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Test of an Equation for Evaporation From Bare Soil

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An empirical equation developed by Idso et al. (1979) at Phoenix, Arizona, to calculate daily average evaporation rates during all three drying stages of a bare soil was tested using measurements made at Agassiz, British Columbia, and is discussed on the basis of available evaporation theory. The results show that their expression for potential evaporation rate did not apply at Agassiz due to differences in the advection regimes at the two locations. The Agassiz potential evaporation rate data was well represented by the Priestley-Taylor equation with a_{PT} ('alpha') = 1.27 ± 0.1. It was concluded that the Idso et al. equation for potential evaporation rate has no greater generality than the Priestley-Taylor or other such semiempirical approaches. The concept of expressing the stage III rate as proportional to the expression for potential evaporation rate worked marginally well at a culti-packed site and quite well at a disc-harrowed site. It was concluded that for soils with stage III rates much greater than 50% of potential evaporation rate, more complete procedures are necessary for calculating evaporation rates during extended drying periods.

INTRODUCTION

Idso et al. [1979] presented the following simple empirical formula for the 24-hour average evaporation rate (latent heat flux density) from bare Avondale loam soil,

$$LE_{I,II,III} = (3/8 + 5/8\ \beta)(S_N + 1.56L_N + 76) \quad (1)$$

where S_N and L_N are the 24-hour average net solar and net long wave radiation flux densities, respectively, β is the soil surface wetness partitioning factor, and all energy flux densities are in W m^{-2}. The factor β was originally defined by *Jackson et al.* [1976] as

$$\beta = (\alpha_d - \alpha)/(\alpha_d - \alpha_w) \quad (2)$$

where α_d is the dry soil albedo, α_w is the wet soil albedo, and α is the daytime average albedo on any given day; β varies from 1 to 0 as the soil surface changes from wet to dry. The Roman numeral subscripts indicate that (1) applies to all three stages of soil drying, as defined by *Idso et al.* [1974].

The evaporation rate during stage I, or the potential evaporation rate (PLE), occurs for $\beta = 1$ and is given by

$$LE_I = PLE = S_N + 1.56L_N + 76 \quad (3)$$

The development of (3) for Avondale loam over all four seasons at Phoenix as well as validation for crop and water surfaces in Arizona and California are described by *Idso et al.* [1975, 1977]. *Idso et al.* [1975] note that (3) is well adapted to remote sensing and suggest that it should describe evaporation rates throughout the complete range of possible advective conditions. *Priestley and Taylor* [1972] also presented a simple semiempirical equation for the potential evaporation rate

$$PLE = a_{PT}[s/(s + \gamma)](R_N - G) \quad (4)$$

where s is the slope of the saturation vapor pressure curve, γ is the psychrometric constant, R_N is the net radiation flux density, G is the soil surface heat flux density, and the coefficient a_{PT} must be locally determined to account for advection, although a value of 1.2 to 1.3 is considered appropriate to 'advection-free' conditions.

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Stage III, or soil moisture limited evaporation, occurs for $\beta = 0$. From (1) it is seen that it takes place at a rate equal to 3/8 times the potential rate expression (3). *Idso et al.* [1979] show that expressing the stage III evaporation in this manner absorbed the seasonal variation in this rate at Phoenix. The stage III rate is mainly a function of soil moisture content and will decrease in some manner as the soil dries. Theoretical arguments by *Gardner* [1959] as well as several field studies [*Ritchie*, 1972] show that the stage III evaporation rate for deeply wetted, homogeneous soils may be described by the relation

$$LE_{III} = Ct^{-1/2} \quad (5)$$

where t is the time in days from the start of stage III evaporation, and C is a constant related to the hydraulic diffusivity of the soil. According to *Jackson et al.* [1976], C is a function of soil temperature and hence varies with season. As is implied by (5), the stage III rate eventually becomes independent of the potential rate within a given drying period. This seems to be somewhat incompatible with (1) with $\beta = 0$, although since L_N is generally a decreasing function of time during stage III due to increasing soil surface temperature, (3) could simulate some of the square root of time behavior of (5).

