ASSESSING BARE SOIL EVAPORATION VIA SURFACE TEMPERATURE MEASUREMENTS[1]

by

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INTRODUCTION

Evaporation of water from bare soils is an important consideration in the scheduling of many farming operations in both irrigated and dryland agriculture (Idso, et al., 1975b). It influences timing of seeding, irrigation, pesticide applications, and various tillage practices; therefore its successful prediction figures highly in the economics of these ventures. In some areas, accurate predictions of bare soil evaporation may serve as the basis for decisions to increase the acreage planted with a given crop. For example, according to Allmaras (personal communication), the recrop zone for wheat in the Columbia Plateau could be extended to areas of lower annual precipitation if appropriate surface residue and internal drainage practices were used to retain the winter rainfall.

Bare soil evaporation has usually been determined by two basic procedures. The first has been to measure evaporation directly by means of lysimeters (Harrold and Dreibelbis, 1958; Pruitt and Angus, 1960; Van Bavel and Reginato, 1965; Ritchie and Burnett, 1968). However, precision lysimeters are costly to install and difficult to maintain. Thus, the second procedure, calculation, has been used much more extensively. In this approach the evaporation process is mathematically modeled by some formula that depends on a variety of soil and meteorological factors (Penman, 1948, 1961; Penman and Schofield, 1951; Slatyer and McIlroy, 1961; Monteith, 1963, 1965; Van Bavel, 1966; Tanner and Fuchs, 1968; Priestley and Taylor, 1972; Davies and Allen, 1973). The first stage of soil drying (potential rate phase, where atmospheric factors dominate) has been modeled fairly successfully by these procedures; but the subsequent falling rate phase, where soil factors are dominant, has presented more problems and cannot yet be said to be satisfactorily modeled.

We present here a simple approach to estimating bare soil evaporation that shows promise of overcoming some of the limitations of previous approaches. It is not strictly a model of the evaporation process, but rather an empirical correlation between the ratio of daily totals of actual to potential evaporation and the amplitude of the diurnal surface soil temperature wave. The rationale for this correlation comes from the thermal inertia theory of remote soil moisture determination by infrared thermometry (Blanchard, et al., 1974; Rosema, 1974), which Idso, et al. (1975a) have shown to be valid for several soils ranging from sandy loams to clays. Although the soil thermal inertia-water content relations were different for these different soils, when soil water pressure was substituted for water content, one single relation adequately described them all. Since evaporation is directly related to the surface soil water pressure, we felt that the soil thermal inertia technique might thus be capable of prescribing relative bare soil evaporation rates, that combined with potential evaporation calculations could allow determination of actual evaporation rates over the entire range of soil drying. If such a relation could be found, it would greatly enhance the potential for remotely determining bare soil evaporation rates from aircraft and orbiting satellites.

EXPERIMENTS

All of the experimental work described in this paper was conducted at Phoenix, Arizona, on a smooth bare field of Avondale loam (fine-loamy, mixed (calcareous), hyperthermic, Torrifluventic Haplustoll). Seven drying experiments were conducted in the 72- × 90-m field in July 1970, March 1971, August 1972, May, September, and December 1973, and November 1974. In the first six experiments, irrigations of approximately 10 cm of water were applied to the field and two lysimeters located therein. Evaporation, soil surface temperature, and screen level air temperature were thereafter measured every 20 minutes -- evaporation by the lysimeters and the temperatures by fine-wire copper-constantan thermocouples. In the November 1974 experiment, only the lysimeters were irrigated. One had a small amount of water added to it each morning thereafter, while the other was allowed to dry. The ratio of the two evaporation rates thus gave the actual evaporation rate as a fraction of

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the potential evaporation rate. These data were valid only for a limited time, however; for although initially both lysimeters experienced identical "island" effects, once the drying lysimeter entered stage III of soil drying (Idso, et al., 1974) it no longer acted as an island and could not be compared with the wet lysimeter still in stage I and surrounded by a dry field. Since both the field and the lysimeters were irrigated in the first six experiments, the ratios of actual to potential evaporation for those experiments were calculated as total daily evaporation divided by total evaporation on the first day of each experiment. It was this ratio of actual to potential evaporation that we wished to correlate with the amplitude of the diurnal surface soil temperature wave.

