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DISCUSSION

ESTIMATING EVAPOTRANSPIRATION FROM SOLAR RADIATION[a]

Closure by Marvin E. Jensen and Howard R. Haise

MARVIN E. JENSEN,[50] M. ASCE, AND HOWARD R. HAISE.[51]—The ummary of Grassi's thesis by Christiansen illustrates a multiple correlation pproach to predicting evapotranspiration, E_t. Grassi related evapotranspiraon rates to all meterological and crop data provided by the authors in ddition to theoretical solar radiation reaching the outer atmosphere. A equential analysis technique was used in an attempt to obtain independent mpirical coefficients for the meteorological variables and crop factors resented. In this procedure, E_t was correlated with the first meteorological riable (either extraterrestrial and cloud cover, or incident solar radiation, evaporation in this case) using only those values of E_t near the potential growth stage. Then, the ratios of E_t to the values obtained from the rrelation equation were correlated with the next variable.

This process was repeated, dividing E_t by the combined value of the evious correlation equations to obtain relationships that gave coefficients use with Eqs. 13, 14 and 15. Coefficients for Eq. 13 were obtained by rrelating E_t ratios with air temperature before correlating them with the rop cover factor. Coefficients for Eq. 14 were obtained by correlating E_t

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[a] December, 1963, by Marvin E. Jensen and Howard R. Haise (Proc. Paper 3737).

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[illegible]

ratios with the crop cover factor before correlating them with air temperature. Because the arbitrary crop cover factor is related to air temperature, the air temperature coefficient would not be expected to have as much influence in Eq. 14 as in Eq. 13, or as Eq. 8 would indicate. For example, when using all crops so that the average crop factor F is equal to 1.0 at stages of growth when the crop cover is not limiting ($C_{Crc} = 1.0$), Eq. 14 is the same as Eq. 8. The value of the product KC_T corresponds to the quantity (0.014T - 0.37) obtained using only data from selected crops when crop cover is not limiting. The product KC_T obtained by Grassi can be expressed by the equation:

$$K\,C_T = 0.33 + 0.003\,T \qquad (17)$$

in which T is mean air temperature, in degrees fahrenheit. Values obtained from equation 17, show less influence of air temperature in the range from 40 to 70°F than indicated by Eq. 16 and the values agree with the quantity (0.014 T - 0.37) at about 64°. Thus Grassi's coefficients used with Eq. 14 do not appear to represent entirely independent variables.

The USBR also analyzed the original data provided by the authors and modified the proposed procedure. The modification resulted in a single curve for each crop in place of a curve for each crop in each climatic region. This was accomplished by computing the estimated potential evapotranspiration E_{tp}, for each sampling period using Eq. 8. Then, the ratio E_t/E_{tp} was plotted as the ordinate instead of E_t/R_s, but the same seasonal scales were used. This technique was evaluated to a limited extent by the authors upon completion of the original analysis but was not presented, pending additional information to verify a basic assumption involved, i.e., the ratio E_t/E_{tp} must be unique at a given stage of growth. The writers indicated in their paper, that the amount of transpiring area per unit land area for potential E_t to occur would be influenced by the magnitude of potential E_t. Likewise, the ratio of E_t/E_{tp} may also depend on the magnitude of E_{tp} in addition to stage of growth. The convenience of using a single curve for each crop may outweigh minor differences if the E_t/E_{tp} ratio versus stage of growth approaches a unique relationship.

The use of a single curve for each crop developed by the USBR has definite advantages besides reducing the need for a crop curve in each region. It should improve the estimate of E_t in a given year because both solar radiation and air temperature are used. This ratio also would reflect minor differences in E_t between crops resulting from differences in sensible heat transfer properties of the foliage when cover is essentially complete.

Analysis of a limited amount of data on alfalfa indicated that this crop may have a greater capacity to absorb sensible heat from the air in arid areas than some crops. This characteristic was noted by observing that the E_t/R_s ratio changed more rapidly as air temperature increased than the mean of other crops as indicated by Eq. 7. The following equation was obtained using only limited alfalfa data and is presented to illustrate that there may be some real differences in E_t rates between crops even when crop cover is considered complete.

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ESTIMATING EVAPOTRANSPIRATION FROM SOLAR RADIATION

By Marvin E. Jensen,[1] M. ASCE, and Howard R. Haise[2]

SYNOPSIS

Recent studies throughout the world have shown that evapotranspiration (consumptive use) in humid and semihumid areas can be predicted on a daily basis as well as for shorter time periods using an energy balance approach. In order to facilitate the application of energy balance concepts to semiarid and arid areas, measured evapotranspiration data from irrigated areas in the western United States, obtained during the past 35 yr, were collected, reevaluated, and combined with estimates of solar radiation. Approximately 1,000 measurements of evapotranspiration for individual sampling periods for various crops were found useable. The results of this study provide mean numerical values to use in a dimensionless energy balance equation for predicting evapotranspiration.

A brief review of the energy balance concept is presented, with a tabular summary of mean measured ratios of evapotranspiration to solar radiation. This ratio represents the combined effects of reflectance or albedo, and relative effects of effective thermal radiation, sensible heat flux to the soil and air, plus other minor components at various stages of crop growth. Procedures and examples are given to permit estimates of evapotranspiration to be made for various crops and potential evapotranspiration.

A summary of weekly mean daily and total monthly solar radiation is also presented for twenty western United States locations. Procedures are given for estimating solar radiation for other areas where only limited climatic

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Note.—Discussion open until May 1, 1964. To extend the closing date one month, a written request must be filed with the Executive Secretary, ASCE. This paper is part of the copyrighted Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, Vol. 89, No. IR4, December, 1963.

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data are available. These data and procedures provide a simple technique for making evapotranspiration estimates in arid and semiarid irrigated areas.

INTRODUCTION

Estimates of evapotranspiration, E_t (consumptive use), were required for construction of the early irrigation projects in the western United States during the latter part of the 19th century. The same type of estimates are needed today, but greater accuracy is required. Several reasons for increased accuracy are: (1) Growing competition for limited water supplies; (2) irrigation projects that required the smallest initial costs have been completed and higher construction costs of new projects demand closer tolerances and less leeway in design to make the projects economically feasible; (3) water litigations between irrigation districts, states, upper and lower river basins, and, in some cases, between countries, require more precise E_t estimates; (4) river basin development for maximum use of water supplies requires long-range planning with reliable estimates of E_t; (5) sprinkler irrigation design requires accurate, short period estimates for 5 days to 10 days to assure adequate but economic capacity to meet peak demands; (6) many drainage problems can be avoided or time of occurrence predicted in advance if accurate E_t estimates are available; and (7) existing projects can often reduce operational wastes by predicting water deliveries several days in advance. Thus, the need for information on evapotranspiration by crops has become more important today than, for example, when E. Mead[3] began making "duty of water" measurements at Fort Collins, Colo., in 1887, and later at Wheatland, Wyo., in 1889.[4]

Notation.—The symbols adopted for use in this paper are defined where they first appear and are arranged alphabetically in Appendix II.

BACKGROUND

The problem of estimating or determining water requirements for irrigation has been studied for more than 70 yr. In the 1890's, the quantity of water applied and yield responses were being observed in Colorado, Utah, and Wyoming.[5,6,7] On July 12 and July 13, 1897, several agricultural experiment

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[3] "Report of Experiments in Irrigation and Meteorology," by Elwood Mead, Bulletin No. 1, Colorado Agric. Experiment Sta., August, 1887.

[4] "Irrigation and Duty of Water," by B. C. Buffum, Bulletin No. 8, Wyoming Agric. Experiment Sta., October, 1892.

[5] "The Use of Water in Irrigation in Wyoming and its Relation to the Ownership and Distribution of the Natural Supply," by B. C. Buffum, USDA-OES Bulletin [illegible] 1900.

[6] "Duty of Water," by L. G. Carpenter, Bulletin [illegible] Experiment Sta., January, 1893.

[7] "Water for Irrigation," by Samuel Fortier, [illegible] Experiment Sta., December, 1893.

station officers and irrigation engineers met in Denver, Colo. to plan a broad study of the duty of water. As a result of this planning conference, extensive duty of water measurements were made in most western states near the turn of the century under the direction of Mead.[8,9] Numerous other studies were conducted during the next 20 yr on seasonal evapotranspiration (consumptive use).[10,11,12,13,14] An excellent summary of some of these early studies can be found in a progress report presented in 1927 and published later.[15]

During this period, one of the classic studies on transpiration was conducted by L. J. Briggs and H. L. Shantz.[16,17] The results and conclusions from this study, conducted 50 yr ago, do not differ materially from many reported during the past 15 yr. Briggs and Shantz recognized that solar radiation was the primary causative factor in transpiration, but they also recognized, especially in their small container studies, that additional heat energy was received from the air (advection).

During the 25 yr following 1920, considerable emphasis was placed on the development of procedures for estimating seasonal evapotranspiration. Air temperature, being readily available, was the major climatic variable in the procedures developed.[18,19,20,21,22] Numerous variations of these general procedures have been made in more recent years. (A detailed review of and other estimating procedures has been prepared by the writers as part of a USDA techanical bulletin that will be available in the near future.)

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[8] "Irrigation and Drainage Investigations of the Office of Experiment Stations," by R. P. Teele, U. S. Dept. of Agric., 1904.

[9] "Review of Ten Years of Irrigation Investigations," by R. P. Teele, Annual Report, OES, 1908.

[10] "The Production of Dry Matter with Different Quantities of Water," Bulletin No. 116, Utah Agric. Experiment Sta., 1912.

[11] "The Duty of Water in the Cache Valley, Utah," by F. S. Harris, Bulletin No. 173, March, 1920.

[12] "Experiments on the Proper Time and Amount of Irrigation, Twin Falls Experiment Station 1914, 1915, and 1916," by M. R. Lewis, 1919.

[13] "Irrigation in Northern Colorado," by R. G. Hemphill, USDA Bulletin No. 1026, 1922.

[14] "The Net Duty of Water in the Sevier Valley, Utah," by O. W. Israelson and L. M. Winsor, Bulletin No. 182, Utah Agric. Experiment Sta., July, 1922.

[15] "Consumptive Use of Water in Irrigation," Progress Report of the Duty of Water Committee of the Irrigation Division, Transactions, ASCE, Vol. 94, 1930, pp. 1349-1399.

[16] "Hourly Transpiration Rate on Clear Days as Determined by Cyclic Environmental Factors," by L. J. Briggs and H. L. Shantz, Journal of Agricultural Research, Vol. 5, No. 14, January, 1916.

[17] "Daily Transpiration During the Normal Growth Period and Its Correlation with the Weather," by L. J. Briggs and H. L. Shantz, Journal of Agricultural Research, Vol. 7, No. 4, October, 1916.

[18] "Consumptive Use of Water by Crops," by C. R. Hedke, New Mexico State Engr.'s Office, July, 1924.