Stage II, or the transition stage evaporation, occurs for $0 < \beta < 1$. The model for this stage is a soil surface partitioned into patches evaporating at either stage I or stage III rates, with the partitioning determined by β.

Idso et al. [1979] suggest that (1) should be tested on other soils and in other climates. The purpose of this paper is to report on the evaluation of (1) using a data set obtained for a bare soil surface in the Lower Fraser Valley during the spring and early summer of 1978. Since the cool, wet, and cloudy climatic conditions of British Columbia contrasted sharply with the mostly clear sky conditions of Phoenix and since two contrasting tillage treatments were studied (culti-packed versus disc-harrowed), this was felt to be an opportunity for a demanding test of (1).

EXPERIMENTAL PROCEDURE

The study was carried out at the Agriculture Canada Research Station at Agassiz, British Columbia, on a Monroe series loam/silt-loam soil (Eluviated Eutric Brunisol). A 145 × 175 m level field, kept bare for this study, was divided into

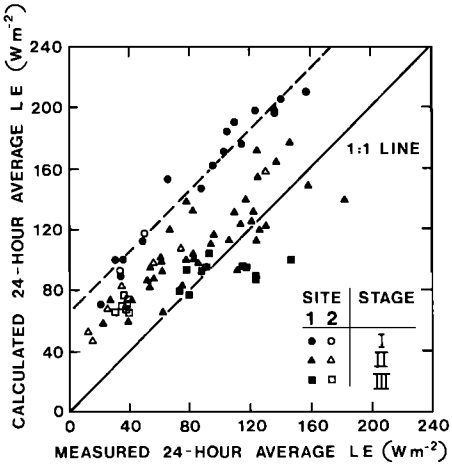

Fig. 1. Plot of daily average evaporation rates calculated from (1) versus measured rates for sites 1 and 2 at Agassiz, British Columbia, 1978. The drying stage of each day is indicated. The dashed line was fit by eye to the stage I data from both sites.

two parts, which will be referred to as sites 1 and 2. The division of the field was done with consideration of the prevailing wind direction and fetch requirements. Site 1 was disc-harrowed, then firmly packed with a culti-packer, while site 2 was disc-harrowed only. The data collection periods were May 17 to July 21 and July 6 to July 21 at sites 1 and 2, respectively. The identical micrometeorological instrumentation was centrally located at both sites. The average bulk densities of the upper 10 cm of soil were 1030 and 870 kg m^{-3} for sites 1 and 2, respectively. Bulk densities below 10 cm were in the range 1000–1300 kg m^{-3} at both sites.

Half-hour average evaporation rates were measured throughout the day by the energy balance/Bowen ratio technique, using the same instrumentation described by *Black and McNaughton* [1971]. Both reversing psychrometers (50-cm separation) were mounted within 1 m of the soil surfaces, which led to a fetch-height ratio of 80 : 1. Net radiation flux densities were measured by Swissteco S-1 net radiometers located 0.65 m above the soil surfaces. The R_N signal and both the wet-bulb and dry-bulb vertical temperature difference signals were continuously integrated using dual-ramping voltage integrators. Soil surface heat flux densities were calculated half hourly from soil temperatures measured at 30 depths down to 1 m and heat capacity profiles calculated from bulk densities and gravimetric water contents (sampled at least every 2 days) by using the null-alignment method described by *Kimball and Jackson* [1975]. Half-hour average solar irradiance was measured (continuous integration as above) by a Kipp and Zonen CM5 pyranometer, while the albedos were spot measured every half hour using inverted Kipp and Zonen CM5 pyranometers located 0.6 m above the soil surfaces. Net long wave radiation flux densities were calculated from measured net radiation flux densities, albedos, and solar irradiance according to $L_N = R_N - S_N$.

