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Methods for Estimating Evapotranspiration under Wet and Arid Field Conditions

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Abstract
In order to establish a suitable technique for estimating evapotranspiration (ET) on dry lands, comparisons of the three methods, i.e. those with heat budget (Bowen ratio), gradient (aerodynamical) and eddy correlation, were made in two locations in Japan: one was Oharai seaside, Ibaraki in November 1989, and another was a wheat field of Tropical Agriculture Research Center (TARC), Tsukuba, Ibaraki in May 1989. When the ET was measured on a wet ground, the values obtained with those three methods varied slightly. In accordance with the increase in aridity of the ground, greater rates of reduction of the estimated ET were observed when the measurements were made with the gradient and eddy correlation methods as compared to those with the Bowen ratio. It may be concluded therefore that the format two methods would be suited for application under dry land conditions. In case where any influence of windbreak forest comes in, the Bowen ratio was recognized to be more suitable than the gradient method in obtaining an accurate estimation.

Discipline: Agricultural meteorology
Additional key words: desert, dry land, latent heat, flux, sensible heat flux, wind

Introduction

In order to attain sustainable agriculture on a marginal dry land, it is very necessary to prevent the land from natural disasters which are frequently caused by drought and wind erosion. Under that condition, efficient use of available water is vital in carrying on dry-land farming. Toward this end, a precise understanding on water movement from the ground would be required. In this connection, an exact estimation of evapotranspiration (ET) from the ground is called for as the main factor of determining water balance and movement.

In the course of implementation of the China–TARC joint research project in Turfan, Xinjiang Uygur Zizhiqu, China, pertaining to the study on water dynamics and soil characteristics in dry land, it was recognized that there was an urgent necessity of choosing a suitable method applicable to an arid environment. This paper discusses the comparative usefulness of some methods for evaluating ET, as applied to the conditions in the experimental fields.

Investigations were made on the following three methods, i.e. those with heat budget (balance) or Bowen ratio (Br), gradient (Gr), and eddy correlation (Ec), with emphasis placed on their applicability to dry land conditions. The results obtained are expected to be useful in interpreting the observations of the study in Turfan, China, where the Br and Gr methods were employed.

There are some other methods available for the same objective as mentioned above, such as Penman's and Morton's[2]. In this respect, Ohba[4] states that the Morton's method, though accurate, uses empirical constants, which seriously limits its wide applicability. The three methods as above were therefore selected, taking into account the extremely dry conditions encountered in northwest China, to which they should have to be applied. The estimates

were compared with those data obtained from a small-pan type evaporimeter.

Observation methods

1) Observations on the sands of seaside

Meteorological observations were made on the seashore sands of the Seaside Park, Oharai, Ibaraki Prefecture, Japan during the period of November 14 to 25, 1989[1]. Details on the varieties and types of instruments used for observations with the Br and Gr methods are described hereafter.

The instruments used are photo-electric types of wind vane (VFO16) and anemometer (AF750) made by Makino Ohyosokki Kenkyusho Inc. Japan. The wet and dry bulb thermometer (TR-203), which consists of a sensor covered with wet gauze and a naked sensor, and also the temperature difference thermometer (TSD-02) used are of thermo-junction type. The soil thermometer (TRG-20) is of a platinum resistance type. The diameter of both rain gauge (MR-100) and small-pan type evaporimeter (NO-41) is 20 cm. The sunshine recorder (H-016), solarimeter (MS-42), net radiometer (CN-40) and heat flow plate (CN-81) are made by Eko Seiki Inc.

The instruments for Ec or direct method comprise an ultrasonic anemometer thermometer (WAT-395) and an infrared hygrometer (AH-100), each made by Kaijo Denki Inc., which are of the types of 5 and 20 cm spans, respectively.

