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Estimation of Daytime Net Radiation over Well-Watered Grass

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Abstract: Net radiation (R_n) is an important component of the modified Penman equation used to calculate reference evapotranspiration (ET_o). Net radiometers, however, require continual maintenance to ensure that the data they generate are reliable. An equation is developed that estimates hourly R_n over well-watered grass from meteorological data, such as solar radiation, vapor pressure, and air temperature, collected by weather stations in various regions in California. The equation is based on Monteith's daily net radiation equation. Empirical equations are also developed to quantify surface albedo and clear sky global transmissivity. The modified Monteith formula for net radiation is tested in coastal, desert, mountain, and interior valley regions within California. After examining the 1984–1989 data from weather stations in the various regions, the absolute mean error of calculated hourly R_n is within 10% of the measured hourly R_n. The absolute mean error of daytime R_n during $\Theta > 10$ degrees is within 8% of the measured R_n. These errors represent an even smaller error in ET_o estimates. The modified Monteith equation for R_n does not require site specific correction factors.

Introduction

A network of weather stations was developed throughout California under a previous project to assist the irrigated-agricultural regions of the state to optimize water-resource management. The network was developed by the University of California at Davis under the California irrigation management information system (CIMIS) project funded by the California State Department of Water Resources (DWR) at Sacramento. This network is operated and managed by the DWR. Water-resource management is particularly important in California because irrigated agriculture uses more than 80% of the state's developed water in years when the supply is adequate. Weather stations were located in different climatic regions of California, mountain, desert, coastal, and interior valleys, to collect meteorological data necessary to calculate hourly reference evapotranspiration (ET_o) using a modified version of the Penman equation (Doorenbos and Pruitt 1977). Reference evapotranspiration is defined as evapotranspiration that occurs over a full, uniform cover of healthy, well-watered, nonstressed, cool-season grass at uniform height between 0.10 m and 0.15 m. Accurate estimations of ET_o are particularly important in irrigation water management since ET_o is directly proportional to crop evapotranspiration.

Net radiation (R_n) is a major component of this modified Penman equation, and consequently the reliability of the ET_o estimate is largely dependent on the accuracy of the R_n measurement. Unfortunately, field-sit-

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uated net radiometers require continuous calibration and maintenance to ensure that accuracy is sustained. Net radiometers that are located permanently in the field are subject to damage by birds and by ultraviolet radiation, which degrades both the black sensing surfaces and the polyethylene domes. For these reasons, we sought to develop a suitable formula for calculating hourly R_n from other meteorological data that the stations collect: solar radiation (R_s), air temperature (T_a), and vapor pressure (e_o). This type of empirical formula would be particularly useful, because no additional sensors would be needed to estimate net radiation. The pyranometer, used for measuring R_s, is more durable and electronically more stable than net radiometers and already exists at each of the stations. Furthermore, the temperature and humidity sensors already in place are needed to calculate other components in the modified Penman ET_o equation.

We selected the equation developed by Monteith (1973) for estimating R_n, because it is theoretical and would, therefore, have wide applicability under diverse climates such as those found in California. This equation is based on shortwave and long-wave radiative exchange, where

$$R_n = (1 - \alpha)R_s + \varepsilon_s[\varepsilon_a(O)(1 - c)\sigma T_a^4 + c(\sigma T_a^4 - k)] - \varepsilon_s \sigma T_s^4 \quad \ldots\ldots (1)$$

in which the $(1 - \alpha)R_s$ component = net shortwave radiation; α = the surface albedo; and R_s = the measured solar radiation received on a horizontal plane at the earth's surface. The $\varepsilon_s[\varepsilon_a(O)(1 - c)\sigma T_a^4 + c(\sigma T^4 - k)]$ component is the downward long-wave radiation absorbed at the surface, where ε_s is the surface absorptivity (which equals surface emissivity). The $\varepsilon_a(O)(1 - c)\sigma T_a^4$ component is the downward long-wave radiation not coming from clouds, where $\varepsilon_a(O)$ is the sky emissivity from clear portions of the sky; c is the fraction of cloud cover, σ is the Stefan-Boltzmann constant and T_a is the air temperature in Kelvin. The $c(\sigma T_a^4 - k)$ component is the downward long-wave sky radiation coming from clouds, where k is introduced as an empirical coefficient to describe local cloud properties (Monteith 1973). This coefficient varies with cloud type, height, and other factors not accounted for by the fraction of cloud cover, c. The $\varepsilon_s \sigma T_s^4$ component represents upward long-wave radiation emitted from the ground surface to the sky, where ε_s is crop surface emissivity, and T_s is surface temperature.

