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Assessment and Error Analysis of the Energy Balance-Bowen Ratio Method for Estimation of Evaporation in an Arid Climate

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ABSTRACT. An energy balance-Bowen ratio equation has been used for the estimation of evaporation at Hada El Sham, 120km NE of Jeddah, an area of potential agriculture activity. Error analyses were made for the Bowen ratio and evaporation terms as obtained from the energy balance equation. In order to test the sensitivity of the method, two contrasting days were used; one was a wet and cloudy day in winter, after heavy rainfall and thunder activity for 24 hours. The other day was dry in spring, with clear sky and maximum solar radiation input. Extensive surface measurements were carried out with hourly temperature and humidity profiles and surface radiative flux components. The method proved sensitive to an increase in the soil water content after the rainy day. The estimated error in evaporation was about 10%, increases to 16% as the surface gets drier. The method is subjected to large errors when the error in the Bowen ratio reaches 25%.

Introduction

In areas which depend on a limited water supply, the question of how to use water in the most economic way is of vital importance. Water is needed to increase the area of agriculture land and hence to produce more food for the continually increasing population. The prevailing climate of the Kingdom of Saudi Arabia is mainly of the arid type (Bailey, 1979; Taha *et al.,* 1981; Siraj, 1985). The average rainfall throughout the kingdom is generally low, being about 125mm annually. Exceptions, however, occur at mountainous areas on the southwestern region. Jeddah and the adjacent areas around are typically arid. However, there are agriculture activities going on in some suburban areas like Hada El Sham at 120km NE of Jeddah. The study of water requirements in these areas is obvious. Estimation of evaporation from the surface is needed to assess these requirements. There are many methods used for the estimation of surface evaporation (Penmann, 1948; Blaney and Criddle, 1950; Monteith, 1965). The energy balance method utilizing the Bowen ratio has been recognized as one of the reliable methods for estimation of evaporation (Fritschen, 1966; Denmead and MacIlroy, 1970; Abdullah, 1974 & 1980; Grant, 1975; Black and McNaughton, 1981; Bingham *et al.,* 1987; Malek *et al.,* 1992). Its successful use was emphasized by comparisons with accurate lysimeters (Fritschen, 1965), water balance method (Malek and Bingham, 1993) and other aerodynamic and soil water content methods (Grant, 1975). Perhaps one restriction of the method is that it needs large area of uniform surface in order to reduce the horizontal flux divergence and satisfy the assumption of equal transfer coefficients for heat and water vapor in the air layer in which measurements are made (Dyer and Hicks, 1970). Another restriction is that when the latent heat flux is exactly matched with the sensible heat flux of the surface. This is usually occur at sunrise and sunset where evaporation is small and can be neglected (Slatyer and McIlroy, 1961).

Site Arrangements

The selected site for this study is located in Hada El Sham Research Farm belonging to Faculty of Meteorology, Environment and Arid Land Agriculture, King Abdulaziz University. The site was a bare soil with enough fetch of 200m available from all sides. The meteorological equipment were located at the middle of a field of area (240m × 240m) facing the north to northwest, which is the prevailing wind direction as estimated from the climatological record of the farm.

Dry and wet bulb temperatures were measured by electrically ventilated psychrometers. Each psychrometer incorporates two glass-encased platinum resistive thermometers. The sensors were protected from direct solar radiation by two nickel chrome concentric tubes. The ventillation rate was constant at 4m/s. Six dry bulb and four wet bulb temperatures were recorded continuously every hour (see Fig. 1). The temperatures were measured with accuracy of 0.1ºC every 5 minutes. The vapor pressures were calculated from the psychrometric equation.

