Reports

Estimating Evaporation: A Technique Adaptable to Remote Sensing

Abstract. *A procedure is presented for calculating 24-hour totals of evaporation from wet and drying soils. Its application requires a knowledge of the daily solar radiation and the maximum and minimum air temperatures (standard Weather Service measurements), moist surface albedo (readily estimated or obtainable from a one-time measurement), and maximum and minimum surface temperatures (obtainable from surface or airborne sensors). Tests of the technique on a bare field of Avondale loam at Phoenix, Arizona, have shown it to be independent of season.*

Evaporation of water from soils and crops is an important factor in managing both irrigated and dryland farming operations. It influences the time of seeding, the scheduling of irrigations, and various tillage practices (*1*). Evaporation is also important in determining the water balance of watersheds, which allows prediction and estimation of runoff and groundwater recharge. Thus, several techniques have been developed over the years to estimate evaporation rates (*2*). Most of these techniques, however, have been of rather limited usefulness in two respects. First, they have depended on many environmental parameters and surface characteristics that are generally difficult to measure over extended areas, that is, vapor pressure, air temperature, wind speed gradients, soil water content, and surface roughness length. Second, many have been applicable only to potential evaporation—the rate that prevails over a surface of any configuration under a given set of meteorological conditions if there is no saturation deficit at the surface, that is, a condition of nonlimiting water supply (*3*).

In light of the seriousness of the current and projected world food shortage, we must overcome these limitations and develop a method of evaporation estimation readily adaptable to rapid application over large areas that handles both the potential rate phase of evaporation and the post-potential (falling rate or soil-limiting) phase of evaporation, where the surface water supply is limiting and acts to decrease evaporation rates below the potential rate that would occur if water were nonlimiting. In this report we describe the first step in the development of such an evaporation estimation technique and its initial tests on a field of bare soil. In addition to standard Weather Service measurements of daily solar radiation and maximum and minimum air temperatures, it requires only a one-time measurement or estimate of moist surface albedo and daily measurements of maximum and minimum surface temperatures.

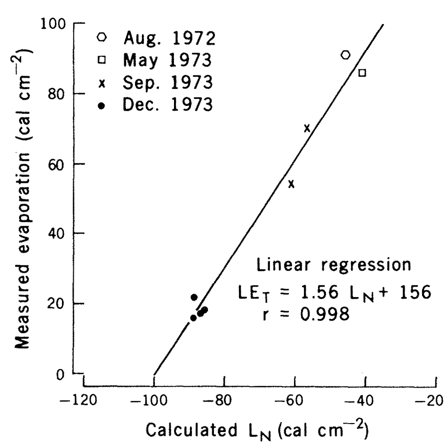

Fig. 1. Total evaporation induced by thermal radiation (LE_T) from a smooth bare field of Avondale loam at Phoenix, Arizona, as a function of the total net thermal radiation (L_N) calculated as ($R_A - R_S$) from average values of T_A and T_S, as determined from nighttime data; r = correlation coefficient.

We note first that the evaporation energy equivalent (LE) is largely proportional to net radiation (R_N) in the potential rate phase, and that net radiation can be readily subdivided into its two component parts: net solar radiation (S_N) and net thermal radiation (L_N). Since S_N is an external forcing function thermally independent of evaporation whereas L_N is in part determined by the evaporation process by virtue of its effects on surface temperature, we assume that the total 24-hour evaporation is directly equal to the daily S_N plus some function of the 24-hour summation of L_N; that is, we assume

$$LE = LE_S + LE_T = S_N + f(L_N) \quad (1)$$

where LE_S and LE_T are, respectively, the components of the total evaporation induced by solar and thermal radiation.

