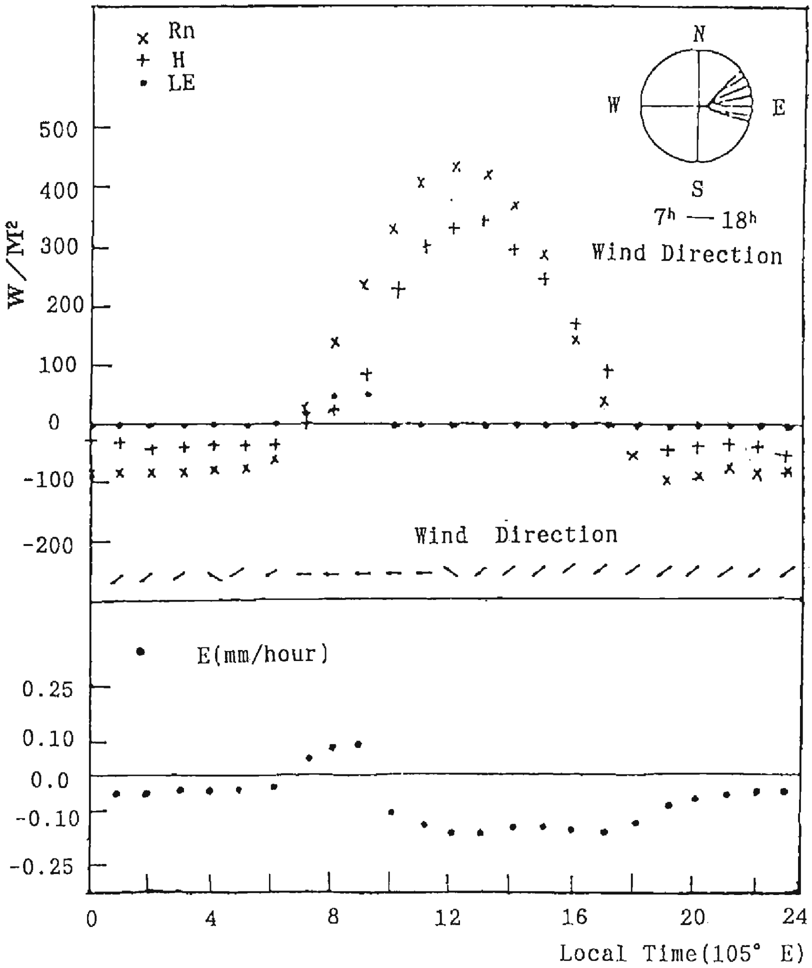
At night, the vapor flux is sometimes negative (e.g. September 4 and 29) or sometimes positive (e.g. August 30). When the vapor flux is positive, i.e. upward, evaporation arises also on the surface. But latent heat flux is almost zero when the water vapor flux at the surface is negative at night.

The integral values of negative water vapor flux in a day are —0.9 mm/day on August 30, —1.5 mm/day on September 4 and —0.65 mm/day on September 29 respectively. This means that the integral value of negative water vapor can amount to 1 mm on a clear day.



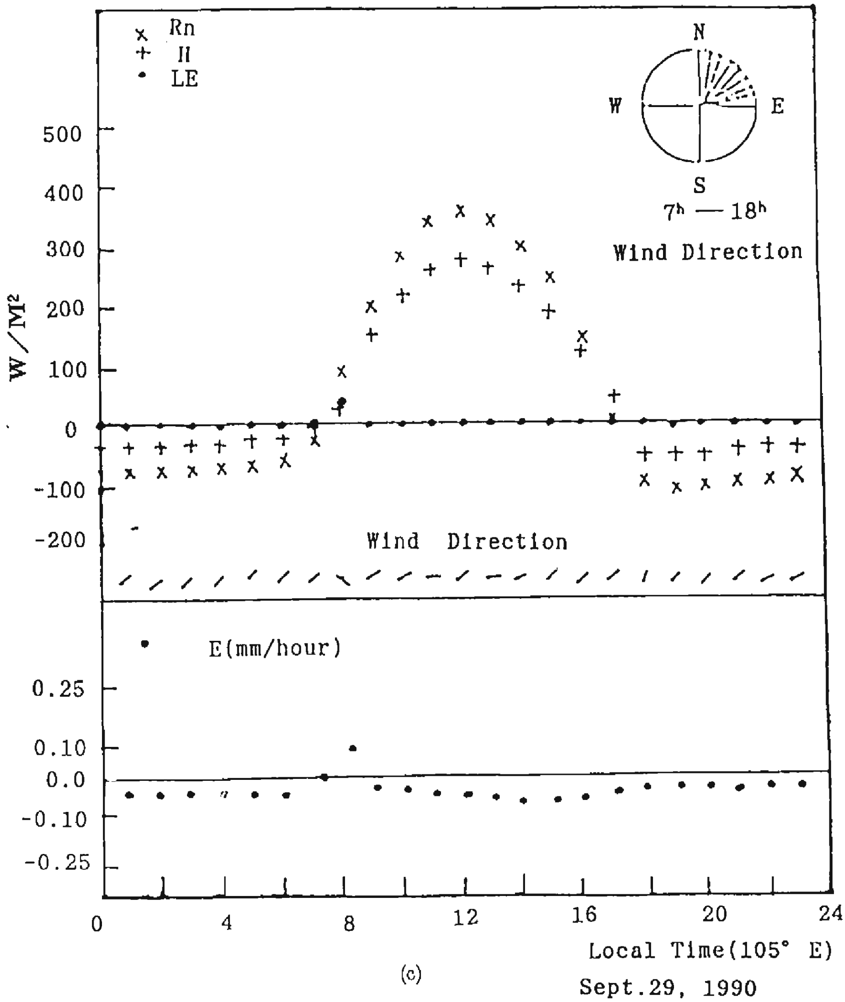
(a)

Fig. 3 a, b, c The energy budget at the surface and turbulent fluxes of water vapor estimated by the profile (4–8 m).


Rn
H
LE
N
W
E
S
7^h — 18^h
Wind Direction
W/M²
500
400
300
200
100
0
-100
-200
Wind Direction
E(mm/hour)
0.25
0.10
0.0
-0.10
-0.25
0
4
8
12
16
20
24
Local Time(105° E)

(b)

Sept.4, 1990



(c)

Upward transport of water vapor was seen at about 8 o'clock in the morning both at the surface and in the boundary layer on all three days.

6. Discussion

A phenomenon of inverse humidity gradient exists over the desert in the daytime on clear days, and the profiles of specific humidity in the air indicates the specific humidity increases with height above the ground. However, the minimum height of our observation was 0.5 m, and the structure of specific humidity could not be described below this level. Even if there is very weak latent heat flux, it is almost zero and can be neglected compared with the sensible heat flux in the daytime. Where does the downward water vapor go and what is the mechanism of inverse humidity near the ground surface? These problems are very important in the research into interaction between land surface and atmosphere, and more measurements are required.

Another problems are where the downward water vapor initiates from and when the phenomenon of inverse humidity gradient arises. It is usually supposed that wet air over an oasis is transported over to the desert by the local advection. However, sometimes air flow is from over the dry desert or Gobi when the phenomenon of inverse humidity gradient appears. This implies that wetter air is transported over to the station by macro- or meso-sclae advection and then transported downwards by turbulence within the atmospheric boundary layer over the desert.

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