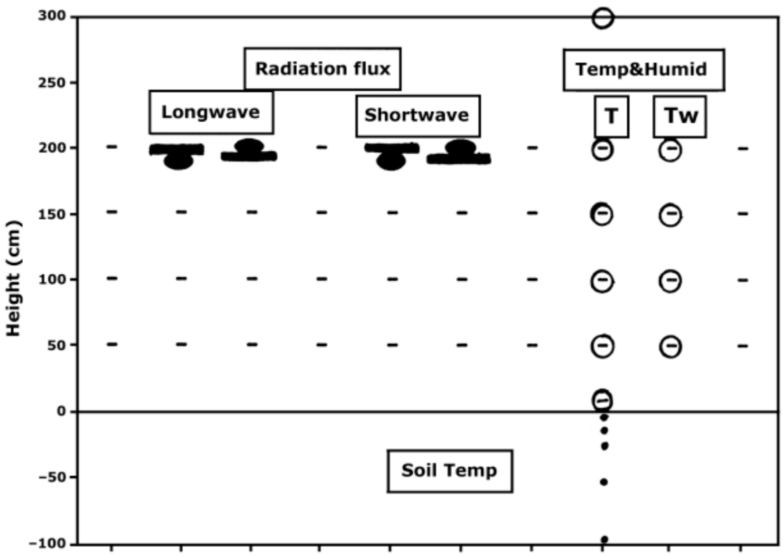

Fig. 1. The equipment in the field at Hada El Sham in 1988.

The hourly radiative flux components of the surface were also monitored continuously. These are used for the estimation of the radiative contribution of each component in the total net radiation of the surface under investigation. Two pyranometers and two pyrageometers were used for the measurements of short and long wave components into and out of the surface (Fig. 1). The soil heat flux was estimated from the soil temperature profiles down to 1m depth. The soil heat capacity and moisture content were also assessed for this soil layer. The radiation and soil temperature measurements were collected by CR21 Campbell Scientific data logger and recorded on a conventional cassette recorder then transferred to computer for analysis.

Theory

The Bowen Ratio-Energy Balance Equation

The Bowen ratio is defined as the ratio of sensible to latent heat fluxes. It is utilized in the energy balance equation as follows:

$$B_o = H / LE = (C_p/L\varepsilon)\,(K_h/K_w)\,(dT/de) \qquad (1)$$

Where

H	is the sensible heat flux,
LE	is the latent heat flux,
C_p	is the specific heat of air at constant pressure,
L	is the latent heat of evaporation,
ε	is the ratio of the molecular weight of air to that of water vapor,
K_h & K_w	are the eddy transfer coefficients of heat and water vapor,
T & e	are dry bulb temperature and vapor pressure of the air.

When the gradients are replaced by finite differences (Δ) measured over the same height interval where the transfer coefficients are assumed equal, an assumption proved acceptable in the constant flux layer near the surface with proper fetch requirements (Denmead and McIlroy, 1970; Garratt, 1973),

Thus, the Bowen ratio can be written as:

$$B_o = \gamma\,\Delta T/\Delta e \qquad (2)$$

Where γ (= $Cp/L\varepsilon$) is the psychrometric constant.

The Bowen ratio can be estimated from the linear relation between dry bulb temperatures and vapor pressures of their profiles (Montieth, 1975).

The energy balance equation is given as:

$$R_n - G = H + LE \qquad (3)$$

Where

R_n is the net radiation flux of the surface (w/m^2),

G is the soil heat flux (w/m^2).

From equations (1) and (3), the latent heat flux can be given as:

$$LE = (R_n - G) / (1 + B_o) \tag{4}$$

The Bowen ratio-energy balance equation (4) had been used for the calculation of the hourly values of evaporation from the surface of a bare soil on one dry day in spring, 4 May 1988, and on another wet day in winter after heavy rainfall, 31 December 1988, in Hada El Sham area. Equation (4) gives infinite value of evaporation as B_o approaches (–1). As mentioned before, this occurs when the latent heat flux exactly matches the sensible heat flux at the surface (see Eqn. 1). This situation sometime occurs at sunrise or sunset. At these times, a smoothing was used to overcome this difficulty. Fortunately, the evaporation at these times is small and any error in its estimation can be neglected (Slatyer and McIlroy, 1961).