Our weather station measurements provide data for R_s, relative humidity, and T_a. We want to use these measurements to estimate the other variables in (1). Empirical formulations to quantify $\alpha, \varepsilon_a(O), c$, and k were either developed as part of this work or selected from the literature and adjusted for conditions specific to California.

Formula Development

General Measurements

R_s, R_n, T_a, and humidity data were collected from a network of 53 automatic weather stations on grass surfaces in the major agricultural regions of California (coastal, desert, mountain, and inland valleys) (Fig. 1, Table 1). R_s was measured using a pyranometer at 2-m height. R_n was measured using a net radiometer at 1 m, T_a by using a thermistor at 1.5 m, and e_o was calculated from air temperature and relative humidity that was measured using a carbon conductivity humidity sensor at 1.5 m above the soil surface. Data were collected each minute, averaged for an hour, and recorded as hourly values using a micrologger. All meteorological data were examined for quality (Snyder et al. 1984) and erroneous readings discarded. Instru-

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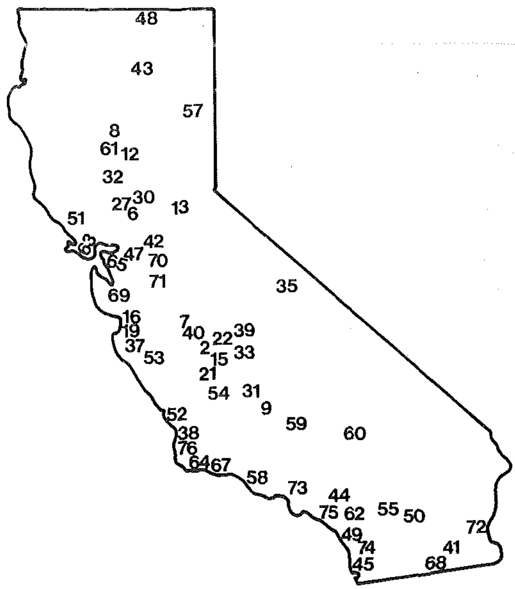

FIG. 1. California Irrigation Management Information System Weather Station Locations (see Table 1)

ments were maintained bimonthly during the growing season (April–September). Field notes gathered by the weather station maintenance group on sensor performance were examined.

Weather stations 2–43 (Fig. 1) were established prior to 1984 and provide five years of hourly data that we used to develop our combined theoretical/empirical model. Weather stations 44–76 were established on or after June 1985. Weather stations shut down prior to December 1988 were not included in this study.

Albedo α

The value for the albedo, α, varies with solar altitude (Θ). Paltridge and Platt (1976) proposed an operational equation for α as

$$\alpha(\Theta) = a + (1 - a)\exp(-b\Theta) \quad (2)$$

where a and b = empirical coefficients that are dependent on the nature of the surface material. We examined two generalized equations derived from (2)

$$\alpha(\Theta) = A + B\exp(-C\Theta) \quad (3)$$

and

$$\alpha(\Theta) = A\Theta + B\exp(-C\Theta) \quad (4)$$

where A,B, and C = empirical constants. We used the shortwave surface albedo data reported for well-watered grass at Davis, California (Morgan et al. 1970). These albedo data were divided into groups based on the bulk shortwave transmissivity of the atmosphere, R_s/I, where I is the irradiance on a horizontal surface at the top of the atmosphere

TABLE 1. California Irrigation Management Information System Weather Stations

Climactic region (1)	Station number (2)	Location (3)
Central coast	16	San Juan
Central coast	19	Castroville
Central coast	37	Salinas
Central coast	47	Brentwood
Central coast	51	Healdsburg
Central coast	53	Greenfield
Central coast	63	Navato
Central coast	65	Walnut Creek
Central coast	69	San Jose
South coast	38	Santa Maria
South coast	45	San Diego
South coast	49	Oceanside
South coast	52	San Luis Obispo
South coast	58	Santa Paula
South coast	62	Temecula
South coast	64	Santa Ynez
South coast	67	Goleta
South coast	74	Escondido
South coast	75	Irvine
Mountain	13	Camino
Mountain	35	Bishop
Mountain	43	McArthur
Mountain	48	Tulelake
Mountian	57	Buntingville
Desert	41	Caliptria
Desert	44	Lodi
Desert	50	Thermal
Desert	55	Palm Desert
Desert	60	Barstow
Desert	68	Seeley
Desert	72	Palo Verde
Sacramento Valley	6	Davis
Sacramento Valley	8	Gerber
Sacramento Valley	12	Durham
Sacramento Valley	27	Zamora
Sacramento Valley	30	Nicolaus
Sacramento Valley	32	Colusa
Sacramento Valley	61	Orland
San Joaquin Valley	2	Five Points
San Joaquin Valley	7	Firebaugh
San Joaquin Valley	9	Lamont
San Joaquin Valley	15	Stratford
San Joaquin Valley	21	Kettlemen
San Joaquin Valley	22	Caruthers
San Joaquin Valley	31	McFarland
San Joaquin Valley	33	Visalia
San Joaquin Valley	39	Parlier
San Joaquin Valley	40	Mendota
San Joaquin Valley	42	Lodi
San Joaquin Valley	54	Blackwells Corner
San Joaquin Valley	59	Tehachapi
San Joaquin Valley	70	Manteca
San Joaquin Valley	71	Modesto

