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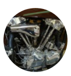
ARTICLE *in* JOURNAL OF HYDROLOGIC ENGINEERING · APRIL 1997

Impact Factor: 1.58 · DOI: 10.1061/(ASCE)1084-0699(1997)2:2(56)

1 AUTHOR:



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SELF-CALIBRATING METHOD FOR ESTIMATING SOLAR RADIATION FROM AIR TEMPERATURE

By Richard G. Allen,[1] Member, ASCE

ABSTRACT: Procedures are introduced for self-calibrating an equation for estimating solar radiation (R_s) in the absence of measurements. The self-calibration is based on computed clear sky solar radiation envelopes and uses daily maximum and minimum air temperature. The resulting calibration can predict both daily and monthly average R_s parameters in evapotranspiration equations. The method was tested at nine locations in the United States representing low, medium, and high elevations, semi-arid and subhumid climates and ocean locations and was generally accurate, especially when predicting monthly R_s. Prediction of daily R_s was less accurate, but was scattered evenly about the 1:1 relationships with measured R_s. The self-calibration procedure was about as accurate on a monthly basis as ratios of R_s to extraterrestrial radiation from regional stations. The self-calibration procedure was more accurate than fixed calibration coefficients. The method is both simple and conservative because it is constrained by computed clear-sky solar-radiation curves.

INTRODUCTION

Solar radiation (R_s) is a primary driver of the evapotranspiration (ET) process and R_s data are an integral part of many ET estimation procedures. For example, the Penman and Penman-Monteith ET equations (Wright 1982; Jensen et al. 1990) require net radiation data, which are commonly estimated using measured R_s (Jensen et al. 1990; Shuttleworth 1992). Solar radiation is not routinely measured at many weather stations and may need to be estimated when a Penman-type ET equation is applied. The common alternative is to use empirically based ET methods, such as the Hargreaves et al. (1985) method, which require only maximum and minimum daily air temperature.

This paper introduces a relatively simple procedure for self-calibrating and applying an air-temperature–based equation for predicting daily and monthly solar radiation. The procedure uses clear-sky solar radiation envelopes and is compared with other temperature-based methods for estimating R_s.

BACKGROUND

Hargreaves and Samani (1982) and Richardson (1985) were among the first to suggest that R_s could be estimated from the difference between daily maximum and daily minimum air temperature and extraterrestrial radiation. The form of the equation introduced by Hargreaves and Samani (1982) is

$$R_s = K_r(T_{max} - T_{min})^{0.5}R_a \quad (1)$$

where T_{max} and T_{min} = mean daily maximum and minimum air temperature (°C) for period (generally one month); R_a = extraterrestrial radiation; and K_r = empirical coefficient. Units of R_s and R_a are the same. Initially, K_r was set to 0.17 for arid and semiarid climates. Hargreaves (1994) later recommended using K_r = 0.16 for "interior" regions and K_r = 0.19 for coastal regions.

Allen (1995a) modified (1) by estimating K_r as a function of elevation as

$$K_r = K_{ra}\left(\frac{P}{P_0}\right)^{0.5} \quad (2)$$

where P = mean atmospheric pressure of the site, kPa; P_0 = mean atmospheric pressure at sea level (101.3 kPa); and K_{ra} = empirical coefficient equal to 0.17 for interior regions and equal to 0.20 for coastal regions. The introduction of PP_0^{-1} was to account for elevation effects on the volumetric heat capacity of the atmosphere. However, as is demonstrated later, (2) does not function well at elevations >1500 m and is therefore no longer recommended.

Eq. (1) is based on the assumption that the difference between daily maximum and minimum temperature provides a general indication of cloudiness. Compared to clear skies, cloud cover usually decreases maximum air temperatures due to lower solar radiation levels, and usually increases minimum air temperatures due to increased downward emission and reflection of long wave radiation by clouds at night. Clearly, many other factors besides R_s and cloudiness affect levels of maximum and minimum air temperature, especially on a daily basis. These factors include wind speed, air-vapor content, availability of soil water for evaporation, elevation, precipitation, and frontal weather systems. However, over periods of as long as one month, many of these weather variables tend to follow long term averages, resulting in a fairly consistent relationship between $T_{max} - T_{min}$ and R_s/R_a. K_r varies somewhat with time, location, and climate. For example, ocean temperature moderates differences between T_{max} and T_{min} at coastal locations.