The Error Analysis in the Calculation of Bowen Ratio

From equation (2), it is clear that the magnitude of the error in the Bowen ratio can be calculated when the experimental errors in the temperature and vapor pressure differences ΔT & Δe are known. Using the root sum square error analysis technique (Topping, 1972), the absolute error in B_o, denoted as (dB_o) can be given as:

$$dB_o = \{ [(\partial B_o/\partial \Delta T)\, \partial \Delta T]^2 + [(\partial B_o/\partial \Delta e)\, \partial \Delta e]^2 \}^{0.5}$$
$$= \{ [(\gamma/\Delta e)\, \partial \Delta T]^2 + [(\gamma \Delta T/\Delta e^2)\, \partial \Delta e]^2 \}^{0.5}$$

and the relative error (dB_o / B_o) can be given as:

$$dB_o/B_o = \{ [\partial \Delta T/\Delta T]^2 + [\partial \Delta e/\Delta e]^2 \}^{0.5} \tag{5}$$

Fuchs and Tanner (1970) gave an expression for the relative errors in the measurements of the differences ($\partial\Delta/\Delta$) as:

$$\partial\Delta/\Delta = r + A/\Delta \tag{6}$$

Where (r) is the inaccuracy of the sensor's calibration which is expressed as the percentage difference in the sensitivity of the used sensors and (A) is the resolution limit of the recording system.

In this study, the resolution of the data logging system was (0.05ºC) for both the wet and dry bulb temperature measurements. The sensitivity differences for the used temperature sensors were found to be (1%) an (5%), for the dry and wet bulb sensors respectively (Abdullah, 1980). Thus, for temperature difference (ΔT) of 1ºC and vapor pressure difference (Δe) of 1mb., the error in the Bowen ratio (B_o) was found from equation (5) to be of order (10%).

It is worth noting that this error increasing with decreased vapor pressure differences, that is when the surface gets dryer. In this case, the evaporation (LE) is also decreased and the Bowen ratio method does not give satisfactory results. In an extremely dry case, the calculated error in (B_o) was found to be about (25%) when the temperature differences (ΔT) were (2.6ºC) and the vapor pressure differences (Δe) were (0.2mb). Angus and Watts (1984) found, in similar arid conditions in Australia, a relative error in (B_o)

of (10%). When the surface was very dry, they found a restriction on (ΔT) and (ΔTW) measurements of one order of magnitude for the same relative error in (B_o).

The Error Analysis in the Calculation of Evaporation

Following similar procedure to that used for (B_o) , the absolute error in evaporation (LE) can be readily obtained from equation (4) as follows:

$$dLE = \{ [(\partial LE/\partial R_n - G)\, \partial R_n - G]^2 + [(\partial LE/\partial \Delta T)\, \partial \Delta T]^2 - [(\partial LE/\partial \Delta e)\, \partial \Delta e]^2 \}^{0.5}$$

$$= \{ [\partial R_n - G/1 + (\gamma \Delta T/\Delta e)]^2 + [(R_n - G)\, \gamma \partial \Delta T/\Delta e\, (1+\gamma \Delta T/\Delta e)^2]^2 +$$

$$[(Rn - G)\, \gamma \Delta T \partial \Delta e/ (\Delta e)^2\, (1+\gamma \Delta T/\Delta e)^2]^2 \}^{0.5} \qquad (7)$$

The above equation (7) gives an estimation of the absolute error in the evaporation as obtained from the Bowen ratio-energy balance equation (4). The relative error ($\partial LE/LE$) can be given as:

$$dLE/LE = \{ [\partial R_n - G/LE\, (1 + B_o)]^2 + [(R_n - G)\, \gamma \partial \Delta T/LE\, (1 + B_o)^2\, \Delta e]^2 +$$

$$[(R_n - G)\, \gamma \Delta T\, \partial \Delta e/LE\, (1 + B_o)^2\, (\Delta e)^2]^2 \}^{0.5}$$

$$dLE/LE = \{ [\partial R_n - G/R_n - G]^2 + [\partial B_o / (1 + B_o)]^2\, [(\partial \Delta T/\Delta T)^2 + (\partial \Delta e/\Delta e)^2] \}^{0.5}$$