Note: Weather station identification number corresponds to those on Fig. 1.

$$I = I_o \cos Z \qquad (5)$$

Here, I_o = the solar constant; and Z = the solar zenith angle. The bulk transmissivity serves as a surrogate for cloud cover. The analysis was performed for situations where $\Theta > 10°$ ($Z < 80°$) and where R_s/I was ≥ 0.375, ≥ 0.40, ≥ 0.45, and ≥ 0.50.

Solar data collected under overcast conditions ($R_s/I < 0.375$) were considered separately, since full overcast results in very diffuse insolation and no dependence of α on Θ was expected. Data collected at $\Theta < 10°$ were removed from the analysis because the pyranometers do not perform well at $\Theta < 8°$.

Constants A,B, and C for (3) and (4) were determined using nonlinear regression analysis. Table 2 shows statistics that compare the two equations and their ability to predict the measured α value when $R_s/I \geq 0.375$. Eq. (4) resulted in a lower Student's t-value and a more representative range of applicability than (3).

We selected (4) since it was the simplest exponential equation that provided a high degree of correlation ($r^2 = 0.99$) with the observations and imposed minimum restrictions on the data. The surface albedo formula for well-watered grass with the appropriate constants is as follows: (1) For clear and partly cloudy sky ($R_s/I \geq 0.375$) and $\Theta \geq 10°$

$$\alpha = 0.00158\Theta + 0.386 \exp(-0.0188\Theta) \quad (6)$$

(2) for overcast sky conditions $R_s/I < 0.375$ the mean value for α was found to be 0.26.

Clear Sky Emissivity $\varepsilon_a(O)$

Several equations are available to estimate clear sky emissivity using near surface values of air temperature and/or vapor pressure. We examined four equations (Brutsaert 1975; Idso 1981; Satterlund 1979) that do not require empirical corrections

$$\varepsilon_a(O) = 1.24 \left(\frac{e_o}{T_a}\right)^{1/7} \quad (7)$$

$$\varepsilon_a(O) = 0.575 e_o^{1/7} \quad (8)$$

$$\varepsilon_a(O) = 0.70 + 5.95\, 10^{-5} e_o^{1500/T_a} \quad (9)$$

and

$$\varepsilon_a(O) = 1.08[1 - \exp(-e_o^{T_a/2016})] \quad (10)$$

TABLE 2. Paired t Test Comparison of Measured Albedo versus Calculated Albedo Using Eqs. (3) and (4), over Well-Watered Grass Surface in Davis, California

Albedo (α)[a] (1)	$\bar{X}$ (2)	s (3)	n (4)	Range (5)	Paired t (6)
Measured	0.249	0.032	343	0.202–0.34	
Eq. (3)	0.249	0.031	343	0.196–0.316	0.06
Eq. (4)	0.249	0.032	343	0.213–0.338	0.04

[a]Measured = measured albedo for $\Theta > 10°$ and clear and partly cloudy sky ($R_s/I > 0.375$).

Note: Eq. (3) is the generalized Paltridge and Platt equation $\alpha(\Theta) = A + B \exp(-C\Theta)$, where $A = 0$, $B = 0.339$, and $C = 0.00742$. We chose to use Eq. (10) as the albedo equation $\alpha(\Theta) = A\Theta + B \exp(-C\Theta)$ where $A = 0.00158$, $B = 0.386$, and $C = 0.0188$

where e_o = the near-ground vapor pressure in millibars. The developers of all four emissivity equations reported that they were usable at $T_a > 0°C$. Eqs. (7) and (8) show significant deviation at $T_a < 0°C$, while (10) appears to have better agreement between measured and calculated clear sky emissivity at $T_a < 0°C$ (Satterlund 1979). Estimates of net radiation using measured R_s and these equations were compared with measurements taken under clear skies ($R_s/I \geq 0.70$) using a linear regression of the form R_n (measured) = $a + bR_n$(calculated). Hourly R_n data were analyzed from at least three weather stations in each of four climatic regions for each season during the two-year period 1986–1987. The hourly weather data for night and early morning hours, when $\Theta < 10°$, were excluded. We were unable to use nighttime clear-sky emissivity data since the network data do not distinguish between clear and cloudy conditions.