[19] "Evaporation and Consumptive Use of Water Formulae," by H. F. Blaney and K. V. Morin, Transactions, Amer. Geophysical Union, 1942, pp. 76-83.

[20] "Consumptive Use of Water for Agriculture," by L. Lowry and A. F. Johnson, Transactions, ASCE, Vol. 107, 1942, pp. 1243-1302.

[21] "An Approach Toward a Rational Classification of Climate," by C. W. Thornwaite, Geographical Review, Vol. 38, 1948, pp. 55-94.

[22] "Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data," by H. F. Blaney and W. D. Criddle, USDA-SCS Technical Publication 96, 1950.

Evapotranspiration studies conducted in the 1950's are too numerous to mention. In general, considerable attention was given to physical laws governing the evapotranspiration process. Two theoretical approaches to the problem were investigated, namely, the mass transfer and the energy balance. The latter approach has received greater acceptance because less refinement is instrumentation is necessary. Theoretical approaches were considered in predicting evaporation from water surfaces before being applied to cropped surfaces. Examples of earlier work on evaporation using energy balance concepts are those of I. S. Bowen;[23] N. W. Cummings and B. Richardson;[24] G. F. McEwen;[25] Richardson;[26] Cummings;[27] R. E. Kennedy and R. W. Kennedy;[28] and Cummings.[29]

The application of theoretical concepts to cropped surfaces received major attention in the 1950's after the work of H. L. Penman.[30] Penman combined two theoretical concepts into an equation for estimating evaporation from a free water surface, and then applied empirical coefficients to adapt the values obtained to evapotranspiration. The two combined theories were the aerodynamic, or turbulent transport of vapor by a process of eddy diffusion, and energy balance in which evaporation is regarded as one method of dissipating incoming radiation. The use of the Penman equation, even though evaluated the world over, has not gained great popularity among engineers, because it requires measurements of mean air temperature, mean dew point temperature, and mean wind velocity over the growing crop. The engineer must be able to predict the E_t rate for an area before a crop is grown and before irrigation water becomes available. Generally, these estimates are dependent on available climatological and meteorological data. Seldom does the engineer have adequate time or funds to make measurements in the area for which estimates are needed. Other "potential evapotranspiration" formulas have been proposed, but most require the rigid assumption that the site in question be surrounded by an unlimited area of actively transpiring vegetation, adequately supplied with water. This rigid requirement automatically restricts many formulas to humid or semihumid areas. Certainly, in irrigated areas, such as the western United States, the occurrence of such boundary conditions is extremely unrealistic.

The evaluation of theoretical approaches to predicting evapotranspiration for short periods, developed within the past 10 yr, has been carried out largely in the more humid areas where economical water table lysimeters can give

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[23] "The Ratio of Heat Losses by Conduction and by Evaporation from any Water Surface," by I. S. Bowen, Physics Review, Vol. 27, 1926, pp. 779-787.

[24] "Evaporation from Lakes," by N. W. Cummings and B. Richardson, Physics Review, Vol. 30, 1927, p. 527.

[25] "Results of Evaporation Studies," by G. F. McEwen, Scripts Institute of Oceanography Technical Series, Vol. 2, 1930, pp. 401-415.

[26] "Evaporation as a Function of Insolation," by Burt Richardson, Transactions, ASCE, Vol. 95, 1931, pp. 996-1019.

[27] "Evaporation from Water Surfaces," by N. W. Cummings, Transactions, Amer. Geophysical Union, Part 2, 1936, pp. 507-509.

[28] "Evaporation Computed by the Energy-Equation," by R. E. Kennedy and R. W. Kennedy, Transactions, Amer. Geophysical Union, Vol. 17, 1936, pp. 426-430.

[29] "The Evaporation-Energy Equations and their Practical Application," by N. W. Cummings, Transactions, Amer. Geophysical Union, Vol. 21, 1940, pp. 512-522.

[30] "Natural Evaporation from Open Water, Bare Soil and Grass," by H. L. Penman, Proceedings, Royal Soc., Series A, Vol. 193, 1948.

reasonably reliable results. A thorough evaluation of the energy balance approach in arid and semiarid areas has not been made. The cost of such a study is high, and 5 yr to 10 yr may be required if new data under different climatic conditions are to be collected.

The study summarized herein was initiated to re-evaluate thousands of short period measurements of E_t that have been made during the past 35 yr, many of which have not been published in detail, and to relate these values to the energy balance equation. A re-evaluation was essential because, in many cases, the measurements were made for other purposes, and their reliability for evaluating short period E_t was questionable. Although re-evaluation of the E_t data may have been subject to bias, using the data without rigid selection standards would include serious errors. The details of this study, including the many contributors and criteria for selection of the data, will be available in the technical bulletin previously mentioned. The purpose herein is to make available the more pertinent results obtained, to permit estimates of E_t for short periods and for seasons in irrigated areas using energy balance concepts. An earlier paper summarized some of the preliminary results obtained and described the general estimating procedure.[31]

Many studies conducted during the past 15 yr have demonstrated repeatedly that net radiation is more closely related to E_t than variables such as air temperature and humidity. The use of the energy balance approach is expected to expand considerably in future studies, with refinements in the relationship of E_t to meteorological conditions.

ENERGY BALANCE

A brief summary of the energy balance concept is presented to illustrate the relative significance of the various terms. The basic principle of the energy balance concept is that evaporation of water requires large quantities of heat energy. When an evaporating surface, such as an actively growing crop, is supplied with adequate water, the rate of E_t is controlled by the available heat energy. The mechanism for removal of water vapor from the area by turbulent transport is seldom a factor limiting E_t in arid and semiarid areas.

The individual vertical components involved in the energy balance concept can be expressed in an energy balance equation for the vegetated crop zone. The equation requires a reasonable assumption; namely, that an adequate boundary of the same crop surrounds the area in question, and that a temperature or vapor pressure gradient does not exist, or is extremely small, in the horizontal direction within the vegetated zone. Thus, it is assumed that the guard area surrounding the E_t site is large enough to eliminate the so-called "clothesline effect" but not the oasis effect. The energy balance equation, in g-cal units per unit area of the vegetated zone then becomes:

$$R_s - r\,R_s + R_a - \left(R_g + R_p\right) - L\,E_t - G - A - P - s = 0 \quad \ldots\ldots (1)$$

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[31] "Estimating Evapotranspiration for Various Crops Using Solar Radiation," by M. E. Jensen and H. R. Haise, Proceedings, Sprinkler Irrig. Open Tech. Conf., March, 1962.

in which R_s represents the solar and sky radiation flux (short wave); r is the reflectance or albedo; R_a is the thermal radiation flux from the atmosphere; $(R_g + R_p)$ represents the thermal radiation flux from the ground and plants; L is the latent heat of vaporization; E_t is the rate of evaportranspiration; G represents the sensible heat flux to the ground (negative for flux from the ground); A represents the sensible heat flux to the air (negative for flux from the air); P represents the radiation flux used in photosynthesis; and s is the heat flux stored in vegetated zone (negative for flux released from storage).

In this equation, the first five terms represent net radiation; R_n, i.e.,

$$R_s - r\,R_s + R_a - \left(R_g + R_p\right) = R_s\,(1 - r) - R_{et} = R_n \;\ldots\ldots\ldots \quad (2a)$$

and

$$R_a - \left(R_g + R_p\right) = - R_{et} \;\ldots\ldots\ldots\ldots\ldots\ldots \quad (2b)$$

which is the effective or net thermal radiation. Eq. 1 can be further simplified by neglecting the terms s, P, and G when considering periods of 1 week to 2 weeks. The heat exchanged in the storage term, s, may be high relative to the other terms for a few hours in early morning and evening[32] but is negligible for 1- to 2-week periods. The photosynthesis term P uses a maximum of 5% of net radiation.[33] M. I. Budyko[34] estimates that P may be as high as 5% of R_s. The change in heat stored in the soil, G, is small compared to R_s for 1-week to 2-week periods. K. J. Kristensen,[35] in Denmark, found that the average rate of heat accumulation in the soil under grass varied from 4.3% to 5.1% of solar radiation from April 1 to August 31. A similar rate of release of heat from the soil occurred during the latter part of the season. Additional simplification can be obtained by converting all energy terms to equivalent rate of evaporation, using a constant value for heat of vaporization (1 g of water = 590 cal).

With these assumptions and rearrangement, Eq. 1 becomes

$$R_s\,(1 - r) - R_{et} - E_t - A \cong 0 \;\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Eq. 3 can be expressed in dimensionless form by dividing by R_s, and, after rearranging, becomes

$$\frac{E_t}{R_s} = 1 - r - \frac{R_{et}}{R_s} - \frac{A}{R_s} \;\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

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[32] "A Simple Aero-Heat Budget Method for Determining Daily Evapotranspiration," by C. B. Tanner, Transactions, 7th Internatl. Congress of Soil Scientists, Vol. 1, 1960.

[33] "Photosynthesis Under Field Conditions: II. An Aerodynamic Method for Determining the Turbulent Carbon Dioxide Exchange Between the Atmosphere and a Corn Field," by E. R. Lemon, Agronomy Journal, Vol. 52, 1960, pp. 697-703.

[34] "The Heat Balance of the Earth's Surface," by M. I. Budyko, W. B. PB 131692, U. S. Dept. of Commerce, 1958.

[35] "Temperature and Heat Balance of the Soil," by K. J. Kristensen, Oikos, Vol. 10, 1959, pp. 103-120.

If desired, one other term in Eq. 1, sensible heat to the soil, can be included as follows:

$$\frac{E_t}{R_s} \cong 1 - r - \frac{R_{et}}{R_s} - \frac{A}{R_s} - \frac{G}{R_s} \;\ldots\ldots\ldots\ldots \quad (4a)$$

The ratio E_t/R_s represents the combined effects of reflectance, (r), relative effects of effective or net thermal radiation R_{et}, heat flux to or from air by vertical turbulent transfer (± A), and heat flux to or from the soil (±G), plus other minor components. If the individual components are measured or predicted, E_t can also be predicted. Of the terms listed in Eq. 4 or Eq. 4a, the "A" term is the most difficult to predict. The ratio E_t/R_s will be 0.55 to 0.6, or E_t will be equal to net radiation, R_n when a green crop is adequately watered and transpiring, and A and G are approximately equal to zero. However, many crops do not have dense, actively transpiring vegetation all season. For example, shortly after planting a row crop, a large part of net radiation may be used in heating of the air and soil (A and G increase), and the reflectance, r, may be higher than with a crop on light colored soils. This causes the E_t/R_s ratio to be small. As the crop develops greater transpiration surface in moderate climates, E_t/R_s will be near 0.6. In arid areas, where additional heat may be received from the air, "A" will become negative, and the E_t/R_s ratio will be greater than 0.55 to 0.6. As the crop matures and transpiration is restricted and reflectance increases, the ratio again decreases. Air temperature has direct effects on the ratio because of the nonlinear saturated vapor pressure-temperature relationship and its effect on effective thermal radiation.