Results and Discussion

The used data in this study were taken from the records of two days in 1988 at Hada El Sham area. The first day was a dry day (4 May) with clear sky all the daytime, while the other day was wet (31 December) with cloudy sky after heavy rainfall on the field site the day before. The complete radiation balance components on these two days are shown in Fig. (2) and (3). The maximum global radiation (S) at 1300 local time (L.T.) were 960W/m^2 and 390W/m^2 while the reflected radiation (AS) were 200W/m^2 and 50W/m^2 for 4 May and 31 December respectively. The corresponding values for the net radiation (RN) were 590W/m^2 and 320W/m^2. The long wave components L(IN) and L (OUT) were ranging from (400-600)W/m^2 for 4 May and (300-400)W/m^2 for 31 December.

It is worth noting that on 31 December (Fig. 3), the long wave radiation from sky is higher than that emitted from the surface during night. On this night, the rainfall had cooled the surface and consequently decreased the emitted long wave radiation. Figure (4) shows surface temperatures of 19ºC & 21.7ºC at the same time (0300L.T.) on the cloudy wet and clear dry days respectively. A positive net radiation was obtained during the night on 31 December.

Figure (5) shows the diurnal variation of the Bowen ratio on both days. On 4 May, B_o reached a maximum of 5 at noon, while on 31 December the maximum was 1. Figure (6) shows the value of evaporation (mm/day) as calculated from the Bowen ratio-energy balance equation (4). It is shown that on the wet day, peak evaporation was 8mm/day at 1300L.T., while it was 4.7mm/day at the same time on the dry day. Also, on 31 December, with B_o = 1, the relative error in LE was less than (10%), while on 4 May, with B_o = 5, the relative error reached (16%). The error increased as the conditions became drier.

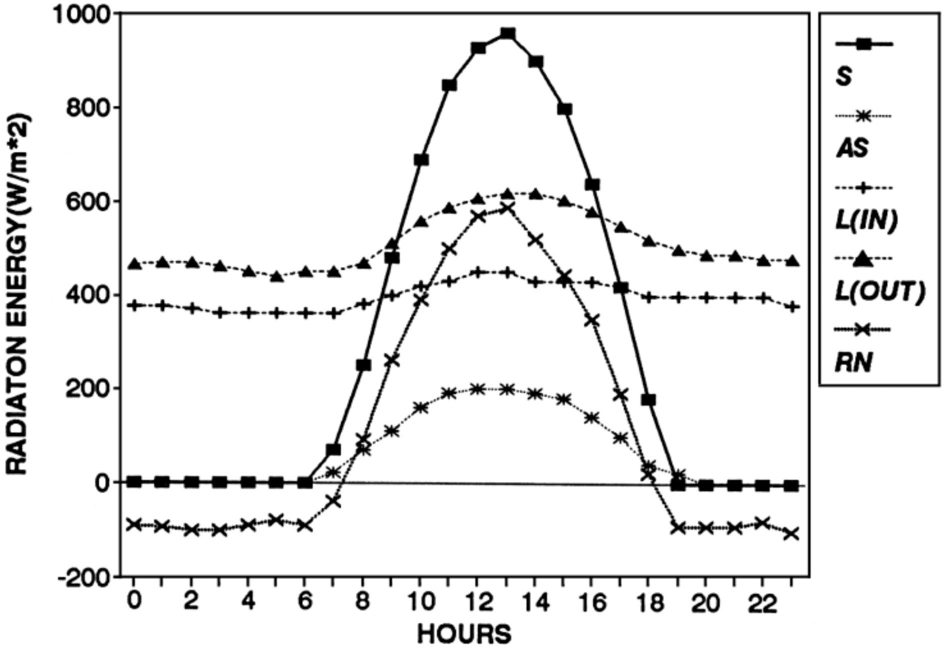

FIG. 2. Radiation components at Hada El Sham, 4 May 1988.