RESULTS AND DISCUSSION

Examination of the Agassiz data shows that the drying stages I, II, and III were approximately delineated by $\beta > 0.8$, $0.8 > \beta > 0.2$, $\beta < 0.2$, respectively [*Novak*, 1981]. This is not inconsistent with Figure 2 of *Idso et al.* [1974], which shows that stages I and III were defined by narrow ranges of α. The values of α_w and α_d used in (2) to calculate β at Agassiz were 0.065 and 0.173, respectively, which were the extreme values of measured daily average albedo for both sites.

In Figure 1, daily average evaporation rates calculated from (1) are plotted against measured rates for both sites. It is evident that (1) did not agree with most of the measurements at site 1 and all of the measurements at site 2. Examination of the potential rate data ($\beta > 0.8$) shows clearly that (3) failed to describe these. This, as well as the agreement of (1) with some of the stage III and near stage III points for site 1, shows that the factor 3/8 in (1) cannot apply to the site 1 data.

While (1) did not adequately describe the measured data, it was decided to investigate whether the concept of expressing the stage III rate as proportional to the potential evaporation rate, as done in (1), would still apply, i.e., whether

$$LE_{I,II,III} = [\delta + (1 - \delta)\beta]\, PLE_{Ag} \qquad (6)$$

would describe the measured LE. PLE_{Ag}, the expression describing the potential evaporation rate at Agassiz, can be determined from the dashed line in Figure 1 and is

$$PLE_{Ag} = S_N + 1.56L_N + 7 \qquad (7)$$

The value of δ for each site was calculated using (6) after averaging $[LE_{III}/(S_N + 1.56L_N + 7)]$ and β over the stage III days (12 for site 1 and 7 for site 2). This was analogous to the graphical procedure used by *Idso et al.* [1979]. Stage III rates at site 2 were about half of those at site 1. This led to $\delta = 0.74 \pm 0.2$ for site 1 and $\delta = 0.34 \pm 0.1$ for site 2, which shows that this factor is a strong function of near-surface soil bulk density and/or structure. Comparison of (6) with the measurements from sites 1 and 2 is shown in Figure 2; the degree of scatter is similar for all three stages and is about ±25 W m^{-2}.

Equation (7) differs from (3) for Phoenix by a constant 69 W m^{-2}. *Jackson et al.* [1976] point out that the coefficient a_{PT} was 1.41 for summer days when 24-hour totals of net

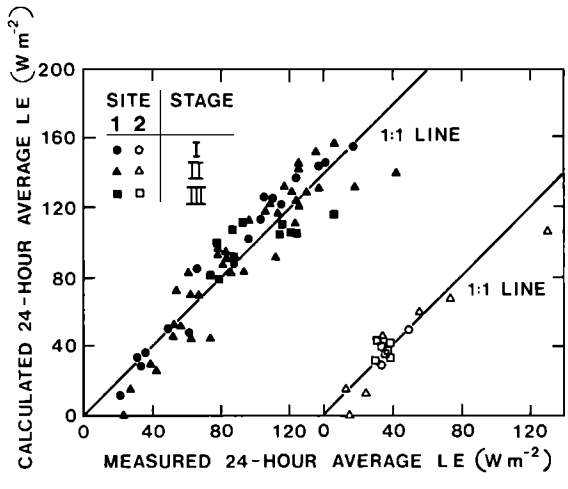

Fig. 2. Plot of daily average evaporation rates calculated from (6) with $\delta = 0.74$ for site 1 and $\delta = 0.34$ for site 2 versus measured rates for these sites at Agassiz, British Columbia, 1978. The drying stage of each day is indicated.