RESULTS AND DISCUSSION

In Fig. 1, the ratio of daily actual evaporation (E) to daily potential evaporation (E_o) is plotted as a function of the amplitude of the diurnal surface soil temperature wave, i.e., $T_{S_{Max}} - T_{S_{Min}}$, for the seven experiments. The line through the data points was drawn by sight. It indicates that the second stage of soil drying that has been described by Idso, et al. (1974) is actuslly only a transitional stage between two basic regimes: stage I, where evaporation is controlled by atmospheric factors, and stage III, where it is controlled almost wholly by soil factors. This fact is also demonstrated by the data plotted in Fig. 2. Here again we wet one lysimeter sufficiently to enable it to evaporate at the potential rate all day, while the other was wet only enough to allow evaporation at the potential rate for 2 hours. From periodic photographs of the drying lysimeter we could determine the percentage surface area of the lysimeter that had dried, and thus could plot the ratio of actual to potential evaporation as a function of the fraction of the total surface area of the drying lysimeter that had entered stage III of soil drying. The linear regression that resulted indicated that as a given small area of surface soil changed from stage I to stage III, its evaporation rate experienced an effectively instantaneous stepwise reduction. As shown in Fig. 1, this occurred at a $T_{S_{Max}} - T_{S_{Min}}$ value of 22.5° C on a daily basis. The end point of the drop is much lower in Fig. 2 than in Fig. 1 (0.58) because we again have the island effect occurring in Fig. 2, where the continually wet lysimeter is surrounded by a dry field, which enhances its evaporation rate and lowers the E/E_o ratio to an unrealistic minimum value.

Figure 1 shows that the empirical relation we found between E/E_o and $T_{S_{Max}} - T_{S_{Min}}$ is fairly independent of season. Thus, there is good reason to believe that it would also be independent of climate, and this would be a logical next step for future research. However, would our results be less similar if different soils were involved? The work of Idso, et al. (1975a) cited in the INTRODUCTION indicates that the relation defined by Fig. 1 may indeed be independent of soil type. Thus, both of these hypotheses should be tested.

In a variation of our basic objective, we next plotted E/E_o vs. $(T_S - T_A)_{Max}$, the maximum value of the surface soil minus air temperature differential, since Idso, et al. (1975a) showed this parameter to be as good as $T_{S_{Max}} - T_{S_{Min}}$ in specifying surface soil water content and pressure. The results are shown in Fig. 3, where the line through the data points is again drawn by sight. The scatter in the data is about the same in Fig. 1 and 3, and the shapes of the lines through the data are identical. This similarity prompted us to normalize the data in each figure by subtracting from the abscissa value of each data point the abscissa value of the stage I to III transition point. Data from both graphs were then combined to produce Fig. 4, which again demonstrates the equivalence of the two approaches. In addition, a linear regression was run on the data that appeared to define stage III (enclosed by dashed line which is ± 2.5 times the resultant standard deviation). Equally good regressions were obtained for the two data sets separately: $r_{Y.X} = 0.879$ and $S_{Y.X} = \pm 0.083$ for $X = T_{S_{Max}} - T_{S_{Min}} - 22.5°$ C, and $r_{Y.X} = -0.855$ and $S_{Y.X} = \pm 0.087$ for $X = (T_S - T_A)_{Max} - 3.5°$ C.

In addition to indicating the degree to which the data satisfy the major objective of our investigation, Fig. 4 also indicates that since only one relation is required to fit the two types of data plotted over the entire range of E/E_o variability encountered, the two normalized abscissa functions must be roughly equivalent in all seasons and for all soil moisture conditions.

That is,

$$T_{S_{Max}} - T_{S_{Min}} - 22.5^{o}\ C \approx (T_S - T_A)_{Max} - 3.5^{o}\ C \quad (1)$$

If we thus make the simplifying assumption that $(T_S - T_A)_{Max}$ is equivalent to $T_{S_{Max}} - T_{A_{Max}}$, equation (1) reduces to

$$T_{A_{Max}} \approx T_{S_{Min}} + 19^{o}\ C \quad (2)$$

Since the surface soil temperature wave generally peaks before the screen level air temperature each day, our simplifying assumption is not quite correct. Nevertheless, it is probably in error by a rather constant amount each day, so that the generalized form of equation (2) would still hold; that is,

$$T_{A_{Max}} \approx T_{S_{Min}} + K \quad (3)$$

where K is a constant somewhat greater than 19^{o} C, since $T_{S_{Max}} - T_{A_{Max}}$ would generally be somewhat less than $(T_S - T_A)_{Max}$.

To check this relation, we have plotted values of $T_{A_{Max}}$ vs. $T_{S_{Min}}$ in Fig. 5 for all of the days represented in Fig. 4, plus some additional days that lacked lysimeter data. The regression analysis of these data indicates a very good correlation between $T_{A_{Max}}$ and $T_{S_{Min}}$, which closely approximates equation (3) with $K \approx 20^{o}$ C. Within the degree of accuracy indicated, it may thus be used to infer maximum air temperatures in remote areas from aircraft- or satellite-derived surface soil temperature near sunrise. More conventionally, it may also be used to predict minimum surface soil temperatures to be expected on the basis of maximum air temperature messurements obtained the previous afternoon. Again, as with the previously derived relations, generality is implied with respect to both climate and soil type; but both of these hypotheses need to be independently checked.

CONCLUDING STATEMENTS

It appears that the thermal inertia technique, which has recently been suggested as a possible means for remotely determining surface water contents of bare soils via infrared thermometry, may also be used to evaluate the relative evaporation rates of bare soils. Each of the two variations of this technique, which use $T_{S_{Max}} - T_{S_{Min}}$ and $(T_S - T_A)_{Max}$ as independent variables, worked successfully on a smooth bare field of Avondale loam at Phoenix, Arizona, on clear day-night periods during all seasons of the year. Together with stage I potential evaporation calculations, this approach would allow evaporation rates from bare soil to be calculated throughout all of the classical stages of soil drying.