MEASURED E_t/R_s RATIOS

Using the E_t data collected and estimates of solar radiation for the periods involved, E_t/R_s ratios were calculated for approximately 1,000 individual sampling periods during the growing season of fifteen crops. The results were grouped into four general climatic regions in the western United States, consisting of the Columbia River Basin, Northern Great Plains States, the Southern Great Plains States, and the Southwest States. Crops were grouped into two categories; namely, field crops and orchard crops.

Annual crops have three general growth periods that influence E_t rates and the magnitude of the E_t/R_s ratio; these are: (1) Emergence to development of adequate evaporating and transpiring surfaces for potential E_t (during this period, E_t increases rapidly from a low value and approaches a potential E_t rate in which available energy is the controlling factor); (2) the period in which the evaporating and transpiring surfaces are not a limiting factor in vaporization of water if adequate soil moisture is available; and (3) crop maturation, in which E_t begins to fall below potential E_t. During crop maturation, the plant limits the transpiration rate, although lack of available soil moisture also can lower the E_t rate below the potential. Crops such as sugar beets, once evaporating and transpiring surfaces have developed, may have an E_t rate near potential E_t, until harvest or severe freeze.

In order to relate solar energy to E_t rates for a given crop over a broad area, or for crops planted at different dates at a given location, the stage of growth had to be converted to a common base. Subdivision of the total growing season into convenient percentage increments was used for crops such as alfalfa. For new crops and other annuals, the growing season was divided into two parts: The first, from planting to a growth stage in which the evaporating and transpiring surfaces were not the limiting factor in vaporization of water, and the second, from this stage to maturity. The former period was subdivided on a percentage basis, as with alfalfa, and the latter was divided on a calendar-day basis. The second period includes the stage of growth when evaporating, and transpiring surfaces are not the limiting factors. The above procedure permitted the development of a characteristic crop curve showing the variation in the E_t/R_s ratio adjusted to a common base. It also illustrates the variations among annual crops, such as corn and sugar beets; perennial crops, such as grasses and alfalfa; and evergreen and deciduous orchards.

The over-all growing season for annual crops was from planting to harvest. For grasses and alfalfa, the over-all growing season was when mean spring and fall temperatures remained above 43° F. The entire year was used for evergreen orchards and other crops grown on a year-round basis.

The potential E_t stage of growth implies that the soil, root system, and plant stem are not limiting factors. Also, this growth stage does not necessarily mean that a complete canopy of vegetation must exist. It merely requires sufficient evaporating and transpiring surfaces to use available heat energy in evaportranspiration. The magnitude of transpiring area per unit land area necessary for this condition will also be influenced by the magnitude of potential E_t.

Measured E_t/R_s ratios for grain sorghum at two locations presented in Fig. 1 illustrate the results obtained on an annual row crop. Grain sorghum is planted about mid-June in the Texas high plains and in western Kansas. The potential E_t in June, shortly after planting, is high, but the E_t/R_s ratio is low. The ratio increases rapidly as a transpiring surface area develops. The maximum ratio, in which evaporating and transpiring surface areas no longer limit E_t and in which E_t approaches potential E_t, occurs just prior to heading (August 12 to August 15). The ratio decreases from heading to maturity, due to changes in plant characteristics and climatic conditions.

In contrast, alfalfa is a perennial and develops adequate evaporating and transpiring surfaces for potential E_t soon after temperatures are favorable (see Fig. 2). (The dashed line in Fig. 2 indicates the weighted average including the cutting periods.) If the periods immediately after cutting are not considered, the E_t/R_s ratio is reasonably constant during the central part of the growing season (solid line). The ratio increases slightly as the season progresses to values above 0.55 to 0.6, indicating that some advection of energy may be occurring with higher air temperatures. The ratio drops markedly when a cutting occurs within a period of measurement. B. Bahrani and S. A. Taylor[36] found that, following the cutting of alfalfa, net radiation and E_t decreased and surface soil temperature increased. With similar climatic conditions, net radiation is affected primarily by reflectance (r) and effective thermal radiation (R_{et}). Reflectance would increase on light colored

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[36] "Influence of Soil Moisture Potential and Evaporation Demand on the Actual Evapotranspiration from an Alfalfa Field," by Bozorg Bahrani and S. A. Taylor, Agronomy Journal, Vol. 53, No. 4, 1961, pp. 233-237.

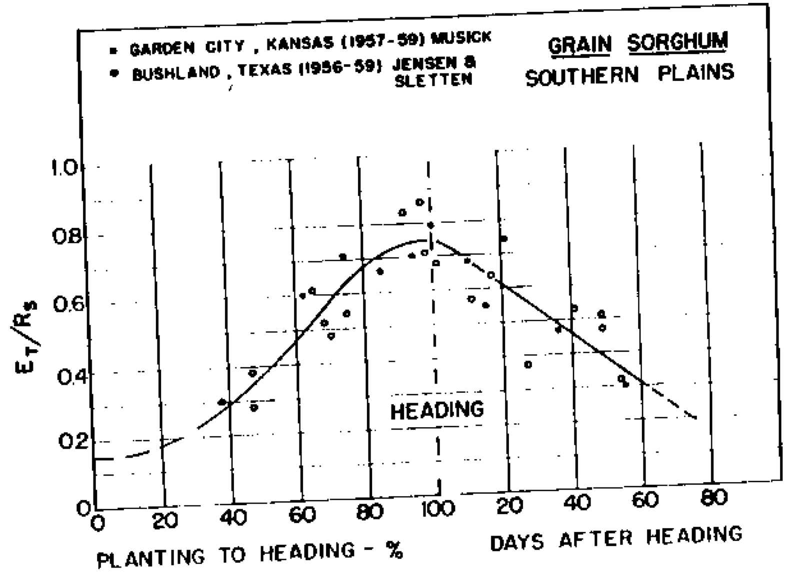

FIG. 1.—VARIATION IN THE E_t SOLAR RADIATION RATIO (E_t/R_s) FOR GRAIN SORGHUM IN RELATION TO STAGE OF PLANT GROWTH EXPRESSED AS A PERCENTAGE OF THE PERIOD FROM PLANTING TO HEADING, AND DAYS AFTER HEADING

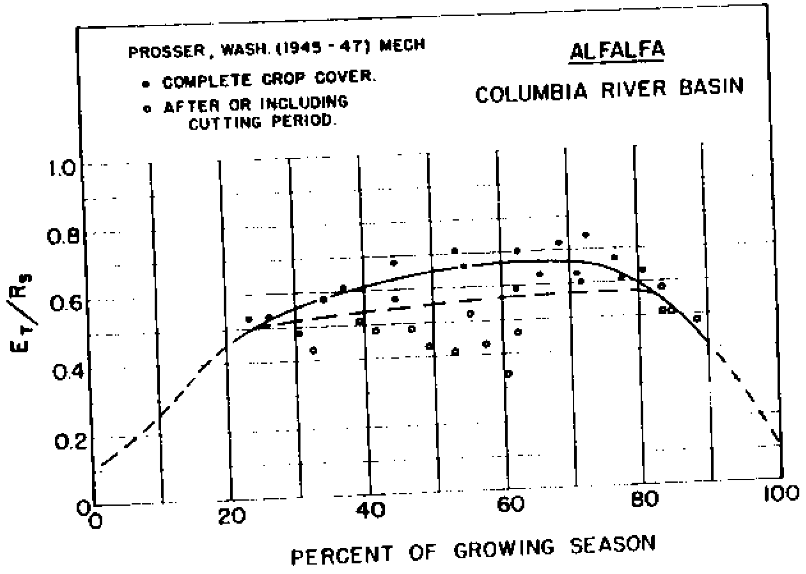

FIG. 2.—VARIATION IN THE E_t/SOLAR RADIATION RATIO (E_t/R_s) FOR ALFALFA IN RELATION TO PERCENTAGE OF GROWING SEASON AT PROSSER, WASH.

TABLE 1.—SUMMARY OF MEAN MEASURED E_t/R_s RATIOS FOR VARIOUS CROPS IN FOUR REGIONS

(a) Columbia Basin Area

Crop	Leaf area development period:%					After potential E_t growth: stage-days						
	0-20	20-40	40-60	60-80	80-100	0-10	10-20	20-30	30-40	40-50	50-60	60-70
Field Crops:												
Corn[a]	0.15	0.21	0.31	0.42	0.55	0.59	0.56	0.52	0.47	0.42	0.37	- - -
Potatoes[b]	0.13	0.19	0.28	0.44	0.59	0.61	0.61	0.60	0.59	0.58	- - -	- - -
Sugar beets[c]	0.12	0.21	0.33	0.47	0.57	0.58	0.58	0.57	0.56	0.54	0.52	0.50
Orchards:	Growing season: 2%											
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100		
Apples with[d] alfalfa cover crop	0.21	0.40	0.55	0.65	0.69	0.71	0.71	0.70	0.62	0.44		

(b) Northern Plains States

Crop	Leaf area development period:%					After potential E_t growth: stage-days						
	0-20	20-40	40-60	60-80	80-100	0-10	10-20	20-30	30-40	40-50	50-60	60-70
Field Crops:												
Field beans[e]	0.17	0.21	0.27	0.38	0.60	0.70	0.66	0.57	0.47	0.37	0.27	- - -
Corn[a]	0.16	0.19	0.28	0.40	0.53	0.57	0.53	0.48	0.43	0.38	- - -	- - -
Oats[f]	0.07	0.10	0.21	0.42	0.62	0.67	0.65	0.52	0.25	- - -	- - -	- - -
Sugar beets[c]	0.14	0.17	0.23	0.36	0.53	0.57	0.57	0.55	0.53	0.51	0.47	- - -

(c) Southern Plains States

Crop	Leaf area development period:%					After potential E_t growth: stage-days					
	0-20	20-40	40-60	60-80	80-100	0-10	10-20	20-30	30-40	40-50	50-60
Field crops:											
Grain sorghum	0.15	0.22	0.37	0.58	0.73	0.72	0.65	0.57	0.50	0.42	0.34

	Jointing											
	Seeding to jointing					to heading		After heading				
	0-20	20-40	40-60	60-80	80-100	0-50	50-100	0-10	10-20	20-30	30-40	40-50
Winter wheat Kansas	0.18	0.17	0.14	0.12	0.24	0.42	0.56	0.61	0.62	0.57	0.43	0.18
Winter wheat Texas	0.18	0.19	0.20	0.22	0.39	0.42	0.56	0.61	0.62	0.57	0.43	0.18

(d) Southwest States

Crop	Leaf area development period:%					After potential E_t growth: stage-days						
	0-20	20-40	40-60	60-80	80-100	0-10	10-20	20-30	30-40	40-50	50-60	60-70
Field Crops:												
Cotton[g]	0.06	0.09	0.32	0.66	0.85	0.82	0.71	0.60	0.50	0.49	0.28	0.17
Grain sorghum[f]	0.15	0.33	0.54	0.74	0.95	0.95	0.80	0.67	0.53	0.39	0.25	0.13
	Month											
Orchards:	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Dates[h]	0.53	0.55	0.57	0.59	0.63	0.69	0.75	0.78	0.74	0.64	0.57	0.54
Grapes[h]	0.06	0.05	0.10	0.21	0.37	0.53	0.62	0.60	0.49	0.36	0.24	0.12
Grapefruit[h]	0.19	0.21	0.24	0.27	0.32	0.38	0.46	0.50	0.47	0.40	0.31	0.33
Lemons & oranges[h]	0.16	0.16	0.18	0.21	0.25	0.30	0.35	0.38	0.38	0.35	0.30	0.22

[a] Potential E_t growth stage developed 10 days after tasseling.