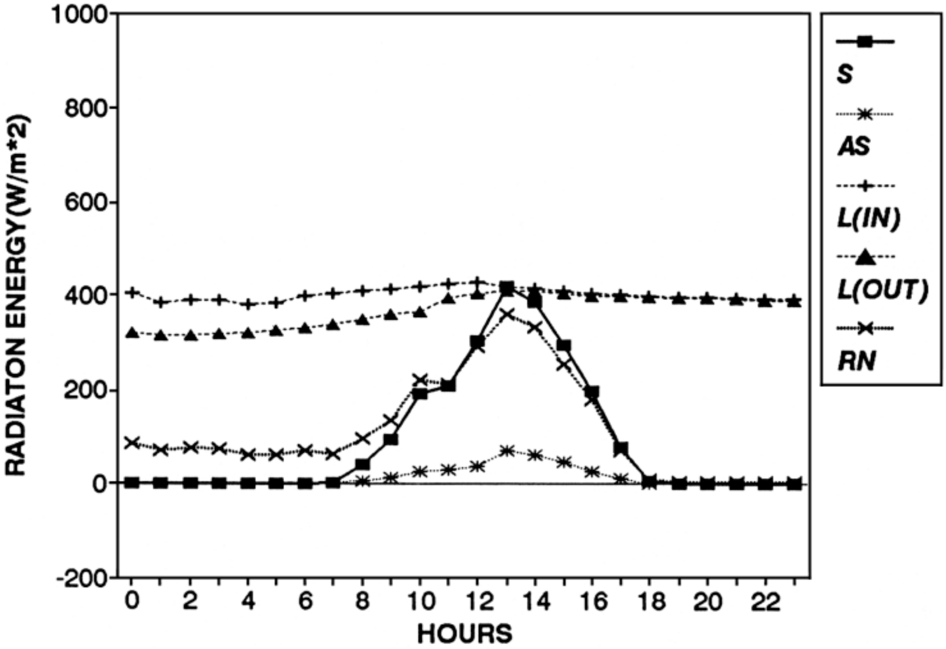

FIG. 3. Radiation components at Hada El Sham, 31 December 1988.