The empirical relations describing these results also indicate that stage II of soil drying is not a unique physical process, but rather an observational artifact arising from the noninstantaneous transition of the entire soil surface from the basic stage I of soil drying (where energy is limiting the evaporation rate) to the basic stage III of soil drying (where soil water content is the limiting factor). In addition, there appears to be a unique relation between maximum clear-sky, screen-level air temperature and minimum surface soil temperature that is independent of season and soil water content. There are some indications that it, as well as the relative evaporation rate-soil thermal inertia relation, may also be independent of climate and soil type. Research in other areas and on different soils is needed to check these hypotheses.

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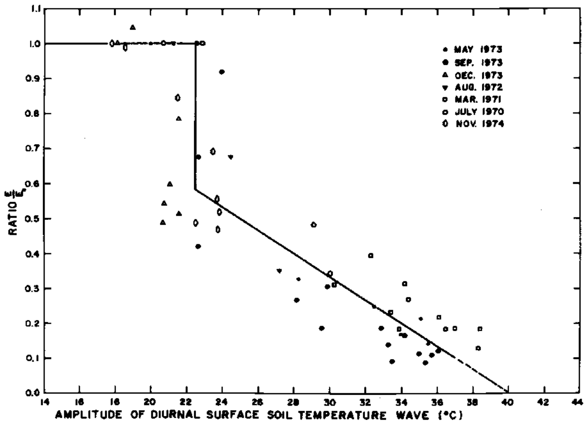

Fig. 1. Ratios of daily total actual evaporation to potential evaporation vs. the amplitude of the diurnal surface soil temperature wave.

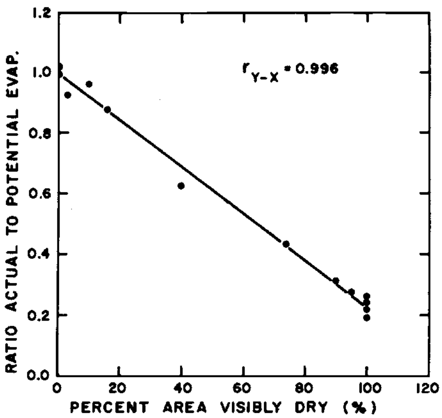

Fig. 2. Ratios of instantaneous rates of actual evaporation to potential evaporation vs. the percentage of the lysimeter area that had visibly dried when the evaporation measurements were made.

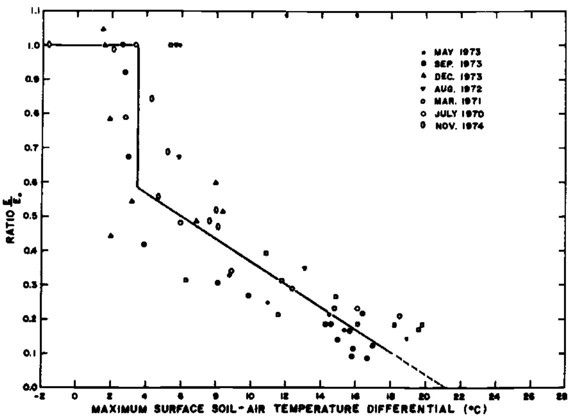

Fig. 3. Ratios of daily total actual evaporation to potential evaporation vs. the maximum value of the surface soil minus air temperature differential.

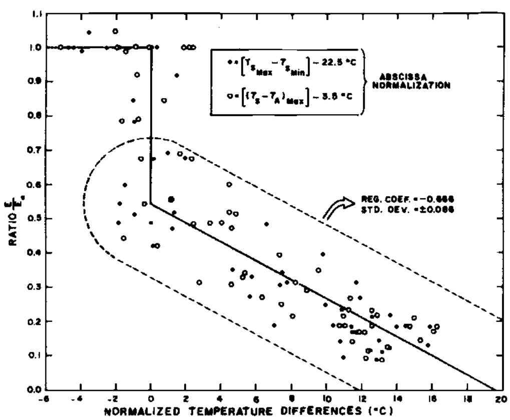

Fig. 4. Ratios of daily total actual evaporation to potential evaporation vs. the normalizations (shown on the figure) of the abscissas of Fig. 1 and 3.

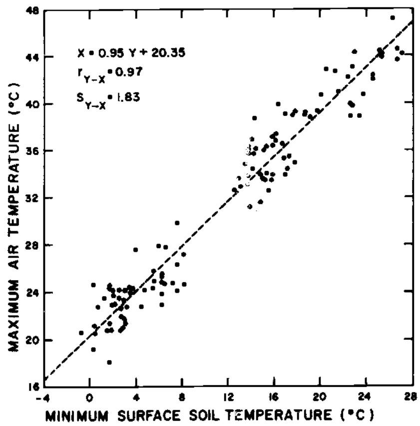

Fig. 5. Maximum screen level air temperature vs. minimum surface soil temperature.