We selected the best emissivity equation based on the regression line with a slope closest to 1 and that expression giving the highest correlation coefficient. The slope and r^2 values for each of the four equations were compared using analysis of variance, Fischer protected least square difference and the Scheffe F test (Table 3). All expressions provided good $\varepsilon_a(O)$ values, and no one equation was superior for all climatic regions in California. The Scheffe F test, a more conservative analysis, indicated no difference in the slopes for coastal and valley stations. Eq. (10) appears to provide a better combination of high r^2 and a slope close to unity than (9) in the mountain region, while (9) performed better than (10) in the desert region. The Fischer test indicated the four equations were significantly different (at the 5% level) for estimating R_n in the regions indicated by the Scheffe's F test. The Fischer tests also indicated that (10) was better than (9) along the coast, and (10) was superior to (8) in the valley. Performance of (7) was similar

TABLE 3. Fischer Protected Least Square Difference (PLSD) and Scheffe F Test Comparing Slope and Regression Coefficients of Calculated versus Measured Net radiation using Four Different Emissivity Equations and Hourly Clear Sky Data from 1986 and 1987

	Coastal		Desert		Mountain		Valley	
$\varepsilon_a(O)$ Equation Comparison[a] (1)	Protected least square difference (2)	Scheffe F (3)	Protected least square difference (4)	Scheffe F (5)	Protected least square difference (6)	Scheffe F (7)	Protected least square difference (8)	Scheffe F (9)
(*a*) Slopes								
7 versus 8	0.007	0.181	0.012	0.071	0.004[a]	5.394[a]	0.015	0.135
7 versus 9	0.007	0.322	0.012	0.286	0.004	0.353	0.015	0.004
7 versus 10	0.007	0.895	0.012[a]	8.643[a]	0.004[a]	10.502[a]	0.015	1.571
8 versus 9	0.007	0.987	0.012	0.643	0.004[a]	8.506[a]	0.015	0.187
8 versus 10	0.007	0.271	0.012[a]	7.143[a]	0.004	0.843	0.015[a]	2.627
9 versus 10	0.007[a]	2.292	0.012[a]	12.07[a]	0.004[a]	14.705[a]	0.015	1.413
(*b*) Regression Coefficients								
7 versus 8	0.015	0.0004	0.008	0.188	0.011	0.057	0.018	0.089
7 versus 9	0.015	0.147	0.008	1.590	0.011[a]	2.635	0.018[a]	2.160
7 versus 10	0.015	1.529	0.008	0.894	0.011[a]	4.818[a]	0.018[a]	4.657[a]
8 versus 9	0.015	0.131	0.008	0.685	0.011[a]	1.914	0.018	1.374
8 versus 10	0.015	1.477	0.008	0.262	0.011[a]	3.823[a]	0.018[a]	3.461
9 versus 10	0.015	0.727	0.008	0.099	0.011	0.327	0.018	0.474

[a]Eq. (7) is the original Brutsaert emissivity equation; Eq. (8) is the modified Brutsaert emissivity equation; Eq. (9) is the Idso's emissivity equation; and Eq. (10) the Satterlund's emissivity equation.

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to (8). Although all of the equations were suitable for our needs, we selected (10), since it was the most general.

Cloud Cover Fraction c

Although several relationships between cloud cover fraction and solar radiation have been proposed (Kasten and Czeplak 1980; Turner and Majahid 1984; Wendler and Kodama 1986), none were developed specifically for California, and only the Kasten and Czeplak (1980) equation was based on a long-term study (10 years of hourly data).

The Kasten and Czeplak equation

$$\frac{R_s}{R_a} = 1 - 0.75c^{3.4} \quad \text{(11)}$$

where R_s = solar radiation; R_a = potential clear-sky global solar radiation; and c = fraction of cloud cover. Potential clear-sky global radiation can be approximated as

$$R_a = K_t I \quad \text{(12)}$$

where K_t = clear-sky global transmissivity (Carroll 1985). To substitute (12) into (11), K_t must be determined. An equation for K_t was developed using nonlinear regression analysis of the K_t versus Θ data obtained by Carroll (1985) for Davis, California, whenever $\Theta \geq 10°$

$$K_t = 0.79 - 3.75/\Theta \quad \text{(13)}$$

with an $r^2 = 0.995$. Eq. (11) can now be written in a form that is compatible with the network weather data

$$c = \left(1.333 - 1.333\frac{R_s}{R_a}\right)^{0.294} \quad \text{(14)}$$

where

$$R_a = \left(0.79 - \frac{3.75}{\Theta}\right) I \quad \text{(15)}$$

Application of this equation is subject to the restrictions that $R_s/R_a \leq 1$ and $c \leq 1$. Eq. (14) is used for daylight hours when $\Theta \geq 10°$.