[b] Potential E_t growth stage arbitrarily set at July 10 for early potatoes and August 20 for late potatoes.

[c] Potential E_t growth stage arbitrarily set at August 1.

[d] Growing season—when mean air temperature reaches and remains above 43° F.

[e] Potential E_t growth stage developed when runners begin to form.

[f] Potential E_t growth stage developed at heading.

[g] Potential E_t growth stage arbitrarily set at September 1.

[h] The presence of heavy weed growth or cover crop can increase the ratios considerably.

soils when alfalfa is cut and the soil surface dries. The higher surface temperature increases outgoing thermal radiation, because it is a function of absolute temperature to the fourth power. Hence, the decreased E_t/R_s ratio observed after cutting alfalfa at Prosser, Wash., can be attributed largely to changes in net radiation, plus some changes in the transpiration capacity of the crop, and must be considered in estimating E_t rates.

A summary of the mean ratios observed for other crops is presented in Table 1. The numerical values taken from crop characteristic curves, such as those in Figs. 1 and 2, represent average E_t/R_s ratios for the indicated period of growth.

In general when annual crops in one region reach a stage of growth in which evaporating and transpiring surfaces no longer limit E_t, the magnitude of the E_t/R_s ratio is approximately the same for all common crops, providing this stage occurs at the same time during each season. If one crop does not develop adequate evaporating and transpiring surfaces for potential E_t until late in the season, its peak E_t/R_s ratio will be lower. Thus, the difference in peak E_t/R_s ratios between crops attaining adequate evaporating and transpiring surfaces for potential E_t at different times during the season does not necessarily mean that a difference exists in their potential transpiration capacities.

When an annual row crop is planted in midsummer (for example, grain sorghum planted about July 1 in Arizona when the potential E_t is high), the E_t/R_s ratio increases rapidly, reflecting primarily the increase in transpiring surface. In contrast, an increase in the ratio may reflect both climatic changes and increases in transpiring area early in the season.

Generally, E_t/R_s ratios for orchards remain much lower than for a dense field crop at the same location. Ratios for orchards will increase considerably if weed growth is allowed or if a cover crop is grown. When a cover crop is used between trees, ratios rarely exceed ratios for the field crops in the area.

Maturation causes a rapid decrease in the ratio for crops such as small grains but has less effect on the ratio for crops such as potatoes and sugar beets because leafy parts generally remain green until harvest or frost. Reflectance changes only slightly, but R_{et}/R_s generally increases in the fall.

All data used in this study were taken from plots and fields where soil moisture was considered adequate for good yields. If irrigation water is withheld, allowing the soil to become extremely dry for short periods during the season, a reduction in seasonal E_t can be expected.

ESTIMATING EVAPOTRANSPIRATION FROM SOLAR RADIATION

Estimating Mean Daily Evapotranspiration Rates.—Solar radiation and the mean measured E_t/R_s ratios can be used to estimate mean daily E_t rates for 5-day periods or longer. Two simple steps are involved: (1) Determine the mean daily solar radiation, R_s, expressed in in. per day at the time of year that corresponds to the specific stage of growth for which an estimate is needed, and (2) multiply this value by the mean measured (E_t/R_s) ratio for the period.

$$\text{Estimated mean daily } E_t = \left(\frac{E_t}{R_s}\right)_m R_s \quad \ldots\ldots\ldots \quad (5)$$

in which $(E_t/R_s)_m$ is the mean measured ratio for the period as shown by the curve in Fig. 1 or Table 1, and R_s is the mean solar radiation for the period, in in. per day.

A summary of mean daily solar radiation, as measured by the United States Weather Bureau (USWB) and converted to evaporation equivalent for twenty locations in the western United States, is presented by weeks, and total solar radiation is presented by months in Tables 2 and 3. Procedures are given in Appendix I for estimating solar radiation from cloudless day values for lodations in the United States using percentage of sunshine or cloud cover now recorded by the USWB. An additional table is provided to estimate solar radiation for various latitudes and months of the year at locations where cloudless day values are not available. Precise estimates of E_t for a specific period in a given year cannot be expected because only the main variable, solar radiation, is considered separately while using average combined values of the other variables. Better estimates could be obtained if all variables could be measured accurately.

Example No. 1.—Determine the average maximum E_t for irrigated grain sorghum near Dodge City, Kans. The following crop data are typical for the area:

Planting date	June 10
Heading date	August 15
Harvest date	October 25
Planting to heading	66 days
Heading to harvest	71 days

Average maximum $(E_t/R_s)_m$ ratio = 0.74 (from Figure 1) (boot to heading state). This maximum ratio occurs during 90% to 100% of the planting to heading period, or from August 8 to August 15. From Table 2, maximum $\bar{R}_s \cong 0.425$ in. per day at the beginning of this period. Estimating E_t = $\left[(E_t/R_s)_m\right](R_s) = (0.74)(0.425) = 0.31$ in. per day.

Estimating Total Evapotranspiration for a Specific Period.—The following equation can be used to estimate total evapotranspiration for a specific period:

$$\text{Total } E_t = \frac{\int_{S_1}^{S_2}\left(\frac{E_t}{R_s}\right)_m R_s\, dS}{S_2 - S_1}\, D \quad \ldots\ldots\ldots\ldots \quad (6)$$

in which $(E_t/R_s)_m$ and R_s are as defined by Eq. 5; dS is the increment of the growing season, in percentage; S_1 and S_2 represent the percentage of growing season or the percentage of growing interval from planting to establishment of potential E_t, evaporating and transpiring surface at the beginning and end of the period in question; and D denotes days in the period.

A modification of Eq. 6 is needed for annual crops covering the period from maximum E_t/R_s to maturity and for crops grown on a year-round basis:

$$\text{Total } E_t = \int_{D_1}^{D_2}\left(\frac{E_t}{R_s}\right)_m R_s\, dD \quad \ldots\ldots\ldots\ldots \quad (6a)$$

TABLE 2.—WEEKLY MEAN VALUES OF DAILY TOTAL SOLAR AND SKY RADIATION (SHORT WAVE) EXPRESSED IN INCHES PER DAY EVAPORATION EQUIVALENT (1 GRAM OF WATER = 590 CALORIES). THE 52ND WEEK IS AN 8-DAY WEEK, AND THE 26TH WEEK IS AN 8-DAY WEEK IN LEAP YEARS. OBTAINED FROM USWB RECORDS.[a]

Solar week (1)	Dates (inclusive) (2)	Phoenix, Ariz., Lat. 33° 26' N (3)	Davis, Calif., Lat. 38° 32' N (4)	Fresno, Calif., Lat. 36° 46' N (5)	Grand Junction, Colo., Lat. 39° 07' N (6)	Boise, Idaho Lat. 43° 34' N (7)	Dodge City, Kan., Lat. 37° 46' N (8)	Glasgow, Mont., Lat. 48° 13' N (9)	Great Falls, Mont., Lat. 49° 29' N (10)	Ely, Nev., Lat. 39° 17' N (11)
1	Jan. 1-7	0.191	0.104	0.116	0.150	0.088	0.168	0.091	0.087	0.148
2	8-14	.198	.104	.121	.155	.092	.173	.100	.092	.153
3	15-21	.210	.114	.133	.165	.102	.179	.109	.103	.166
4	22-28	.228	.126	.146	.180	.114	.187	.119	.113	.183
5	Jan. 29-Feb. 4	.245	.142	.164	.192	.127	.199	.138	.127	.197
6	Feb. 5-11	.266	.163	.186	.211	.144	.213	.162	.149	.219
7	12-18	.282	.187	.209	.229	.162	.228	.184	.170	.237
8	19-25	.302	.213	.235	.251	.182	.242	.211	.190	.260
9	Feb. 26-Mar. 4	.324	.240	.262	.270	.205	.258	.232	.212	.285
10	Mar. 5-11	.343	.261	.283	.282	.223	.271	.250	.229	.303
11	12-18	.364	.276	.300	.300	.233	.285	.267	.244	.319
12	19-25	.384	.302	.322	.310	.265	.303	.277	.259	.337
13	Mar. 26-Apr. 1	.406	.325	.341	.328	.285	.314	.292	.279	.359
14	Apr. 2-8	.421	.344	.353	.351	.303	.338	.305	.291	.375
15	9-15	.439	.359	.363	.358	.322	.356	.313	.296	.381
16	16-22	.452	.374	.375	.371	.335	.354	.328	.306	.392
17	23-29	.460	.381	.380	.383	.346	.364	.346	.313	.393
18	Apr. 30-May 6	.475	.403	.393	.385	.368	.363	.363	.330	.401
19	May 7-13	.486	.425	.415	.402	.386	.369	.386	.345	.416
20	14-20	.495	.437	.421	.415	.395	.401	.398	.361	.421
21	21-27	.501	.450	.438	.432	.401	.416	.396	.370	.431
22	May 28-June 3	.504	.459	.454	.449	.404	.422	.395	.368	.444
23	June 4-10	.500	.470	.459	.466	.421	.440	.399	.391	.462
24	11-17	.497	.480	.473	.477	.436	.440	.407	.399	.483
25	18-24	.485	.469	.476	.477	.455	.441	.417	.407	.491
26	June 25-July 1	.476	.488	.468	.478	.460	.451	.426	.415	.483
27	July 2-8	.462	.478	.461	.466	.457	.434	.434	.423	.465
28	9-15	.445	.466	.445	.453	.448	.432	.437	.431	.439
29	16-22	.437	.455	.435	.441	.434	.434	.431	.429	.423
30	23-29	.425	.446	.428	.436	.428	.429	.423	.423	.421
31	July 30-Aug. 5	.419	.436	.421	.421	.414	.425	.403	.401	.416
32	Aug. 6-12	.412	.424	.414	.407	.398	.404	.385	.379	.415
33	13-19	.411	.409	.403	.402	.382	.393	.352	.359	.413
34	20-26	.407	.391	.390	.383	.362	.382	.330	.336	.400
35	Aug. 27-Sept. 2	.398	.373	.376	.367	.341	.371	.306	.315	.391
36	Sept. 3-9	.393	.353	.360	.358	.325	.359	.277	.295	.371
37	10-16	.378	.333	.342	.336	.306	.334	.266	.267	.349
38	17-23	.358	.309	.323	.319	.286	.309	.240	.243	.333
39	24-30	.342	.282	.301	.304	.259	.292	.222	.227	.313
40	Oct. 1-7	.322	.260	.280	.283	.236	.277	.204	.200	.295
41	8-14	.303	.238	.261	.259	.210	.260	.201	.184	.270
42	15-21	.287	.217	.241	.234	.186	.245	.168	.163	.247
43	22-28	.272	.200	.222	.216	.171	.228	.146	.142	.229
44	Oct. 29-Nov. 4	.253	.173	.201	.194	.146	.212	.132	.125	.208
45	Nov. 5-11	.239	.152	.179	.182	.130	.199	.114	.109	.197
46	12-18	.224	.137	.161	.173	.114	.188	.102	.101	.183
47	19-25	.209	.124	.147	.159	.100	.175	.092	.091	.166
48	Nov. 26-Dec. 2	.201	.114	.132	.156	.094	.167	.085	.084	.160
49	Dec. 3-9	.193	.102	.117	.147	.086	.162	.082	.080	.151
50	10-16	.191	.100	.113	.143	.085	.159	.076	.077	.145
51	17-23	.189	.098	.108	.145	.086	.162	.078	.078	.147
52	24-31	.188	.107	.110	.144	.087	.164	.084	.081	.144