The instruments for observations and the conditions of their installation are as follows:

Air temperature was measured with a dry bulb thermometer at the heights of 2 and 1 m each, and two temperature differences were measured at the heights of 0.6 and 1.4 m, and of 1.5 and 2.5 m. Measurements of wet bulb temperature and relative humidity were taken at the two heights of 2 and 1 m. Wind speed was measured at the heights of 3, 2, 1, 0.5 and 0.3 m each and wind direction was specified at the height of 4 m. Soil temperature and soil transfer heat were determined at depths of 1 and 6 cm each. Net radiation was investigated at the 1.5 m height, and solar radiation, sunshine duration and albedo were measured at the 1 m height. Rain and evaporation were measured with a small type evaporimeter at the ground level.

An ultrasonic anemometer and an infrared hygrometer were set for taking measurements at 138 and 127 cm, respectively, as a middle of the sensor height. The standard height for the Br method was fixed at the ground level, and the average heights for the Gr and Ec methods were 150 (100 to 200) and 132 cm, respectively.

The distances between the anemometer, and the thermometer, hygrometer, soil thermometer and soil flow plate were 2 m in the Br and Gr methods. The distance between ultrasonic anemometer and infrared hygrometer was 1 m in the Ec method.

The meteorological data for the former two methods were recorded in a card memory for analyses, and those for the latter method were in the hard-disk of a PC-98 computer.

2) Observations in the wheat field

The meteorological observations[1] were made in the wheat field of the TARC (Hachimandai) during the period of May 15 to June 5, 1989. The observation elements and their installation conditions were almost the same as those at the Oharai seaside with some exceptions for several levels of observation heights. The wind speed was measured at the heights of 4, 3, 2, 1.6 and 1.2 m, and the air temperature and humidity were at the heights of 2 and 1 m.

Methods for analyses

1) Three equations of the evapotranspiration

Three equations of the evapotranspiration[3,5] for data analyses are made available as follows:

(1) Bowen ratio method

Bowen ratio (β), sensible heat flux (H) and latent heat flux (lE) are expressed by the following equations.

$$\beta = 0.5 \frac{T_1 - T_2}{e_1 - e_2}, \quad \cdots\cdots (1)$$

$$H = \beta \frac{Rn - B}{1 + \beta}, \quad \cdots\cdots (2)$$

$$lE = \frac{Rn - B}{1 + \beta}, \quad \cdots\cdots (3)$$

where T_1, T_2 and e_1, e_2 are air temperatures (°C) and water vapor pressures (mmHg) at the heights (z) of level 1 and 2. Rn: net radiation, B: soil heat flux, and l: latent heat.

(2) Gradient method

The water vapor flux (E) is expressed by the

equation (4).

$$E = \frac{-\rho \kappa^2 (u_2-u_1)(q_2-q_1)}{\ln(z_2/z_1)^2}, \quad \cdots\cdots (4)$$

where ρ: air density, κ: Karman's constant ($=0.4$), ln: natural logarithm, u_1, u_2 and q_1, q_2 are wind speeds and specific humidities at the heights of z_1 and z_2, respectively.

(3) Eddy correlation method

The water vapor flux (E) averaged with time (t) is expressed by the equation (5).

$$E = \rho < q' w' >_t, \quad \cdots\cdots (5)$$

where $'$ denotes a value of turbulent fluctuation, w is a vertical wind component and $< >$ is a mean over time (t).

2) Observations at the seaside

It rained during the period of Nov. 17 to the early morning of Nov. 18. The sand surface of the seaside ground was fully wet. Clear and fine days continued from Nov. 18 until Nov. 25.

3) Results in the wheat field

The equation (4) is utilized for the gradient method. However, in that equation, the zero plane displacement (d) has to be subtracted from the height (z) because the wheat plants grown on the ground surface make roughness. The water vapor flux (E) for the wheat field is therefore expressed by the equation (6).

$$E = \frac{-\rho \kappa^2 (u_2-u_1)(q_2-q_1)}{(\ln(z_2-d)/(z_1-d))^2}. \quad \cdots\cdots (6)$$

The equatioins (2) and (3) for the Br method are also applicable to the wheat field.