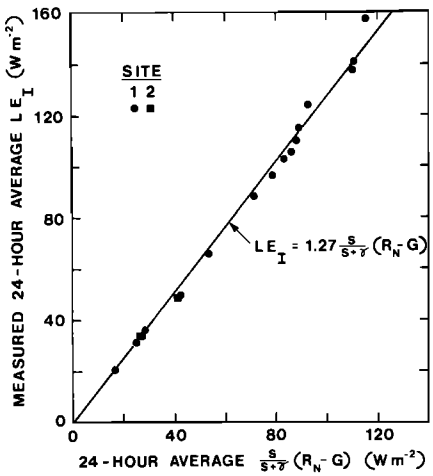

Fig. 3. Plot of measured daily average stage I ($\beta > 0.8$) evaporation rates versus equilibrium rates for sites 1 and 2 at Agassiz, British Columbia, 1978. The solid line was fit to the data by eye.

radiation were used and soil surface heat flux densities were assumed negligible. This indicates that some advective enhancement occurred at the Phoenix site. At Agassiz the average 24-hour value of a_{PT} (G not neglected) for the stage I days was 1.27 ± 0.1, as shown in Figure 3, indicating minimal advection on these days. This shows that (3) is not applicable over the full range of atmospheric advective regimes. Therefore formulae such as (3) and (7) have no advantage over (4) except perhaps at a single site and after calibration. Furthermore, it is noted that (4) with a_{PT} in the range 1.0–1.3 described the half hourly evaporation rates on stage I days quite well, while (7) failed to do so at all (overestimating by up to 120%).

The ±30% variability in δ for each of the two Agassiz sites is not inconsistent with the scatter in Figure 1 of *Idso et al.* [1979]. However, for site 1 the variability is not random. Calculating values of δ at site 1 for the first and last thirds of the experiment (there were no stage III days in the middle third due to cloudy and rainy weather) shows that δ decreased from 0.84 ± 0.1 in the first third to 0.62 ± 0.1 in the last third. During the first third of the experiment the average volumetric soil moisture content at site 1 in the upper 0.06 m of soil on the stage III days was 0.27 ± 0.01, whereas during the last third this value was 0.23 ± 0.01. The average stage III evaporation rates corresponding to these moisture contents were 119 ± 20 and 82 ± 10 W m^{-2}, respectively, while the corresponding values of PLE_{Ag} given by (7) were 137 ± 15 and 123 ± 15 W m^{-2}, respectively. It is seen that the 10% decrease in PLE_{Ag} could not compensate for the 31% decrease in stage III rate between the first and last thirds of the experiment. This suggests that had the experiment continued further into the drier summer weather, the calculated site 1 δ would have decreased even more and (6) with δ = 0.74 would not have described the data adequately.

Whether this would have been true for site 2 as well is difficult to assess since that site was monitored for only 16 days. However, the already low stage III rates observed at this site (30–40 W m^{-2} or ≃ 25% of the potential rate) suggest that (6) with δ = 0.34 would have described site 2 evaporation adequately over a longer period. Therefore for soils with stage III rates initially well in excess of 50% of potential rate, such as for site 1, equations of the form (6) will not work well over extended drying periods. In these cases, formulae such as (5) will have to be used to describe the stage III evaporation rates, as is detailed by *Jackson et al.* [1976]. It is noted that (5) did not describe the stage III evaporation rates at either site 1 or site 2. This was attributed to the relatively short drying periods (typically 2–4 days with a maximum of 10 days) and variable cloudiness, the presence of a water table at a depth of 1–3 m, and the bulk density (and textural) variations with depth.

CONCLUSIONS

Equation (3), developed by *Idso et al.* [1975] to describe potential evaporation at Phoenix, Arizona, did not apply at Agassiz, British Columbia. However, subtracting from it a constant 69 W m^{-2} gave good agreement. This value accounted for the difference in advection between the two locations and demonstrates that formulae such as (3) and (7) have no greater generality than the Priestley-Taylor formulation represented by (4).

Expressing the stage III evaporation rate as proportional to the expression for potential evaporation worked only marginally well on the firmly packed site (δ = 0.74 ± 0.2) and quite well at the disced site (δ = 0.34 ± 0.1). The results show that this concept is applicable to soils with stage III rates much less than 50% of potential rate, but that on soils with stage III rates (initially) much greater than 50% of potential rate, a more complete procedure should be used for extended drying periods.

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