Cloud and Surface Emissivity ε_s**, and Surface Temperature** T_s

We assumed a cloud emissivity of 1.0. The emissivity may vary between 0.95 to 1.0 depending on the wavelength. We found that any value within this range was relatively insensitive to our calculated R_n value. We assumed grass surface emissivity ε_s of 0.98 (Rosenberg et al. 1983; Jensen et al. 1973). We also assumed T_s at the grass surface = T_a at 1.5 m above the soil surface. Since $T_s < T_a$ during early morning and evening hours and $T_s > T_a$ during the afternoon hours, very little error is introduced into daytime R_n estimation. That is, a 2° temperature discrepancy in T_a and T_s during the day results in only an 11–13 watts/m² error in daily R_n.

When calculating hourly R_n, hourly differences in T_s and T_a can be much more than two degrees. T_s was compared with T_a over well-watered grass in Davis, California, using data provided by Morgan et al. (1970). Surface temperature was measured using an infrared thermometer, and air temperature at 2 m was measured using an aspirated thermopile. Meteorological data were collected twice every 1.5 minutes and averaged over 0.5 hour intervals. Only data with sun angle $\theta > 10°$ were used in our analysis. Temperature averages for 356 half-hour intervals taken for 19 days (June 1–3; July 12–14; and October 13 and 14 of 1966; and April 27 and 28; May 2–5 and 9; September 28 and 29; and October 7 and 9 of 1967) were analyzed for differences in T_a and T_s (Table 4). The mean difference in temperature $(T_s - T_a)$ is 2.1°C ± 3.5°C and the percent error relative to net radiation $[(\varepsilon\sigma T_s^4 - \varepsilon\sigma T_a^4)/R_n]$ was 0.8%. The largest positive difference ($T_s - T_a$ = 5.9°C) occurred near solar noon in July with a relative error of 23% of net radiation. The largest negative difference ($T_s - T_a = -7.7$°C) occurred near sunset in October with a relative error of 40% of net radiation.

Empirical Coefficients E and K

Eq. (1) by Monteith (1973) can be rewritten as

$$R_n = R_n(O) - ck \quad (16)$$

where $R_n(O) = R_n$ when $c = 0$. The term ck is the product of fraction cloud cover, c, and an empirically determined cloud factor, k, to correct for local cloud conditions when $c > 0$. Our data indicate that (16) can be replaced by a multiplicative error term, E, without the restriction of $c > 0$

$$R_n = ER_n(O) \quad (17)$$

The empirical term E during the 5th–25th day of each month at each of the 47 stations using 1985–1988 hourly data was computed to be 0.11 ± 0.04 ($n = 564$). Eq. (17) can be written as

$$R_n = 0.89R_n(O) \quad (18)$$

Formula Verification

A comparison of calculated net radiation, R_n', and measured net radiation, R_n, is shown in Table 5 for 1985–1987 data and Table 6 for April 1984 and March 1989. The hourly data used to compile Table 5 were from days 1–5 and day 26 to the end of the month for each month. These days were not the same days used for computing the error term E in (17). During April 1984, stations 2–43 were operational and net radiation data were available.

TABLE 4. Comparison between Grass Surface Temperature T_s and Air Temperature T_a over Well-Watered Grass in Davis, California

Hourly and daily means (1)	T_s (degrees) (2)	T_a (degrees) (3)	R_n (w/m²) (4)	$\varepsilon\sigma T_s^4 - \varepsilon\sigma T_a^4$ (w/m²) (5)	$\frac{\varepsilon\sigma T_s^4 - \varepsilon\sigma T_a^4}{R_n}$ (6)
Hourly mean	21.2	19.1	355	11.7	0.008
Standard error	4.6	4.8	177	20.1	0.172
$n = 356$					
Daily mean	21.1	19.1	354	11.2	0.003
Standard error	2.9	4.0	74	10.3	0.058
$n = 19$					

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TABLE 5. Comparison between Measured Hourly Net Radiation (R_n) and Calculated Net Radiation (R'_n) [Daytime net radiation was computed as the average of hourly net radiation during daylight hours and the sunangle θ was >10 degrees. Sample number is indicated by "n"]