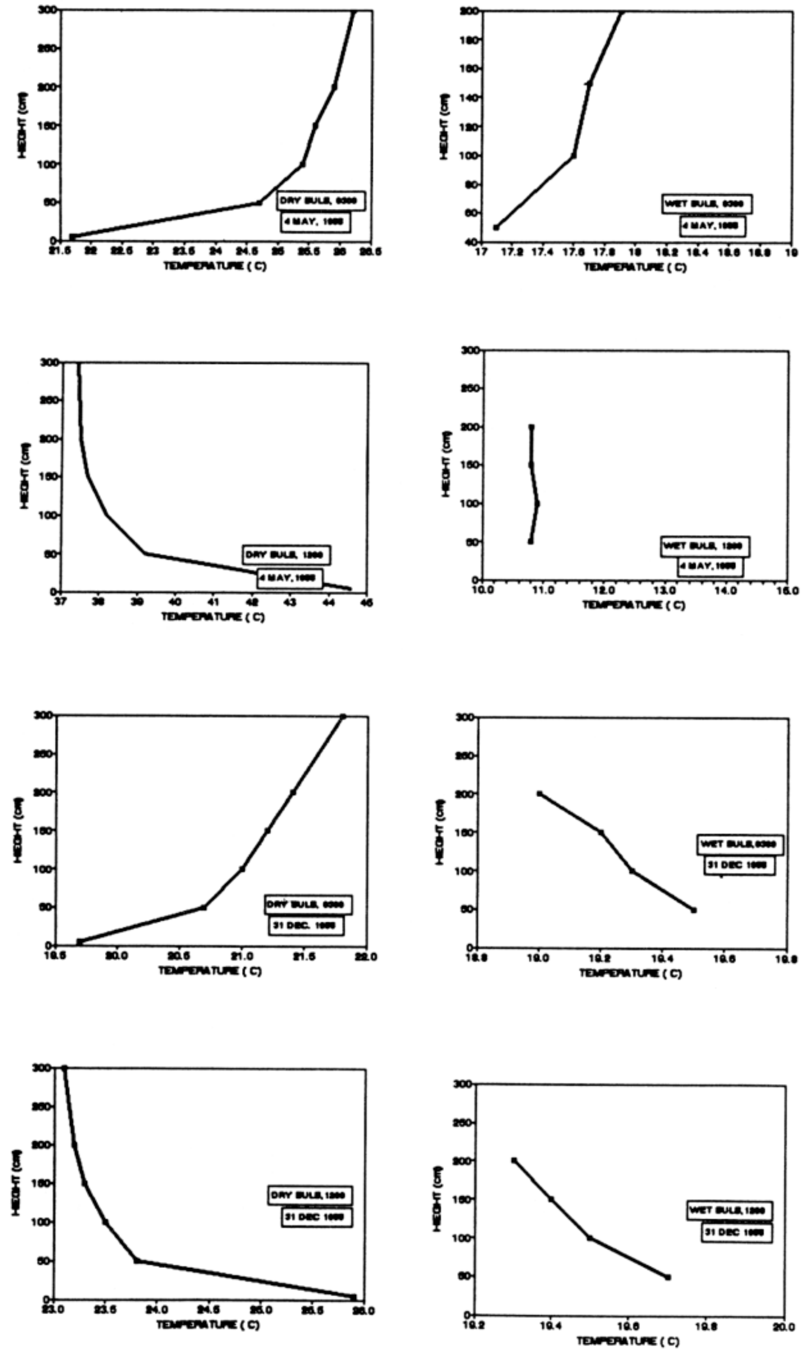

Fig. 4. Temperature and humidity profiles at Hada El Sham, 1988.