Solar week (1)	Dates (inclusive) (2)	Bismarck, N. Dak., Lat. 46° 46' N (12)	Stillwater, Okla., Lat. 36° 08' N (13)	Astoria, Ore., Lat. 46° 09' N (14)	Medford, Ore., Lat. 42° 22' N (15)	Rapid City, S. Dak., Lat. 44° 02' N (16)	Brownsville, Tex., Lat. 25° 54' N (17)	Fort Worth, Tex., Lat. 32° 49' N (18)	Midland, Tex., Lat. 31° 56' N (19)	Prosser, Wash., Lat. 46° 15' N (20)	Spokane, Wash., Lat. 47° 37' N (21)	Lander, Wyo., Lat. 42° 48' N (22)
1	Jan. 1-7	0.094	0.142	0.059	0.070	0.116	0.179	0.171	0.187	0.074	0.067	0.144
2	8-14	.103	.137	.061	.077	.126	.189	.172	.191	.080	.075	.149
3	15-21	.113	.140	.065	.087	.134	.202	.173	.195	.093	.085	.156
4	22-28	.126	.147	.076	.102	.149	.209	.165	.208	.102	.094	.171
5	Jan. 29-Feb. 4	.142	.161	.087	.115	.164	.216	.198	.220	.115	.105	.187
6	Feb. 5-11	.162	.178	.101	.131	.164	.212	.208	.232	.134	.119	.207
7	12-18	.181	.204	.119	.153	.204	.221	.224	.252	.158	.139	.229
8	19-25	.199	.218	.131	.171	.223	.230	.234	.271	.177	.159	.253
9	Feb. 26-Mar. 4	.219	.235	.154	.193	.242	.234	.248	.287	.202	.181	.275
10	Mar. 5-11	.231	.248	.169	.211	.255	.270	.276	.313	.224	.202	.296
11	12-18	.247	.261	.180	.225	.274	.272	.295	.332	.243	.212	.309
12	19-25	.258	.279	.203	.254	.288	.284	.318	.345	.265	.244	.322
13	Mar. 26-Apr. 1	.279	.288	.209	.279	.306	.290	.329	.356	.290	.259	.341
14	Apr. 2-8	.297	.302	.225	.299	.322	.285	.331	.366	.323	.276	.355
15	9-15	.301	.309	.248	.322	.328	.297	.331	.375	.348	.304	.368
16	16-22	.317	.318	.267	.332	.331	.308	.335	.383	.378	.309	.377
17	23-29	.331	.317	.289	.347	.340	.331	.343	.390	.397	.329	.376
18	Apr. 30-May 6	.347	.322	.310	.367	.343	.347	.353	.397	.407	.342	.386
19	May 7-13	.368	.327	.323	.382	.355	.363	.371	.404	.419	.358	.393
20	14-20	.383	.337	.326	.400	.374	.379	.365	.406	.430	.380	.404
21	21-27	.374	.358	.319	.408	.378	.387	.402	.419	.434	.393	.420
22	May 28-June 3	.375	.385	.315	.415	.380	.398	.423	.422	.435	.399	.426
23	June 4-10	.383	.406	.316	.429	.395	.401	.432	.425	.451	.415	.442
24	11-17	.393	.413	.311	.434	.401	.400	.437	.433	.456	.416	.455
25	18-24	.407	.425	.330	.451	.409	.406	.440	.429	.467	.422	.464
26	June 25-July 1	.415	.412	.337	.463	.421	.403	.433	.429	.476	.442	.461
27	July 2-8	.420	.398	.343	.465	.413	.411	.427	.422	.477	.448	.459
28	9-15	.415	.398	.357	.466	.403	.411	.422	.415	.481	.452	.442
29	16-22	.407	.387	.349	.456	.384	.408	.420	.414	.477	.411	.425
30	23-29	.396	.385	.352	.449	.378	.413	.414	.408	.478	.433	.418
31	July 30-Aug. 5	.378	.381	.339	.434	.366	.404	.418	.404	.458	.416	.399
32	Aug. 6-12	.362	.370	.323	.413	.367	.387	.411	.399	.425	.389	.392
33	13-19	.341	.365	.315	.396	.368	.370	.401	.390	.405	.371	.389
34	20-26	.320	.354	.292	.369	.358	.340	.387	.383	.375	.346	.379
35	Aug. 27-Sept. 2	.300	.343	.269	.341	.345	.324	.374	.376	.348	.312	.371
36	Sept. 3-9	.276	.336	.229	.322	.321	.318	.354	.366	.336	.290	.353
37	10-16	.263	.318	.229	.297	.300	.312	.337	.340	.309	.266	.325
38	17-23	.247	.297	.211	.273	.279	.309	.337	.317	.283	.235	.311
39	24-30	.226	.282	.187	.248	.260	.300	.299	.297	.254	.207	.291
40	Oct. 1-7	.213	.258	.143	.222	.244	.288	.291	.278	.218	.183	.271
41	8-14	.190	.238	.143	.196	.222	.274	.273	.268	.191	.159	.251
42	15-21	.166	.222	.123	.173	.198	.258	.256	.254	.163	.141	.220
43	22-28	.149	.204	.112	.153	.180	.236	.241	.243	.138	.126	.197
44	Oct. 29-Nov. 4	.125	.190	.079	.129	.160	.215	.219	.234	.121	.109	.179
45	Nov. 5-11	.111	.181	.079	.110	.145	.200	.210	.228	.102	.096	.169
46	12-18	.102	.173	.069	.092	.135	.190	.204	.222	.083	.091	.160
47	19-25	.093	.165	.062	.083	.121	.186	.192	.207	.079	.072	.152
48	Nov. 26-Dec. 2	.090	.155	.059	.074	.117	.187	.186	.198	.074	.069	.146
49	Dec. 3-9	.087	.145	.053	.066	.113	.181	.173	.191	.067	.063	.137
50	10-16	.084	.143	.051	.063	.108	.177	.170	.189	.069	.060	.133
51	17-23	.086	.137	.054	.062	.111	.171	.169	.187	.064	.059	.135
52	24-31	.087	.138	.056	.067	.111	.173	.168	.187	.065	.059	.136

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[a] Value given is for the end of the solar week; for solar week No. 1 the value is the mean of weeks 52, 1, 2, 3, etc.

TABLE 3.—SUMMARY OF MEAN MEASURED VALUES OF MONTHLY TOTAL SOLAR AND SKY RADIATION (SHORT WAVE) EXPRESSED IN INCHES EVAPORATION EQUIVALENT (1 GRAM WATER = 590 CALORIES) AND YEAR-TO-YEAR STANDARD DEVIATIONS (COMPUTED FROM WEEKLY MEAN VALUES FROM USWB RECORDS).

Location & latitude		Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Phoenix, Ariz.	Total	6.22	7.64	11.02	13.16	15.17	14.93	13.80	12.78	11.41	9.26	6.91	5.93
33° 26' N	S. Dev.	.61	.67	.62	.58	.50	.59	.59	.55	.57	.85	.40	.15
Davis, Calif.	Total	3.33	4.85	8.40	10.77	13.32	14.31	14.43	12.91	10.08	7.23	4.32	3.15
38° 22' N	S. Dev.	.52	1.01	.79	.67	.71	.57	.37	.19	.30	.60	.89	.77
Fresno, Calif.	Total	3.86	5.49	9.10	10.90	12.93	14.04	13.81	12.66	10.36	7.94	5.08	3.56
36° 46' N	S. Dev.	.63	1.08	1.01	.76	1.08	1.21	1.35	1.20	1.04	.91	.54	.64
Grand Junction, Colo.	Total	4.90	6.13	9.11	10.75	12.62	14.20	14.02	12.55	10.22	7.85	5.31	4.45
39° 07' N	S. Dev.	.42	.70	1.22	1.05	.97	.62	.89	.77	.85	1.02	.43	.38
Boise, Idaho	Total	2.97	4.24	7.09	9.63	12.04	12.96	13.86	12.09	9.29	6.36	3.64	2.64
43° 34' N	S. Dev.	.52	.67	.57	.65	.70	1.08	.67	.54	.67	.81	.65	.47
Dodge City, Kan.	Total	5.42	6.14	8.66	10.60	11.82	13.24	13.43	12.42	10.15	7.93	5.77	4.96
37° 46' N	S. Dev.	.63	.84	1.30	1.38	.97	.78	1.11	.83	.86	1.18	.63	.33
Glasgow, Montana	Total	3.18	4.80	8.07	9.46	11.83	11.98	12.71	11.52	8.07	5.47	3.31	2.38
48° 13' N	S. Dev.	.31	.27	.39	.55	.79	.38	.19	.92	.69	.90	.74	.17
Great Falls, Mont.	Total	2.92	4.45	7.34	8.86	10.85	11.93	12.74	11.53	8.41	5.53	3.18	2.48
47° 29' N	S. Dev.	.41	.47	.56	.59	.76	.78	1.38	.76	.81	.86	.38	.37
Ely, Nevada	Total	4.90	6.16	9.60	11.38	12.96	14.29	13.79	12.84	10.59	8.24	5.71	4.55
39° 17' N	S. Dev.	.29	.41	.94	.56	.99	.71	.43	.70	.68	.91	.43	.20
Bismarck, N. Dak.	Total	3.29	4.75	7.49	9.04	11.52	11.72	12.82	10.85	7.95	5.72	3.19	2.60
48° 46' N	S. Dev.	.22	.22	.52	.54	.92	.80	.94	.52	.70	.82	.28	.27
Stillwater, Okla.	Total	4.25	5.23	8.14	9.53	10.24	12.18	11.69	11.28	9.57	7.08	5.29	4.46
36° 08' N	S. Dev.	.75	.83	.75	.75	.82	.82	1.52	.72	1.43	.97	.72	.60
Astoria, Ore.	Total	2.03	2.93	5.56	7.51	10.26	9.43	11.07	9.84	7.18	4.72	2.15	1.59
46° 09' N	S. Dev.	.35	.64	.75	1.10	1.17	.85	1.14	1.24	.73	1.15	.36	.16
Medford, Ore.	Total	2.49	3.93	6.84	9.62	12.04	12.99	14.36	12.53	9.04	5.93	3.01	1.99
42° 22' N	S. Dev.	.27	.54	.71	.99	1.20	1.22	1.09	.34	.74	.71	.44	.35
Rapid City, S. Dak.	Total	3.97	5.39	8.28	9.81	11.20	11.99	12.40	11.35	9.11	6.69	4.18	3.38
44° 02' N	S. Dev.	.36	.26	.87	.68	1.09	1.05	.76	.05	.67	.80	.06	.06
Brownsville, Tex.	Total	5.94	6.05	8.36	8.94	11.46	12.04	12.75	11.73	9.42	8.31	5.80	5.43
25° 54' N	S. Dev.	1.22	.80	1.03	1.09	.84	1.18	.94	.97	.91	1.33	.51	.82
Fort Worth, Tex.	Total	5.26	6.04	8.79	9.89	11.70	13.23	13.10	12.58	10.19	8.34	6.23	5.29
32° 49' N	S. Dev.	.90	1.12	1.12	1.60	1.24	1.18	1.20	.98	1.41	1.29	.92	.73
Midland, Tex.	Total	5.94	6.75	10.08	11.25	12.53	12.90	12.88	12.24	10.29	8.20	6.73	5.79
31° 56' N	S. Dev.	.61	.76	1.05	.27	.53	.64	1.32	.49	.97	.99	.36	.53
Spokane, Wash.	Total	2.40	3.57	6.42	9.06	11.37	13.01	13.88	11.72	8.10	4.81	2.64	1.85
47° 37' N	S. Dev.	.46	.86	.77	.59	.78	.92	.51	.89	.84	1.07	.49	.73
Lander, Wyo.	Total	4.70	6.07	9.39	11.00	12.34	13.55	13.68	12.14	9.89	7.56	4.91	4.15
42° 48' N	S. Dev.	.24	.29	.77	.73	1.14	.95	1.18	.40	1.22	.68	.26	.36