The plant height at the time of investigation was 105 cm, with zero plane displacement (d) = 75 cm and leaf area index (LAI) = 5.08.

The data taken on May 18 and 22, 1989 were subjected to analyses, on the basis of which results the three methods for estimating ET are compared in the present paper.

Results

1) Results on the sands of seaside

(1) Bowen ratio method

Variations of heat flux elements observed on Nov. 18, 19 and 24 are shown in Fig. 1. Since it was clear and fine on Nov. 18 and 24, the variations in solar and net radiations were both small and the former exceeded 500 W/m^2 around noon in those three days. The variation patterns show that the maximum values of sensible and latent heat fluxes were seen at 12:00–14:00 on Nov. 24. The time lag of variations of lE or H and S or Rn was possibly caused by the drier condition of the sand surface. The values of latent heat flux were larger on Nov. 18 and 19 than those on Nov. 24. The ET considerably decreased due to the dry condition of the sand surface. The soil heat flux was high in the morning, reaching almost zero at 13:00, and dropped to

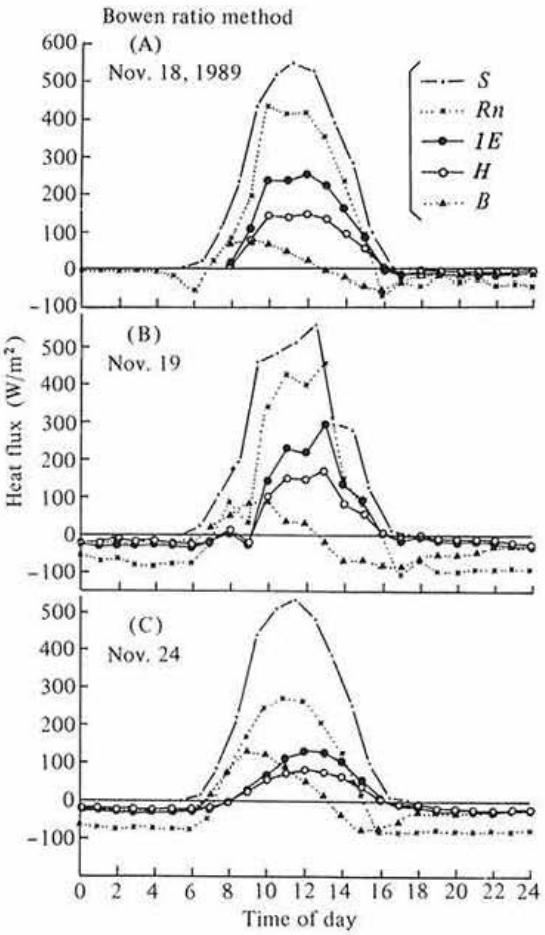

Fig. 1. Patterns of variations in heat fluxes measured with a Bowen ratio method
S: Global solar radiation, Rn: Net radiation, lE: Latent heat flux, H: Sensible heat flux, B: Soil heat flux.