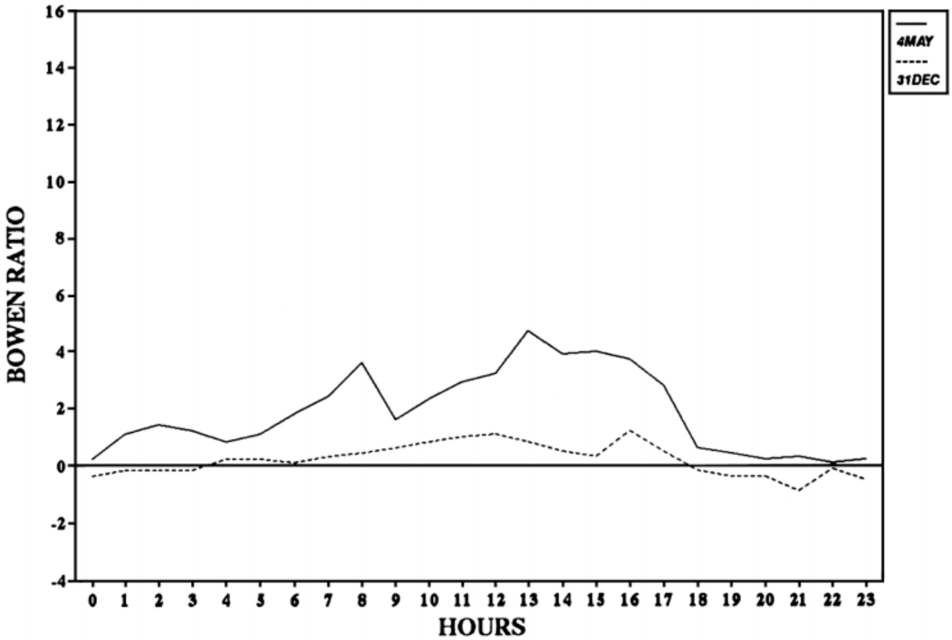

Fig. 5. Diurnal variation of Bowen ratio at Hada El Sham, 1988

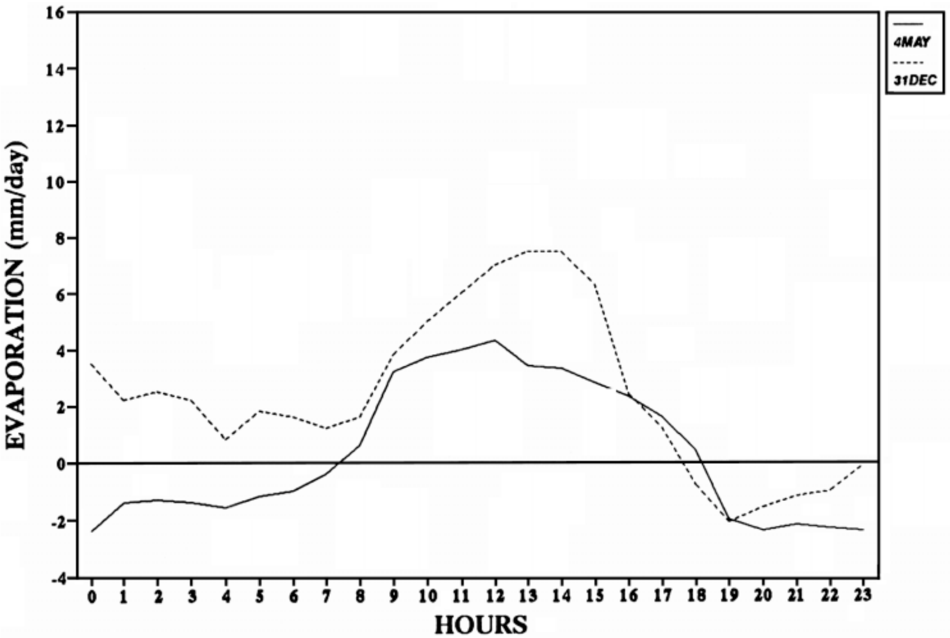

Fig. 6. Diurnal variation of evaporation at Hada El Sham, 1988.

Conclusion

The Bowen ratio-energy balance method for estimation of evaporation showed a good sensitivity to an increase in evaporation after a rainy day. The hourly evaporation could be estimated with accuracy of about (10%) over wet surface, increased to (16%) as the surface became relatively dry.

In the case of very dry surface, in arid areas, the small values of the vapour pressures became very difficult to be measured with enough accuracy. In this case, the method is subjected to large errors as the error in the Bowen ratio reaches (25%), and a severe restriction is imposed on the accuracy of the instruments used for measuring the temperature and vapour pressure differences above the surface.

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تقييم وتحليل أخطاء معادلة توازن الطاقة لتقدير التبخر في مناخ جاف

محمد أيمن عبد اللّه

قسم الأرصاد ، كلية الأرصاد والبيئة وزراعة المناطق الجافة

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المستخلص . استخدمت في هذا البحث معادلة توازن الطاقة بدلالة النسبة بين الفيض الحراري وفيض بخار الماء لتقدير التبخر في منطقة هدى الشام على بعد ١٢٠كم شمال شرقي مدينة جدة وهي منطقة ذات نشاط زراعي ملحوظ . اشتقت معادلات رياضية لتحليل الأخطاء الناجمة من تطبيق معادلة توازن الطاقة وتم اختيار يومين متباينين لاختبار حساسية المعادلة المستخدمة ، يوم رطب ملبد بالغيوم في فصل الشتاء تسبقه ٢٤ ساعة من الأمطار الشديدة والرعد ، واليوم الآخر جاف في فصل الربيع سماؤه صافية بلغ فيه إشعاع القبة السماوية نهاية عظمى بالنسبة لمعدله في هذا الفصل من العام . أخذت قياسات ساعية لدرجات الحرارة والرطوبة السطحية وعلى عدة ارتفاعات في طبقة الهواء القريبة من السطح . تم في نفس الوقت قياس جميع مركبات الإشعاع الشمسي الكلي اللازمة لحساب ميزانية الطاقة . أثبتت هذه المعادلة حساسيتها في تقدير التبخر من السطح بعد يوم ممطر . في ظل هذه الظروف كان الخطأ في التبخر حوالي ١٠٪ يزداد إلى ١٦٪ كلما ازداد السطح جفافا . تعطي هذه المعادلة أخطاء غير مقبولة عندما يصل الخطأ في حساب النسبة بين فيضي الحرارة وبخار الماء (Bo) حوالي ٢٥٪ .