in which D_1 and D_2 are the number of the day at the beginning and end of the specific period (using 1 - 365), and dD is the increment of the period, in days.

Example No. 2.—How much water will irrigated grain sorghum use during the month of August, under average climatic conditions, using the same crop conditions as used in Example No. 1? July 31 to heading: August covers part of the after-heading period. Therefore, both Eq. 6 and 6a are used. July 31 = $\left[\frac{20\text{ (June)} + 31\text{ July}}{66}\right]$ 100 = 77% of the planting to heading period; heading = 100% of the planting to heading period. The first half of August represents 23% of the planting to heading period (100 - 77 = 23). (For long periods, divide into several increments.) For the first half of August, the following data are obtained from Fig. 1 or Tables 1 and 2 for Dodge City, Kans.:

Increment	Midpoint, in %	$(E_t/R_s)m$	$\bar{R}_s$, in in. per day
77-100	88.5	0.73	0.41

Estimated E_t for July 31 to August 15 = (0.73)(0.41) 15 = 4.5 in. August 15 to 31:

Days after heading	Midpoint in days	$(E_t/R_s)_m$	$\bar{R}_s$, in in. per day
0 - 16	8	0.70	0.39

The estimated total for August 15 to 31 = (0.70) (0.39)16 = 4.4 in. The estimated total E_t for August = 4.5 + 4.4 = 8.9 in.

If quick estimates are needed for a month, total solar radiation for the month, obtained from the monthly table can be used, providing the $(E_t/R_s)m$ ratio is relatively constant or changes uniformly.

Example No. 3.—Using the total radiation for the month of August for the problem in Example No. 2, what is the estimated total E_t for the month? Mean total R_s for August = 12.42 in., from Table 3. Average $(E_t/R_s)m$ for August (77% to 100% of the planting to heading period, and 0 to 16 days after heading) ≅ 0.71, from Fig. 1 or Table 1. Therefore, the estimated total E_t for August = (0.71) (12.42) = 8.8 in.

Estimating Seasonal Evapotranspiration.—Seasonal estimates can be made using Eqs. 6 and 6a and 10 day to 15 day periods. If the E_t/R_s ratio is changing linearly, periods of a month can also be used satisfactorily. Monthly increments will be used for this example.

Example No. 4.—How much water will irrigated grain sorghum use during an average growing season at Dodge City, Kans., if adequate soil moisture is maintained throughout the season? (Use the same crop conditions as used in Example 1.). The results are shown in Table 4.

Estimating Potential Evapotranspiration.—Potential evapotranspiration, as used herein refers to the E_t that can occur in irrigated fields located in arid and semiarid areas. It does not imply a homogeneous or unlimited boundary area of well watered, actively growing vegetation. In order to arrive at an estimate of potential E_t, data were selected from crops in which evaporating and transpiring surfaces were not limiting the vaporization of water. The crops used were alfalfa, from Arizona, near the coast of California, Nebraska, and Washington (no cutting periods used); cotton, in August, in

TABLE 4

Increment (1)	Increment of Fig. 1 (2)	Avg. $(E_t/R_s)_m$ (3)	$\bar{R}_s$, in inches (4)	Col. 3 x 4, in inches (5)
June 10-30	0-30%	0.17	8.83[a]	1.5
July	30-77%	0.41	13.43	5.5
August	77-100% and 0-16 days	0.71	12.42	8.8
September	16-46 days	0.52	10.15	5.3
October 1-25	46-71 days	0.30	6.42[b]	1.9
			Total	23.0 in.

[a] 2/3 of 13.24 in. for month of June

[b] (0.81) (7.93) in. for month of October

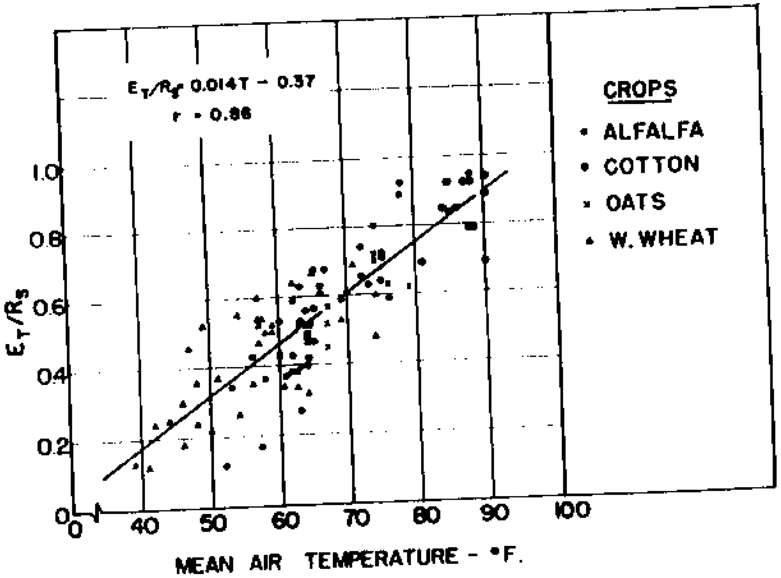

FIG. 3.—VARIATION IN THE E_t/R_s RATIO FOR SELECTED FIELD CROPS IN RELATION TO MEAN AIR TEMPERATURE

Arizona and California; oats in Nebraska; and winter wheat in Kansas and Texas. The E_t/R_s ratios from these data are plotted against mean air temperature (° F) in Fig. 3. The E_t/R_s ratio increases linearly with mean air temperature. There are several reasons for this relationship. As air temperatures increase, the saturated water vapor pressure increases in a nonlinear manner. Thus, a larger vapor pressure gradient above the crop can be expected with higher air temperatures, resulting in more rapid removal of water vapor and, thus, less heating or air (smaller "A"). Further increases in temperature apparently coincides with warm air advection, (air temperatures are higher than the evaporating surfaces and "A" becomes negative). Mean air temperature also influences effective thermal radiation. The linear relationship between the E_t/R_s ratio and mean air temperature indicates that the E_t/R_s ratio (for potential E_t) can be estimated from mean air temperatures with the following equation:

$$\left(\frac{E_t}{R_s}\right)_p = 0.014\ T - 0.37 \qquad (7)$$

in which $\left(\frac{E_t}{R_s}\right)_p$ is the potential ratio, and T is the mean air temperature, in °F.

Eq. 7 represents an empirical relationship between the combined effects of reflectance, r, relative effects of net thermal radiation, R_{et}, heating or cooling of air ± A and soil ± G, and mean air temperature. Because the data were based on crops with adequate soil moisture, Eq. 7 can be used to estimate potential E_t as follows:

$$E_{tp} = (0.014\ T - 0.37)\ R_s \qquad (8)$$

in which E_{tp} represents potential evapotranspiration, in in. per day; T is the mean air temperature, in ° F; and R_s represents solar radiation, in in. per day. Eq. 8 is based on data for periods greater than 5 days. Therefore, reasonably reliable estimates using Eq. 8 can be expected for periods as short as 5 days to 10 days, because two variables are used. Eq. 8 was evaluated using E_t data from a 20-ft weighing lysimeter at Davis, Calif.[37] Two and one-half years of mean measured monthly E_t values from frequently clipped ryegrass are plotted in Fig. 4, together with computed estimates using Eq. 8. Estimated values of potential E_t were in general agreement with measured values, except for May to September, during which estimates were 15% higher. Computed values using Eq. 8 averaged 11% higher than the measured values for the 2-1/2 yr period. There are several possible reasons for this difference. First, all medium to strong north wind, warm air advection days were not included in the mean measured values. Also, there are possibilities that a crop such as alfalfa, with more leaf area per unit land area than clipped grass, may have used more water. G. F. Makkink[38] ob-

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[37] "Correlation of Climatological Data with Water Requirements of Crops," by W. O. Pruitt, Dept. of Irrigation, Univ. of California, Berkeley, Calif., August, 1962.

[38] "Testing the Penman Formula by Means of Lysimeters," by G. F. Makkink, Journal of the Institution of Water Engineers, Vol. 11, No. 3, May, 1957.