	Hourly R_n (w/m²)					Daytime R_n (w/m²)				
Station (1)	n (2)	R_n (3)	R'_n (4)	$R_n - R'_n$ (5)	$\|R_n - R'_n\|$ (6)	n (7)	R_n (8)	R_n (9)	$R_n - R'_n$ (10)	$\|R_n - R'_n\|$ (11)
					(*a*) 1985					
2	1042	332	326	6	21	110	311	306	5	14
6	1059	288	305	−17	28	117	268	284	−17	23
7	1202	272	283	−11	22	121	258	270	−13	17
9	1230	285	289	−3	27	121	271	275	−4	11
12	959	287	281	6	20	95	268	263	5	14
13	672	229	253	−24	31	78	216	240	−24	27
15	1142	327	315	12	24	123	307	297	10	17
16	563	221	222	−2	26	72	212	214	−3	15
19	540	311	309	2	26	57	296	295	1	16
21	1205	294	310	−16	26	120	279	296	−16	20
22	997	290	297	−6	25	105	274	282	−8	18
27	944	275	272	3	29	95	259	256	3	23
30	565	275	277	−2	21	66	249	253	−4	15
31	832	280	282	−13	25	95	258	272	−13	18
32	477	245	254	−9	26	59	228	236	−9	16
33	789	277	287	−10	22	89	254	265	−11	17
35	604	288	291	−3	26	67	269	273	−3	15
		281[a]	285[a]	−5[a]	25[a]		263[a]	269[a]	−6[a]	17[a]
					(*b*) 1986					
2	944	321	304	17	24	105	300	284	16	19
6	1071	275	278	−3	24	110	255	259	−3	17
7	1231	273	293	−19	27	125	261	279	−19	21
8	1012	285	278	7	28	112	262	256	6	24
9	1247	269	292	−23	29	122	255	279	−24	25
12	783	285	272	12	32	83	261	252	9	25
13	867	288	307	−19	27	97	267	286	−18	19
15	995	280	320	−40	41	108	263	301	38	38
16	1152	282	284	−2	25	125	266	268	−2	13
19	469	220	245	−25	33	56	216	238	−23	26
22	960	262	276	−14	22	101	246	262	−15	17
27	709	292	319	−27	31	68	275	302	−28	28
30	1021	287	301	−14	29	115	265	280	−15	24
31	1126	314	324	−11	22	121	294	307	−13	20
32	782	244	260	−16	26	94	228	243	−15	19
33	1148	289	308	−18	26	124	271	288	−17	19
35	1109	330	317	13	29	121	315	303	13	19
		282[a]	293[a]	−11[a]	28[a]		265[a]	276[a]	−6[a]	22[a]

TABLE 5. (Continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
					(c) 1987					
2	655	304	309	−5	21	77	276	270	−6	6
6	1156	284	292	−8	22	118	263	272	−9	15
7	1263	264	282	−18	23	125	251	269	−18	20
8	1109	278	270	9	23	113	258	250	8	18
9	1239	298	290	9	30	121	282	276	6	21
12	1069	260	260	0	27	111	243	243	0	20
13	1088	299	292	7	30	119	273	270	3	25
15	688	250	279	−30	31	84	232	260	−28	28
16	1117	271	280	−10	24	122	251	262	−11	15
19	588	259	270	−11	28	71	246	254	−8	21
21	958	284	293	−9	22	99	268	275	−7	17
22	1224	278	298	−19	23	121	264	282	−18	20
27	963	293	295	−2	23	97	272	274	−2	17
30	1135	298	305	−8	25	124	276	285	−8	15
31	1016	306	310	−4	24	111	286	290	−4	16
33	1156	299	310	−12	25	125	278	290	−11	17
35	715	293	300	−7	26	75	285	291	−7	16
		283[a]	290[a]	−7[a]	25[a]		265[a]	271[a]	−7[a]	18[a]

[a]Denotes mean.

During March 1989, stations 48–76 were operational and recorded measured net radiation while 2–43 provided calculated net radiation.

The mean hourly difference ($R_n - R'_n$) for all stations during 1985, 1986, and 1987 ranged from −40 to 17 w/m^2 with the mean of −5, −11, and −7 w/m^2 for years 1985, 1986, and 1987, respectively (Table 5). This represents a 2%, 4%, and 2% difference from the measured hourly R_n for their respective years. The mean hourly absolute difference $|R_n - R'_n|$ for each station during 1985, 1986, and 1987 ranged from 21 to 41 w/m^2 with a mean of 25, 28, and 25 w/m$_2$ for their respective year. This represents approximately 10% difference from the measured net radiation. Daytime net radiation was computed as the mean of the hourly values when $\theta > 10°$. The mean daytime $|R_n - R'_n|$ for each station during 1985, 1986, and 1987 ranged from 11 to 38 w/m^2 with a mean of 17, 22, and 18 w/m^2 for their respective years. This represents approximately 8% difference from the measured net radiation. R_n was also compared with R'_n for April 1984 and March 1989 data (Table 6), because no data from 1984 or 1989 were used to compute the error term E. The mean hourly and daylight $|R_n - R'_n|$ for all stations were in a similar range as found for the 1985, 1986, and 1987 data. For April 1984 and March 1989, the mean hourly $|R_n - R'_n|$ for all stations was 31 w/m^2 or a 10% difference.