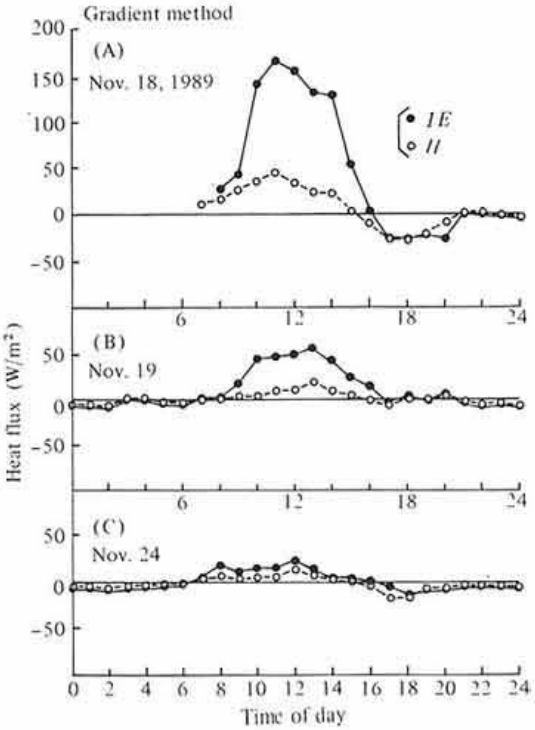

Fig. 2. Diurnal variations of latent and sensible heat fluxes measured with a gradient method

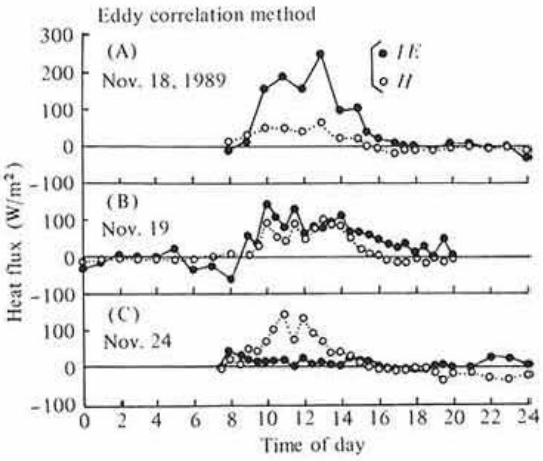

Fig. 3. Diurnal variations of latent and sensible heat fluxes measured with an eddy correlation method

a negative level at 14:00. The heat fluxes were negative almost throughout the night. The net radiation on Nov. 19 and 24 varied with large negative values

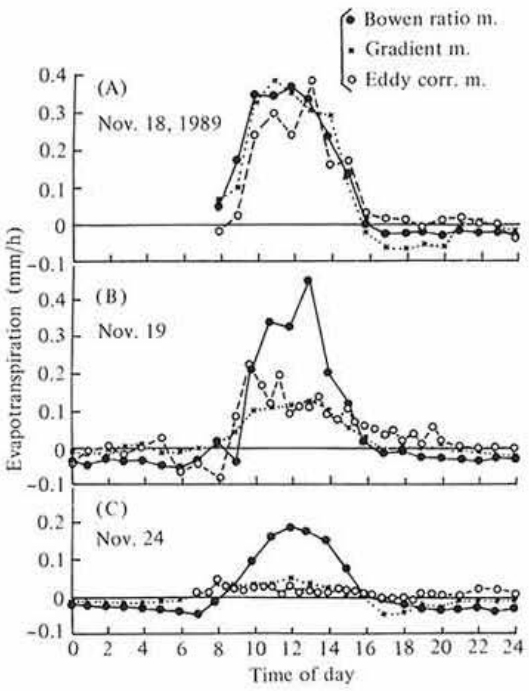

Fig. 4. Evapotranspiration on the seaside sands measured with Bowen ratio, gradient and eddy correlation methods

of about −100 W/m^2, which could be explained by the fact that the radiation increased in accordance with the intensified aridity.

(2) Gradient method

The sensible and latent heat fluxes on Nov. 18, 19 and 24 are shown in Fig. 2. A significant decrease in both parameters was observed during the period under study. The high *lE* values on Nov.18 were caused by the rainfall preceding the measurement for a short while. The rapid decline of the *lE* values in the following days could be explained by the dehydration process of the ground surface. The negative values observed during the night were smaller as compared with those indicated by the other methods. The *lE* and *H* values obtained with this method were smaller than those with others.