Eq. (1) is primarily intended for application on monthly (30 d) calculation time steps. When applied on daily (24-h) time steps, the method has substantially greater uncertainty and prediction error, for reasons given in the previous paragraph.

OTHER APPROACHES AND PREVIOUS WORK

Many studies have used (1) or other formulations based on $T_{max} - T_{min}$ for estimating daily and monthly R_s data, including weather synthesizing software (Richardson 1985; Keller 1987; Samani et al. 1987; Walker et al. 1995). Bristow and Campbell (1984) used an exponential relationship between R_s/R_a and $T_{max} - T_{min}$ that produces estimates similar to (1). Persaud and Change (1985) applied time series analysis to estimate R_s from T_{max}.

Allen (1995a) analyzed mean monthly solar radiation and associated weather data from 900 weather stations in 20 countries and concluded that the most consistent and accurate method for predicting R_s on a monthly basis was the ratio of R_s/R_a from a regional station within about 400 km (250 mi) of the location multiplied by R_a for the local site. Hubbard (1994) suggested that the regional station should be within 30 km to produce daily estimates of R_s that explain 90% of variance in the actual R_s.

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Note. Discussion open until September 1, 1997. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on April 1, 1996. This paper is part of the ***Journal of Hydrologic Engineering***, Vol. 2, No. 2, April, 1997. ©ASCE, ISSN 1084-0699/97/0002-0056–0067/$4.00 + $.50 per page. Paper No. 12939.