Hourly R_n was measured for three consecutive days (March 1–3, 1989) at Oceanside, California (station 49). Hourly R_n was calculated using the equation developed here along with the R_s,e_o, and T_a data collected at the station during this time interval. Fig. 2 shows the calculated and measured values of R_n. These data are presented for this location and time of year since these three consecutive days represent a partly cloudy sky, a cloudy sky, and a clear sky, respectively. The absolute mean difference between calculated and measured hourly net radiation for the three days was 24

TABLE 6. Comparison between Measured (R_n) and Calculated (R'_n) Hourly Net Radiation

		Hourly R_n (w/m²)				Daytime R_n (w/m²)			
Station (1)	n (2)	R_n (3)	R'_n (4)	$R_n - R'_n$ (5)	$\|R_n - R'_n\|$ (6)	R_n (7)	R'_n (8)	$R_n - R'_n$ (9)	$\|R_n - R'_n\|$ (10)
				(*a*) 1984					
2	50	405	398	7	21	405	398	7	15
6	41	357	316	42	43	358	313	45	45
7	55	343	356	−13	28	343	356	−13	13
8	45	348	324	23	39	362	334	28	34
9	44	342	351	−8	28	342	345	−2	15
12	32	230	235	−5	25	232	237	−5	7
13	45	302	339	−37	38	297	334	−38	38
15	55	403	368	35	42	403	368	35	35
16	45	320	312	8	24	319	311	8	8
19	34	234	246	−12	14	234	246	−12	12
21	55	344	364	−20	21	344	364	−20	20
27	55	344	340	4	19	344	340	4	16
30	55	321	335	−13	28	321	335	−13	21
31	55	379	370	9	28	379	370	9	11
32	50	256	310	−53	54	248	302	−54	54
33	55	377	350	26	38	377	350	26	26
35	50	356	318	39	44	355	317	38	38
37	55	368	349	19	29	368	349	19	20
39	50	368	389	−21	36	368	389	−21	23
40	54	377	354	23	31	377	354	23	23
41	49	359	393	−34	42	355	390	−35	36
42	55	348	360	−13	18	348	360	−13	14
43	55	314	332	−17	19	314	332	−17	17
		339[a]	339[a]	−1[a]	31[a]	339[a]	339[a]	0[a]	24[a]
				(*b*) 1989					
48	47	244	256	−12	21	244	256	−12	13
49	49	395	359	36	48	395	360	36	36
52	47	309	334	−25	28	309	334	−25	25
55	36	391	381	10	35	394	382	12	16
57	48	235	237	−2	14	237	238	−1	11
58	50	341	333	8	22	341	333	8	12
60	40	310	343	−33	39	309	341	−32	32
62	46	378	369	9	39	380	370	10	12
63	50	247	284	−37	38	219	262	−44	44
65	44	207	249	−42	42	213	255	−42	42
67	45	349	362	−12	23	351	363	−12	12
68	47	390	374	16	31	392	376	16	16
69	50	219	251	−32	32	219	251	−32	32
70	43	190	240	−49	53	198	246	−48	48
71	48	271	245	26	30	273	247	27	27
72	47	350	362	−12	22	351	364	−13	14
73	39	329	332	−3	32	329	332	−2	4
74	50	365	345	21	26	365	345	21	21
75	48	318	334	−16	28	320	335	−16	16
76	50	356	354	2	16	356	354	2	4
		310[a]	317[a]	−7[a]	31[a]	310[a]	317[a]	−7[a]	22[a]

[a]Denotes means.

Note: Table uses data from five consecutive days (April 13–17, 1984 and March 17–21, 1989) during daylight hours when solar altitude θ was 10°.