(3) Eddy correlation method

Variations of sensible and latent heat fluxes observed with the eddy correlation method are shown in Fig. 3. The maximum values of the sensible heat fluxes were over 100 W/m^2, reaching the highest level of 250 W/m^2 on Nov. 18, which declined to some extent on Nov. 19 and more markedly on Nov. 24.

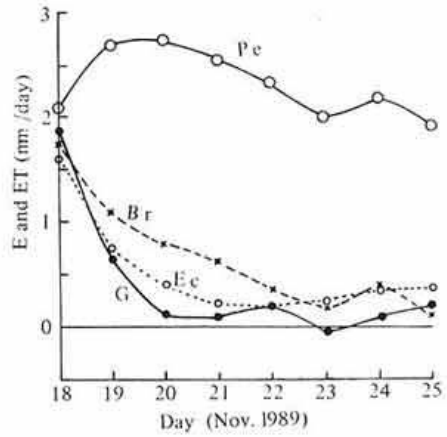

Fig. 5. Daily variations of evapotranspiration (ET) by Bowen ratio (Br), gradient (Gr) and eddy correlation (Ec) methods and evaporation (E) by pan evaporimeter (Pe)

During the nights, the sensible heat fluxes dropped to be negative.

(4) Comparisons of ET among the three methods

ET values estimated with the three methods under study are shown in Fig. 4. Those values on Nov. 18 well agreed with each other, possibly because the ground surface was wet. The ET values decreased as the ground surface got dry. Those values obtained with the Ec and Gr methods were particularly small. The Br method gave considerably large values on Nov. 19. The seaside sand was dried up on Nov. 24, when the magnitude of ET estimated with the Gr and Ec methods significantly decreased to the minimal level. This diminution might have been caused partly by the difference of the heights at which the measurements for each method were taken: i.e. 2 and 1 m for the Gr, 1.3 m for the Ec, and 2, 1 m and ground level for the Br method.

The ET values based on the Ec method were larger in the morning, particularly early in the morning because of higher soil moisture, and the negative values at nighttime were smaller, as compared with the other two methods.

The ET values estimated with the Gr and Ec methods generally agreed with each other on Nov. 20 to 23. The values with the Gr method seemed to increase in the morning.

(5) Evaporation from a pan evaporimeter

The evaporation (E) from a pan evaporimeter was

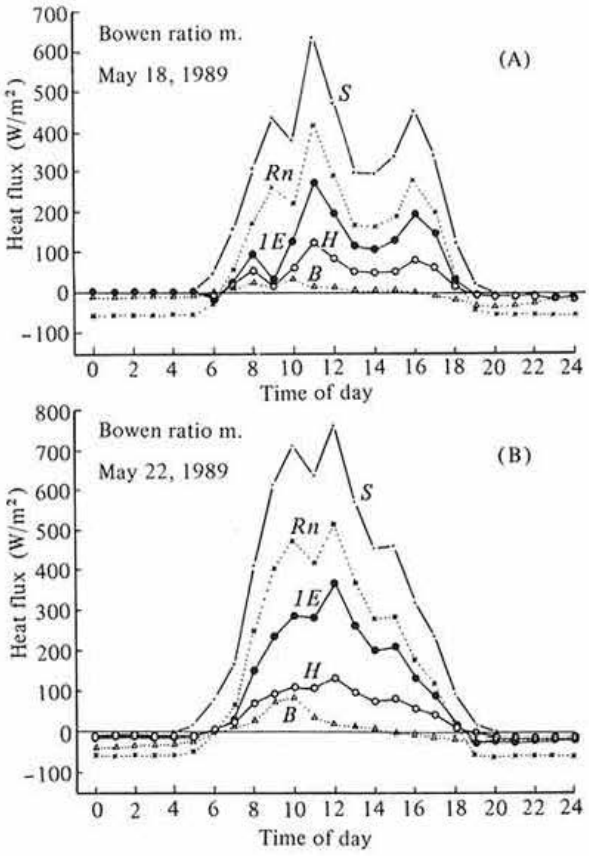

Fig. 6. Patterns of variations of heat fluxes by a Bowen ratio method
Abbreviation: Same as in Fig. 1.