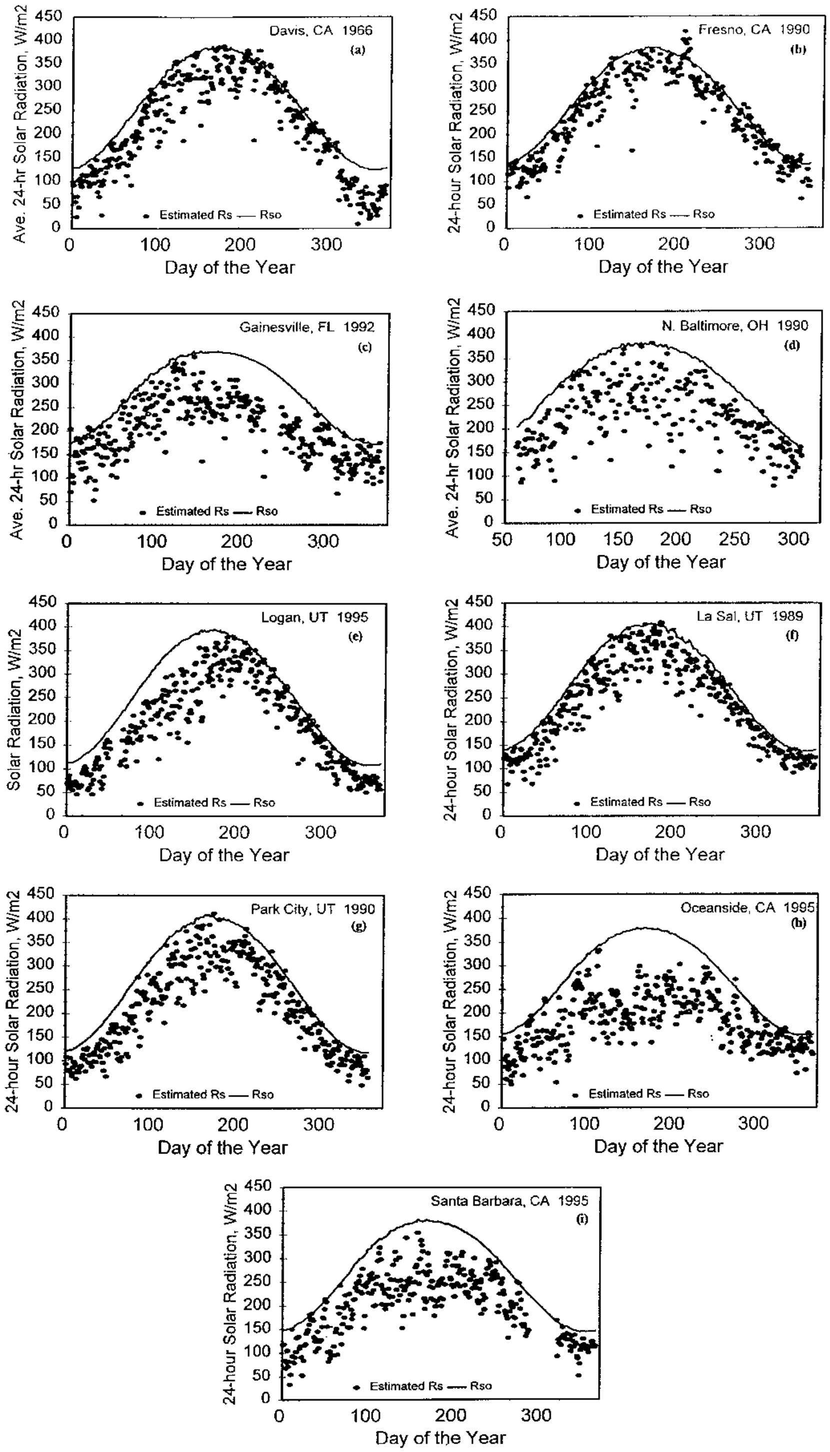

FIG. 1. 24-h Average R_s from Self-Calibrated Eq. (1) for: (a) Davis; (b) Fresno; (c) Gainesville; (d) North Baltimore; (e) Logan; (f) La Sal; (g) Park City; (h) Oceanside; (i) Santa Barbara

When applying R_s/R_a ratios from a nearby station, the types of cloudiness and general climates of the two sites should be similar; R_s can vary markedly along coastlines due to fog and cloud banks at low elevations and clear sky at higher elevations, between windward and leeward sides of islands, and in steep mountain valleys. When R_s/R_a ratios are not available from regional stations, Allen (1995a) recommended using (1) with $K_r = 0.17$ for interior locations and $K_r = 0.19$ for coastal locations. These coefficients are similar to ones proposed by Hargreaves (1994). Coastal locations were defined as locations situated on or adjacent to the coast of a large land mass whose inland width exceeds 20 km. Allen (1995a) found little correlation between R_s/R_a and $T_{max} - T_{min}$ for island locations (defined as land masses having inland widths less than 20 km), due to the large and variable dampening of air temperatures by the ocean, and estimated monthly R_s as $R_s = 0.7\ R_a - 46$, where R_s and R_a have units of W m^{-2}.

R_s was estimated for weekly and monthly periods at 32 stations across Europe using (1) and $K_r = 0.16$ (inland) and 0.19 (coastal); average standard error of estimate (SEE) was 30 W m^{-2} with some underestimation at the highest levels of monthly R_s (Allen 1995a). Results were similar for 26 weather stations across the U.S. However, in both the European and U.S. studies, monthly R_s was best estimated using R_s/R_a from a regional station (SEE for Europe = 25 W m^{-2}), even though the average distance between locations was 230 km with a maximum distance of 1,200 km in the European study, and 420 km with a maximum distance of 760 km in the U.S. study.

PROCEDURE

Eq. (1) produces relationships between R_s/R_a and $T_{max} - T_{min}$ that are generally consistent throughout the year. Eq. (1) is conservative in the prediction of R_s/R_a, i.e., it rarely overpredicts R_s when skies are clear. These attributes make self-calibration possible by comparing estimates from Eq. (1) with an envelope of R_s expected under completely clear-sky conditions.