To explicitly derive the relation $LE_T = f(L_N)$, we utilized nighttime data, when no solar radiation was present. On several clear nights we measured evaporation from a smooth bare surface of Avondale loam with two weighing lysimeters. We plotted these measurements against nighttime totals of L_N, obtained from calculations of ($R_A - R_S$) where R_A is the incoming atmospheric thermal radiation and R_S is the outgoing surface thermal radiation. The quantity R_A was obtained from the Idso-Jackson formula (*4*) as

$$R_A = \sigma T_A^4 (1 - 0.261 \exp[-7.77 \times 10^{-4}(273 - T_A)^2]) \quad (2)$$

where σ is the Stefan-Boltzmann constant and T_A is the air temperature measured at 1 m above the surface. The quantity R_S was obtained from the Stefan-Boltzmann equation for blackbody radiation as

$$R_S = \sigma T_S^4 \quad (3)$$

where T_S is the surface temperature. Values of both T_A and T_S were obtained from fine-wire, copper-constantan thermocouples at 20- or 30-minute intervals through the night. The results (Fig. 1) indicated that, when the soil surface is moist and evaporation is in the potential rate phase,

$$LE_T = 1.56\, L_N + 156 \quad (4)$$

In testing our basic hypothesis, we next computed 24-hour representative values of T_A and T_S as averages of their maximum and minimum values and used these average values to compute 24-hour totals of L_N (which were all negative). These values were then used as the independent variable in the linear regression equation (Eq. 4) to determine the negative evaporation component to be algebraically added to the daily S_N. We compared

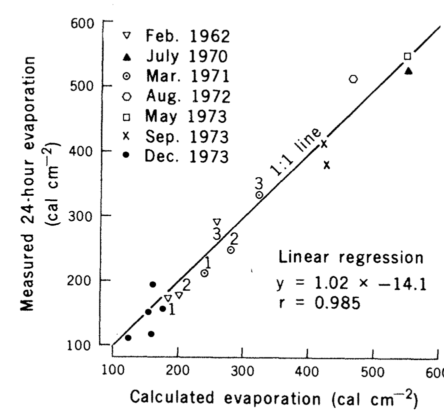

Fig. 2. Total 24-hour measured evaporation (LE) plotted against the 24-hour evaporation calculated as $LE = S_N + 1.56\, L_N + 156$, with L_N in this instance calculated from the averages of the maximum and minimum values of T_A and T_S for the 24-hour period.

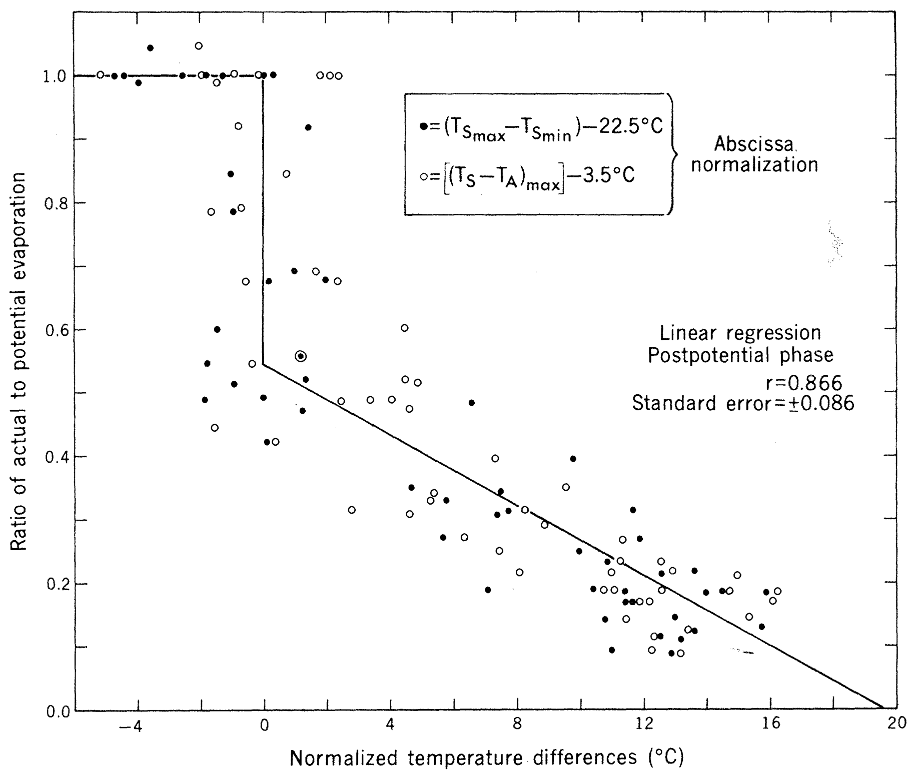

Fig. 3. Ratios of total 24-hour actual-to-potential evaporation as a function of the two thermal parameters defined at the top center of the graph, as determined for a field of Avondale loam at Phoenix, Arizona.

the results of this procedure with measurements of potential evaporation (Fig. 2), which showed that our basic hypothesis produced acceptable results.