2.1, 2.7 and 2.2 mm on Nov. 18, 19 and 24, respectively (Fig. 5). Those values were different from those with the Gr and Ec methods, particularly under a dry condition. It is in striking contrast each other that the pan evaporation increased with the intensified ground aridity, while the pattern of changes of the ET values based on the above three methods varied in an opposite manner.

Daily variations of ET estimated with the three methods as well as of the evaporation measured with a pan evaporimeter are shown in Fig. 5. In case where the ET values were high, there was a good agreement among them. However, the ET values decreased significantly in order of the Br, Gr and Ec methods. The positive ET values with the Gr and Ec methods decreased significantly after Nov. 19, remaining almost constant during the period of

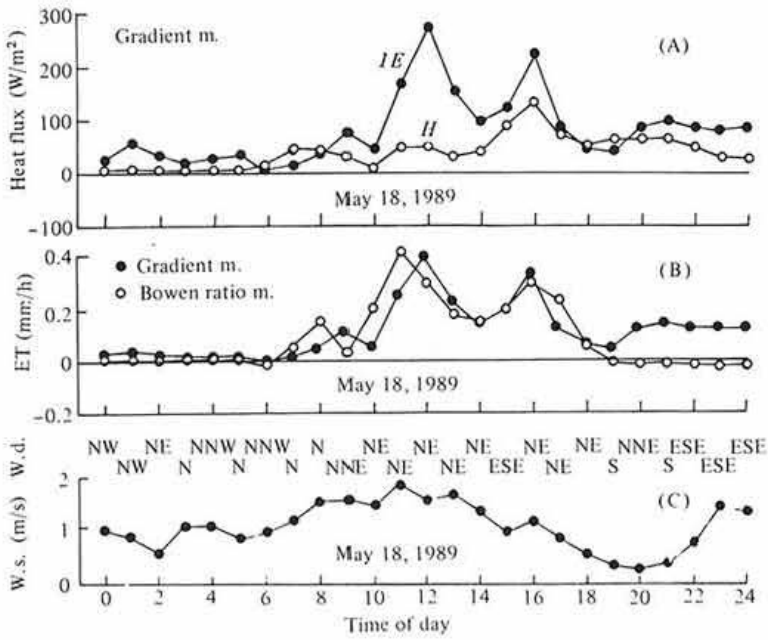

Fig. 7. (A) Diurnal variations of latent and sensible heat fluxes with a gradient method
(B) Evapotranspiration in the wheat field with Bowen ratio and gradient methods
(C) Changes of wind direction and wind speed on May 18

Nov. 20 to 25. The ET values with the Br method still fluctuated in the period of Nov. 19 to 24.

2) Results in the wheat field

(1) Bowen ratio method

The results of the Br method on May 18 and 22 are shown in Fig. 6. As compared with those at the seaside, the latent heat flux in the wheat field was larger, indicating that much more evaporation from the ground surface and transpiration from the wheat plants took place in the field. The soil heat flux was large in the morning of daytime, but small with negative values later in the afternoon, suggesting the possible effect of crop canopy with a height of 1 m.

(2) Gradient method

The sensible heat flux measured with the Gr method was in good agreement with that under the Br method in the daytime. However, the latent heat flux with the Br and the ET values (Figs. 7 & 8) were much larger in the daytime than those in other time of the day due to the solar and net radiations involved. The values under the Gr method were closely related to the wind speed in the daytime and the peak occurred in the afternoon. As the wind directions were E to S and the wind was disturbed by a windbreak forest during the night, i.e. 0:00 to 6:00 and 20:00 to 24:00, May 18 and 22, the recorded values were positive, and particularly large for the period 3:00 to 4:00, May 22 (Figs. 7 & 8). Similar results were obtained on May 15, 16 and 24.