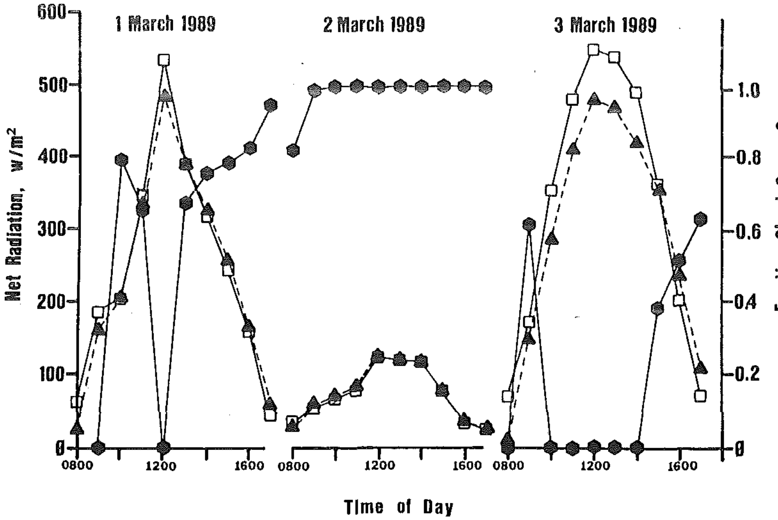

FIG. 2. Relationship between Hourly R_n Measured (□) with Fritchen Net Radiometer and R_n Calculated (▲) using Equation. Data are from Station #49 between March 1, 1989, and March 3, 1989

W/m^2, which represents an 11% difference hourly. For $\Theta > 10°$, the error was 5% daily.

After the development of the equation it was noted that the value for long-wave surface absorptivity used in $\varepsilon_s[\varepsilon_a(O)(1 - c)\sigma T_a^4 + c(\sigma T^4 - k)]$ was $\varepsilon_s = 1$ instead of $\varepsilon_s = 0.98$. Considering the uncertainty of other measurements, this error was allowed to remain and is a component of the error term $E = 0.89$.

Summary and Conclusions

We developed and evaluated equations for estimating hourly net radiation over well-watered grass given measured R_s, T_a, and humidity. The modified Monteith equation we developed was

$$R_n = 0.89[(1 - \alpha)R_s + \varepsilon_a(O)(1 - c)\sigma T_a^4 + c\sigma T_a^4 - 0.98\sigma T_a^4] \quad \ldots . (19)$$

The empirical equations used to calculate the various parameters in the modified Monteith equation for daylight hours, when the sun is at least $\Theta \geq 10°$ above the horizon are

$$\alpha = 0.00158\Theta + 0.386 \exp(-0.0188\Theta), \qquad \text{when } \frac{R_s}{I} \geq 0.375,$$

$$\alpha = 0.26 \quad \text{when } \frac{R_s}{I} < 0.375 \quad \ldots\ldots\ldots\ldots [(6)]$$

$$\varepsilon_a(O) = 1.08[1 - \exp(-e_o^{T_a/2016})] \quad \ldots\ldots\ldots\ldots [(10)]$$

where e_o is expressed in millibars and T_a in Kelvin

$$R_a = \left(0.79 - \frac{3.75}{\Theta}\right) I \qquad [(15)]$$

$$c = \left(1.33 - 1.33 \frac{R_s}{R_a}\right)^{0.294} \quad \text{if} \quad c > 1 \quad \text{then } c = 1,$$

$$\text{if} \quad c < 0 \quad \text{then} \quad c = 0 \qquad [(14)]$$

The equations developed here are for calculating net radiation during daylight hours over well-watered grass and do not require site specific correction factors. Although the equation is based on data from California, we believe the model may be applicable for other locations where $\varepsilon_a(O)$,α, and c values can be quantified from R_s,e_o, and T_a data. The absolute mean error of calculated hourly R_n was within 10% of the measured hourly R_n. For calculating daily net radiation using the equations developed here, cloud cover c during night time must be estimated. Cloud cover from sunset, $\Theta < 10°$, to midnight can be estimated as c at the hour nearest to sunset with $\Theta \geq 10°$ and c from midnight to sunrise; $\Theta < 10°$ can be estimated as c at the hour nearest to sunrise with $\Theta \geq 10$. We did not test the suitability of these estimates of c.

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Appendix I. References

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A,B,a,b,C = empirical constants used for calculating α;
c = fraction cloud cover;
E = error term;
ET_o = modified Penman reference evapotranspiration;
e_o = vapor pressure, in millibars;
I = extraterrestrial radiation recieved on horizontal surface;
I_o = solar constant;
K_t = clear sky transmissivity coefficient;
k = empirical coefficient for cloud cover for each month;
R_a = potential clear sky global solar radiation in watts per square meter;
R_n = net radiation, in watts per square meter;
R_s = global solar radiation, in watts per square meter;
T_a = air temperature, kelvin;
T_s = surface temperature, kelvin;
Z = zenith angle: $Z = 90 - \Theta$;
α = surface albedo over well-watered grass;
$\varepsilon_a(O)$ = sky emissivity for clear portion of sky;
ε_s = crop surface emissivity, 0.98;
θ = solar altitude in degrees; and
σ = Stefan Boltzmann constant, 5.67×10^{-8} Jm^{-2} K^{-4} s^{-1}.

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