Equations developed to calculated evaporation will often give good results in one season or climate but not in another (*2*); that is, in a windy, dry situation they may do well, but in a calm, humid situation they may perform poorly, or vice versa. We consider our approach potentially adaptable to various situations, for it incorporates T_S, which is directly and strongly linked to the evaporation rate. For example, between day 1 and day 3 after heavy irrigations of our field (72 by 90 m) in February 1962 and again in March 1971, the average daily wind speed more than doubled, greatly increasing the evaporation rates; yet our calculation procedure, which does not explicitly account for wind speed, gave equally good results under both sets of conditions. Why? Because the increased evaporation rates on the windy days lowered the T_S of the soil relative to T_A, which resulted in a less negative L_N flux for the day and a less negative value of LE_T to be algebraically added to the LE_S component of the total evaporation. There is a similar automatic adjustment for humidity variations. Over the range of conditions depicted in Fig. 2, vapor pressure, another component not explicitly accounted for in our procedure, varied by a factor of 5; yet our evaporation calculations were equally good over the entire range. In addition, no specification of surface type was made in developing our technique. Thus, we believe that relations similar to the one derived for bare soil in Fig. 1 could be developed for other surface types such as crops.

For bare soils, we next confront the problem of postpotential (falling rate or soil-limiting) phase evaporation, where the surface becomes dry and evaporation rates drop significantly. For this problem we again utilized T_S and T_A. Idso *et al.* (*5*) have shown that for several soils, ranging from sandy loams to clays, both the maximum value minus the minimum value of the daily surface soil temperature wave ($T_{S,max} - T_{S,min}$) and the maximum value of the surface soil temperature minus the air temperature $[(T_S - T_A)_{max}$ are good predictors of soil water pressure potential (the work required to move a unit mass of water against a force field from zero potential to the point in question), independent of the soil type. Thus, since evaporation is probably related to water pressure potential of the surface soil in the drying stages, we felt it would also be related to these thermal parameters.

To test this idea, we plotted ratios of 24-hour actual-to-potential evaporation against the thermal parameters $[(T_{S,max} - T_{S,min}) - 22.5°C]$ and $[(T_S - T_A)_{max} - 3.5°C)]$ for several periods after approximate 10-cm irrigations of our field (Fig. 3). The potential evaporation for all days was taken to be equal to the measured potential evaporation at the start of each time series before the surface soil dried, that is, day 1 immediately after irrigation. (Weather conditions for all days of each drying run were very similar.) On the normalized basis depicted in Fig. 3, one line adequately describes the relation between relative evaporation and both of the thermal parameters. Combined with our procedure for obtaining actual potential evaporation totals for the initial days of such drying periods, these results allow estimates of actual evaporation totals to be made throughout both the potential and postpotential stages of soil drying, although there still remains some uncertainty at the transition point between these two regimes.

The prime significance of these results lies in the fact that they indicate that actual evaporation rates throughout all stages of soil drying may be obtained from remotely acquired surface temperatures and routine weather network data. Measurements of maximum and minimum air temperatures are the most basic measurements made at all weather stations; solar radiation is rapidly becoming a standard measurement also. Moist surface albedo can be obtained from information in the literature (*6*) or from a one-time measurement. Thus, maximum and minimum surface temperatures are the only additional data needed for successfully estimating evaporation, and these measurements can be made over large areas by radiometric means. Such temperature measurements may thus be capable of specifying actual soil evaporation rates wherever air temperature and solar radiation data are available.

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References and Notes

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7. Contribution from the Agricultural Research Service, U.S. Department of Agriculture.

14 April 1975; revised 27 May 1975