(3) Comparisons of ET between the Br and Gr methods

The ET values obtained with the two methods were in good agreement on May 18. When the N and W wind prevailed, the effect of the windbreak forest on the ET estimated with the Gr method was not significant. However, when the wind directions were S to E, this method was not applicable due to the short distance of the wheat field from the windbreak forest (Figs. 7 & 8).

The evaporation estimates were 3.0 and 5.4 mm per day with the Br and Gr methods, respectively, on May 22. However, the measurements in the daytime 6:00 to 18:00 were 3.4 and 3.6 mm, respectively,

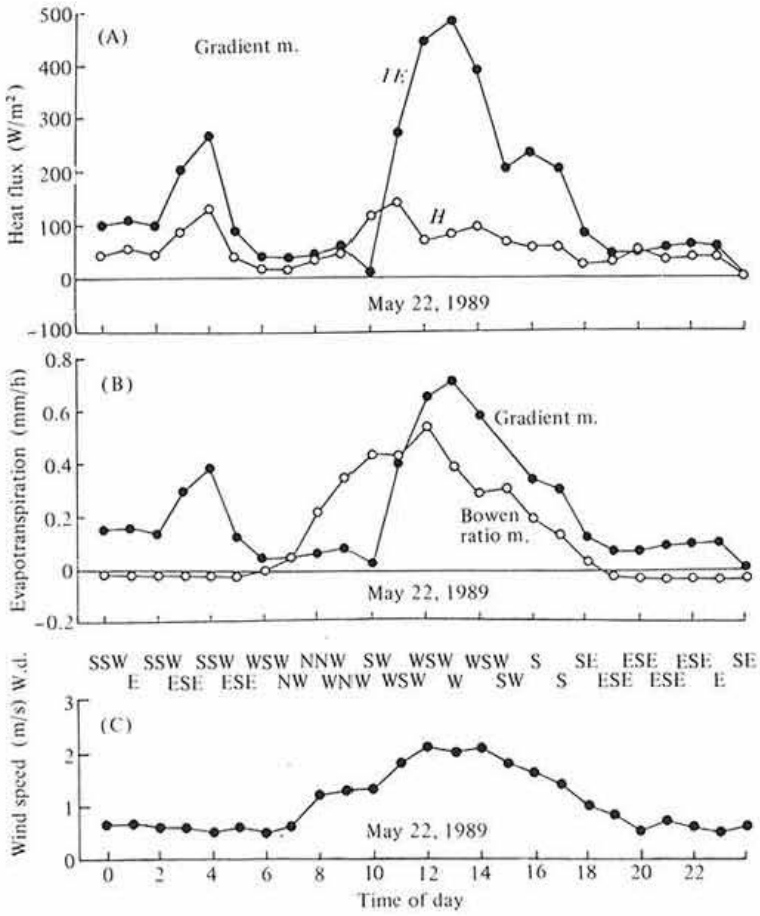

Fig. 8. Same as in Fig. 7 on May 22

which were in a good agreement with the estimates.

Discussions

Lower ET estimates were obtained with the above three methods under a dry condition, as compared with those under a wet condition, though the Br gave less-decreased values. This implies that the Br equation might be more suitable for the wet condition of ground surface, while it tends to give excessive estimates on dry sand. The estimates with the Br method well agreed with those through the Gr method. The estimates measured with the Ec method seem to be most precise, because no hypothesis is needed in the calculation. The Gr and Ec methods are both suited for the application to arid land.

When the investigation on air temperature were made in Turfan, China, the measurements were faced with some difficulties caused by dust particles born in the erosive wind. Those particles were stuck on the gauze around the wet bulb thermometer, interfering with its function, whenever such an equipment was installed.

The ultrasonic anemometer and infrared hygrometer might be the best system for the Ec method, if maintained properly, under the condition of high temperature and low humidity.

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