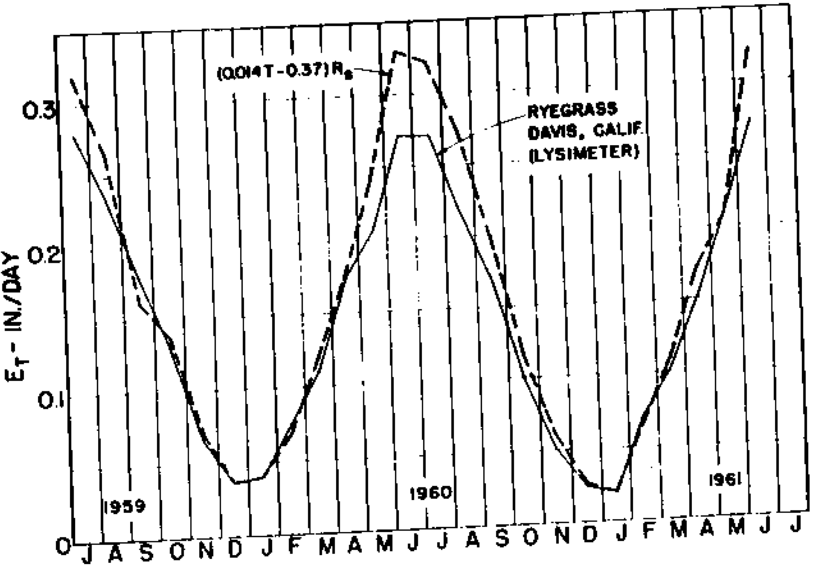

FIG. 4.—COMPARISON OF ESTIMATED MONTHLY MEAN POTENTIAL E_t USING EQ. 8 AND E_t MEASURED IN A 20-FT DIAMETER LYSIMETER AT DAVIS, CALIF. (DATA FROM PRUITT)

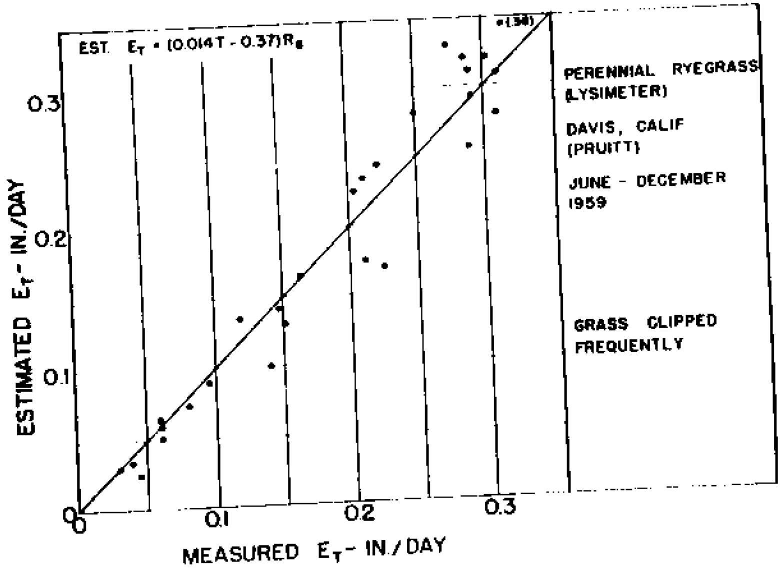

FIG. 5.—COMPARISON OF ESTIMATED WEEKLY MEAN POTENTIAL E_t USING EQ. 8 AND E_t MEASURED IN A 20-FT DIAMETER LYSIMETER AT DAVIS, CALIF. (DATA FROM PURITT)

served that the E_t increased as the height of grass increased. There are possibilities that some drainage may still have been present in some of the E_t values from which Eq. 8 was derived. Additional comparisons were made on a weekly basis by plotting Pruitt's data (July-December, 1959)[39] against estimated values of potential E_t in Fig. 5. The results show good agreement throughout a wide range in E_t.

Eq. 8 appears to give simple, reasonable estimates of potential E_t in which crop cover and available water are adequate. Preliminary evaluation in other semiarid and more humid climatic zones indicates that the estimates obtained may be exceeded in extremely windy conditions.

Eq. 8 can be used for (1) Estimating peak E_t rates for design of surface and sprinkler irrigation systems; (2) adjusting the peak E_t/R_s ratios for the various field crops if they are to be transposed to different climatic zones; and (3) estimating seasonal E_t for alfalfa. However, for alfalfa, several adjustments are needed. Based on observations, the E_t/R_s ratio for alfalfa would be approximately equal to that given by Eq. 7 except early in the year and immediately after a cutting. After cutting alfalfa, the ratio has been observed to drop to one-half its normal value, but in 20 days it has increased again to that of Eq. 7. Similarly, in the spring the E_t/R_s ratio can be assumed to be about one-fourth of that of Eq. 7 when alfalfa just begins to grow. The low ratio in the spring should increase to the potential value in 20 days to 30 days. In this manner, a complete curve for the season can be formulated for most areas.

Estimating Irrigation Water Requirements.—Estimates of irrigation water requirements must include adjustments of evaportranspiration for irrigation efficiency and effective rainfall in the area. Recommended irrigation efficiencies and procedures for estimating effective rainfall are included in several of the references cited. A refined analysis of methods for arriving at a suitable design irrigation efficiency and the effective rainfall would be a comprehensive subject in itself. Therefore, it is not included herein.

CONCLUSIONS

A re-evaluation of existing evapotranspiration data collected during the past 35 yr in the western United States indicates that reasonably reliable estimates of evapotranspiration can be made using solar radiation as the main parameter. Curves for individual crops in four climatic regions present mean measured ratios of evapotranspiration to solar radiation. This ratio reflects the combined effects of reflectance or albedo, and relative effects of effective thermal radiation, sensible heat flux to the air and soil, plus other minor energy balance components at various stages of crop growth. The ratios presented may be used for estimating mean weekly, monthly, or seasonal evapotranspiration, then potential evapotranspiration in irrigated fields can be predicted with reasonable accuracy for a given week or longer, using solar radiation and mean air temperature.

A summary of solar radiation data for the western United States is presented. For locations in which solar radiation data are not available, reliable

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[39] "Correlation of Climatological Data with Water Requirements of Crops," by W. O. Pruitt, 1959 Annual Report, September, 1960.

estimates of monthly solar radiation can be made using percentage of sunshine and clear-day values of solar radiation summarized in Appendix I.

ACKNOWLEDGMENTS

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APPENDIX I.—SOLAR RADIATION

Measured Solar Radiation.—A summary of measured weekly mean values of daily total solar and sky radiation (short wave) expressed in in. per day evaporation equivalent (1 gram water = 590 calories) is presented in Table 2. These data were obtained from USWB records and represent an average of 8 yr to 10 yr for most locations. The values given are from a 4-week moving average used to obtain a smooth curve. Conversion to calories per sq cm per day can be made by multiplying in. per day by 1,500, and to BTU per sq cm per day by multiplying in. per day by 5,530.

A similar table has been prepared giving the total solar radiation on a monthly basis together with the year-to-year standard deviation (Table 3.) Solar radiation received for a given month can be expected to equal average values, ± one standard deviation for two out of three years. The monthly values represent an average of 7 yr to 9 yr for most locations. Additional data can be obtained from a paper written by I. F. Hand.[40]

Estimating Solar Radiation.—Solar radiation for a given month and latitude is affected primarily by degree of cloud cover. Procedures are available to estimate solar radiation on a monthly basis within 5% to 10% using degree of cloud cover or percentage of possible sunshine for the period in question. S. Fritz and J. H. MacDonald[41] used United States data to develop constants for an equation of the form proposed by Angström in 1925.

$$R_s = R_{so}\ (0.35 + 0.61S) \quad \text{. . . . . (9)}$$

in which R_s represents solar radiation under existing conditions; R_{so} represents solar radiation on cloudless days (see Table 4); and S is the fraction of possible sunshine for the time period.

C. E. Hounam[42] in Australia, and Mateer (1955) (from Hounam), in Canada, obtained similar constants for their respective areas. Percentage of sunshine for daytime hours is published by many USWB stations.

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[40] "Weekly Mean Values of Daily Total Solar and Sky Radiation," by I. F. Hand, U. S. Dept. of Commerce, Weather Bureau Technical Paper No. 11, 1949.

[41] "Average Solar Radiation in the United States," by S. Fritz and J. H. MacDonald, Heating and Ventilation Guide, Vol. 46, 1949.

[42] "Evaporation Pan Coefficients in Australia," by C. E. Hounam, Climatology and Micrometeorology, Proceedings, Canberra Symposium, UNESCO, 1958.

Cloudless day values of total monthly solar radiation are given in Table 5. These values were computed by Fritz,[43] based on air mass penetrated at a location, and absorption of short wave radiation by precipitable water vapor, and then corrected for dust depletion.

Estimating Solar Radiation in Other Areas.—In areas where mean measured solar radiation data and cloudless day values are not available, other techniques must be used. Budyko[34] presented a table of observed average total monthly cloudless day solar radiation for various months and latitudes (reproduced as Table 6). These values for several western United States locations are about 10% higher than those of Table 5 from September through April. During the summer months, they differ by only 3%. Budyko's values were obtained from curves connecting observed high points and are recognized as being slightly high due to the instrumentation used. The dust depletion correction used by Fritz was determined by comparing data from a curve drawn just below the highest observed values to values computed based on air mass penetrated and absorption by water vapor. When observed cloudless day values are not available, the values in Table 6 may be used with Eq. 9 using percentage of sunshine, or with an equation proposed by Angström and modified by Savinov (from Budyko).[34]

$$R_s = R_{so}\left[1 - (1 - k)\frac{n}{10}\right] \quad \ldots\ldots\ldots\ldots\ldots \quad (10)$$

in which n represents cloud cover in tenths (n varies from 0 to 10), and k is the mean annual coefficient computed from data for 62 locations (see Table 7). Eq. 10 underestimates solar radiation in the western United States as much as 20% to 30%. The manner of observing and reporting cloud cover in the United States apparently results in higher values than those used to derive the k coefficient. Estimates using percentage of sunshine in Eq. 9 are much more accurate than using cloud cover in Eq. 10.

TABLE 5.—AVERAGE TOTAL CLOUDLESS DAY SOLAR AND SKY RADIATION (SHORT WAVE) BY MONTHS EXPRESSED IN INCHES EVAPORATION EQUIVALENT (1 GRAM WATER = 590 CALORIES).[a]

Location	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Phoenix, Ariz.	6.6	7.8	11.2	13.4	15.1	15.0	14.3	13.0	11.0	8.9	7.2	6.0
Davis, Calif.	5.6	7.1	10.5	13.0	14.9	15.0	15.3	13.2	10.6	8.7	6.2	5.2
Fresno, Calif.	5.4	7.3	10.8	13.0	15.1	15.4	15.5	14.1	11.0	8.7	6.2	4.8
Indio, Calif.	7.2	8.0	11.6	13.6	15.5	15.4	15.3	13.9	11.4	9.5	7.4	6.2
Riverside, Calif.	6.4	7.7	11.0	12.4	13.9	13.8	13.9	12.6	10.6	8.9	6.6	5.6
Denver, Colo.	5.6	6.9	10.1	13.0	14.7	14.6	15.1	13.2	10.6	8.7	6.0	4.8
Fort Collins, Colo.	5.6	7.1	10.5	13.0	14.9	15.0	15.3	13.4	11.0	8.7	6.0	5.0
Boise, Idaho	4.5	6.2	9.7	12.4	15.1	15.2	14.9	12.4	10.0	7.4	4.6	3.9
Twin Falls, Idaho	5.0	6.5	10.1	12.4	14.9	15.2	14.9	13.0	10.0	7.7	5.0	4.1
Great Falls, Mont.	3.9	5.4	9.3	12.0	15.1	15.0	14.7	12.6	9.6	7.2	4.0	3.1
Lincoln, Neb.	5.4	7.1	10.5	12.8	14.9	14.8	14.9	13.4	10.6	8.5	5.8	4.8
Ely, Nev.	5.8	7.5	11.2	13.2	15.5	16.0	15.7	13.9	10.8	8.5	6.0	4.8
Albuquerque, N. Mex.	7.4	9.1	13.0	15.2	17.0	16.0	15.7	14.3	11.8	9.7	7.2	6.4
Bismarck, N. Dak.	4.1	5.4	9.3	12.0	14.7	14.6	14.7	12.6	9.6	7.4	4.2	3.1
Oklahoma City, Okla.	6.4	7.8	11.4	13.4	15.3	15.4	14.9	13.6	11.4	9.3	6.8	5.8
Corvallis, Ore.	4.5	6.3	9.9	12.8	15.5	15.4	15.3	13.6	10.2	7.7	5.0	4.1
Medford, Ore.	5.0	6.3	9.9	12.6	15.3	15.0	15.1	13.4	10.2	7.7	5.0	4.1
Brownsville, Tex.	7.9	8.8	11.6	13.2	14.1	14.0	14.3	13.4	11.6	10.1	8.2	7.2
El Paso, Tex.	7.9	9.5	12.8	14.6	16.3	15.8	15.5	14.7	12.4	10.1	7.8	7.0
San Antonio, Tex.	7.7	8.6	11.6	13.2	14.3	14.4	14.3	13.4	11.6	9.7	7.8	6.8
Seattle, Wash.	3.5	5.2	9.1	12.0	14.9	15.4	14.9	13.0	9.6	6.8	4.0	2.9
Spokane, Wash.	3.5	5.2	8.9	12.0	14.9	15.2	14.9	12.8	10.0	6.8	4.0	2.9
Lander, Wyo.	5.0	6.7	10.5	13.6	15.7	16.0	15.7	14.1	10.8	8.5	5.0	4.1

[a] Based on observed and computed values for the 15th of each month (from Fritz[43]).

TABLE 6.—TOTAL SOLAR AND SKY RADIATION FOR CLOUDLESS SKIES (CALCULATED FROM BUDYKO,[34] TABLE 1) EXPRESSED IN INCHES EVAPORATION EQUIVALENT (1 GRAM WATER = 590 CALORIES).

Latitude, ° N	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
60	1.1	2.6	6.4	10.3	13.9	14.9	14.4	10.9	7.0	4.1	1.7	0.8
55	2.0	3.7	7.7	11.1	14.3	15.1	14.7	11.8	8.2	5.1	2.7	1.5
50	3.1	5.0	9.0	11.9	14.7	15.3	15.0	12.5	9.5	6.4	3.9	2.5
45	4.4	6.3	10.3	12.7	15.1	15.5	15.3	13.4	10.7	7.7	5.1	3.8
40	5.8	7.7	11.3	13.3	15.3	15.7	15.5	14.1	11.7	8.9	6.5	5.1
35	7.2	9.1	12.3	14.0	15.3	15.7	15.5	14.5	12.5	10.1	7.9	6.4
30	8.5	10.1	13.0	14.4	15.3	15.7	15.5	14.8	13.2	11.0	9.1	7.6
25	9.5	11.0	13.5	14.5	15.3	15.6	15.4	14.9	13.7	11.7	10.0	8.7
20	10.3	11.7	13.9	14.5	15.1	15.3	15.1	14.8	14.0	12.3	10.9	9.7
15	11.1	12.2	14.0	14.4	14.7	14.8	14.7	14.5	14.1	12.8	11.5	10.5
10	11.6	12.7	14.0	14.2	14.1	14.1	14.1	14.1	14.1	13.1	12.0	11.1
5	12.0	13.0	13.9	13.9	13.6	13.2	13.4	13.7	13.9	13.3	12.4	11.5
0	12.3	13.2	13.6	13.5	12.8	12.0	12.5	13.1	13.6	13.3	12.7	12.0

TABLE 7.—MEAN ANNUAL VALUES OF k FOR USE WITH EQ. 10 (FROM BUDYKO,[34] TABLE 2).

Latitude												
0	5	10	15	20	25	30	35	40	45	50	55	60
0.35	0.34	0.34	0.33	0.33	0.32	0.32	0.32	0.33	0.34	0.36	0.38	0.40

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[43] "Solar Radiation During Cloudless Days," by S. Fritz, Heating and Ventilation, January, 1949.

An equation similar to Eq. 10 was developed and used in this study because only cloud cover data was available for the earlier E_t data. The magnitude of cloud cover recorded in the 1930's and 1940's was generally lower than that obtained in the 1950's, apparently because of the manner in which it was observed. The developed equation considers deviations in cloud cover from the long-time average using a given observation method, and thus compensates for the method of observation. Also, using long-time average solar radiation compensates for mean water vapor absorption at a location.

$$R_s = \bar{R}_s + K_{ss} (\bar{n} - n) \quad \text{(11)}$$

in which $\bar{R}_s$ is the 4-week long-time moving average solar radiation for the period; K_{ss} is the correction coefficient; n is the mean cloud cover from sunrise to sunset, in tenths (clear = 0, cloudy = 10); and $\bar{n}$ is the 4-week long-time moving average of cloud cover for the period in question. The magnitude of the correction coefficient was determined for all locations and may be expressed as a linear function of mean solar radiation as follows:

$$K_{ss} = a + b \bar{R}_s \quad \text{(12)}$$

Values of a and b, which reflect the type of cloud cover at a location and its effect on solar radiation, are presented in the bulletin mentioned previously.

APPENDIX II.—NOTATION

The following symbols have been adopted for use in this paper:

A = sensible heat flux to the air (negative for flux from air);

D = days in a period;

E_t = rate of evapotranspiration;

G = sensible heat flux to the ground (negative for flux from the ground);

K_{ss} = correction coefficient;

k = coefficient (Budyko);

L = latent heat of vaporization;

n = cloud cover;

$\bar{n}$ = 4-week long-time moving average of cloud cover;

P = radiation flux used in photosynthesis;

R_a = thermal radiation flux from the atmosphere;

R_{et} = effective thermal radiation;

R_g = thermal radiation flux from the ground;

R_p = thermal radiation flux from the plants;

R_s = solar and sky radiation flux (short wave);

$\bar{R}_s$ = 4-week long-time moving average solar radiation;

R_{so} = solar and sky radiation flux on cloudless days;

r = reflectance or albedo;

S = fraction of possible sunshine;

S' = percentage of growing season or interval from planting to potential E_t growth stage;

s = heat flux stored in vegetated zone (negative for flux released from storage); and

T = mean air temperature, in °F.

$$\frac{E_{ta}}{R_s} = (0.021T - 0.84) \dots\dots\dots\dots\dots\dots (18)$$

in which E_{ta} is evapotranspiration for alfalfa excluding cutting periods, in inches per day; T is mean air temperature, and R_s represents solar radiation, in inches per day. As more refined and more accurate E_t data along with supporting climatic and crop data are collected, improvements in the reliability of E_t estimates for individual crops at all stages of growth are anticipated.

Errata.—The following corrections should be made in the original paper: "review of these"

Page 17, line 3 from bottom: "review of" should read "review of these"
Page 17, footnote 11: Add "Utah Agric. Experiment Sta."
Page 20, line 4: "evaportranspiration" should read "evapotranspiration"
Page 20, Eq. 4: "=" should read "≥"
Page 20, reference 32: "Soil Scientists" should read "Soil Science"
Page 22, line 3: "For new crops" should read "For row crops"
Page 22, Line 23: "evaportranspiration" should read "evapotranspiration"
Page 22, reference 36: "Evaporation Demand" should read "Evaporative Demand"
Pages 24 and 25, column headings: "After potential E_t growth: stage-days" should read "After potential E_t growth-stage:days"
Page 24, column heading: "Growing season: 2%" should read "Growing season: %"
Page 24, line 1 from bottom: "Grain sorghum" should read "Grain sorghum^f"
Page 25, line 1: Delete "Jointing"
Page 25, line 2: "to heading" should read "Jointing to heading"
Page 27, line 9: "for lodations" should read "for locations"
Page 27, line 28: "Estimating E_t = " should read "Estimated E_t = "
Page 27, Eq. 6 and lines 6 and 7 from bottom: S should read S'
Page 27, line 4 from bottom: "of potential E_t, evaporating" should read "of potential E_t evaporating"
Page 28, solar week 12, column 7: ".285" should read ".258"
Page 31, standard deviations for Rapid City, S. Dak.; .05 for August should read .50; .06 for November should read .19; .06 for December should read .18
Page 32, lines 5 and 6: "August covers part of the after-heading period." should read "August covers part of the planting to heading and part of the after heading period."
Page 32, line 7: "31 July)" should read "31(July)"
Page 34, footnote 37: "Berkeley" should read "Davis"
Page 36, line 25: "evaportranspiration" should read "evapotranspiration"
Page 36, line 5 from bottom: "transpiration then potential," should read "transpiration. When vegetative cover is adequate so as not to limit evapotranspiration, then potential"
Page 37, line 15: "cm per day. . ." should read "ft per day"
Page 37, line 5 from bottom: "(see Table 4)" should read "(see Table 5)"
Page 37, reference 41: "Ventilation Guide" should read "Ventilating Guide"
Page 38, reference 43: "Ventilation" should read "Ventilating"

KEY WORDS: energy; evapotranspiration; irrigation; meterology; solar energy

ABSTRACT: Measured evapotranspiration (consumptive use) data from irrigated areas in western United States were collected, re-evaluated, and combined with estimates of solar radiation. Approximately 1,000 measurements for individual sampling periods for various crops were useable. The results provide mean numerical values to use in a dimensionless energy balance equation for predicting evapotranspiration.

REFERENCE: "Estimating Evapotranspiration from Solar Radiation," by Marvin E. Jensen and Howard R. Haise, Journal of the Irrigation and Drainage Division, ASCE, Vol. 89, No. IR4, Proc. Paper 3737, December, 1963, pp. 15-41.