Self-calibration involves calculation of R_s by applying (1) on a daily (24-h) basis using daily measurements of T_{max} and T_{min} and an initial value for K_r. The estimates are plotted over time for at least one year and are then overlain by calculated clear sky solar radiation, R_{so}. The value for K_r is varied until the highest estimates of R_s contact the R_{so} envelope. The weather data required are daily maximum and minimum air temperature, with humidity, either measured or estimated, used during calculation of R_{so}. The R_{so} envelope represents expected R_s when the sky is free of clouds. Examples of calculations for R_s from (1) and R_{so} over 1-yr periods are shown for nine U.S. locations in Fig. 1.

During calibration, all temperature data should be based on the same averaging interval for maximum and minimum daily values (i.e., instantaneous, 1-min. averages, 1-h averages of measurements). Differences between daily maximum- and minimum-temperature measurements decrease and consequently K_r increases for longer averaging intervals.

R_{so} envelopes have been estimated in various ways (Heerman et al. 1985; Jensen 1990; Allen 1996). The R_{so} envelopes in Fig. 1 were based on a procedure by Majumdar et al. (1972) modified by Allen (1996). This procedure is reproduced in Appendix I. The waviness of the R_{so} curves results from day-to-day changes in the estimated depth of precipitable water in the atmosphere and its attenuation of direct beam solar radiation. The depth of precipitable water can be estimated using dewpoint temperature or minimum daily air temperature (Allen 1996). If possible, the method for calculating R_{so} should be validated for the region using R_s measurements from pyranometers that are traceable to the international standard (National 1992).

If the relationship in (1) is conservative and valid for daily time steps, then the estimation for R_s should not exceed R_{so}. Therefore, self-calibration is accomplished by varying the value for K_r until the upper "surface" of estimated R_s is largely bounded by the R_{so} curve, as shown in Fig. 1 for the nine locations. The fitting is best accomplished using graphical plots as shown in Fig. 1 to interpret and deal with occasional days that may lay above the R_{so} envelope. Some of these points may be due to faulty temperature readings. Some may be due to rare, large differences in maximum and minimum air temperatures, e.g., Fresno in Fig. 1(b) where maximum air temperatures in the data record during 1990 exceeded 40°C during a 5-d period in late July, yet minimum temperatures were low. Because the R_s estimates for this short period were clearly anomalous, this period was ignored during the fitting of K_r. The calibrated K_r can be used for both daily and monthly R_s estimation across a wide range in climates and elevations as shown below.

TESTING THE PROCEDURE

The self-calibration procedure was tested at nine locations within the United States where daily R_s has been measured. The locations were selected to represent a diverse range in climate, latitude and elevation, and included the locations in California, Utah, Ohio, and Florida. Elevations, latitudes, and longitudes are listed in Table 1. The first five locations are typical agricultural weather stations. Locations 6 and 7 are high elevation sites and locations 8 and 9 are near the Pacific Ocean. Data sources were W. O. Pruitt (1986) for Davis; W. Williams (1994) for Gainesville; J. R. Holman (1994) for North Baltimore; R. W. Hill (1996) for La Sal and Park City; and California Irrigation Management Information Services for Fresno, Oceanside, and Santa Barbara.

Several years of data were evaluated for most locations, with one year summarized in figures. Similar values for K_r and similar statistics among years indicate that the same value for K_r is applicable from year to year at the same location. The basic averaging interval for the temperature maximums and minimums was 1 min. at all locations. Humidity measurements were used in the calculation of R_{so}.

Table 1 includes adjustment multipliers that forced the upper surface of measured R_s to match computed clear-sky R_{so} envelopes. This was based on the assumption that there were some clear-sky days at each location and that a single factor could act as a calibration correction for the pyranometer. The corrections assume that the atmospheric transmission model by Majumdar et al. (1972) (6) and resulting clear sky curves are more accurate than the field instrument calibrations. This assumption was subjective, except at Logan where the correc-

TABLE 1. Location Elevation, Latitude, Longitude, and Correction to Measured R_s

Location (1)	Elevation (m) (2)	Latitude (°) (3)	Longitude (°) (4)	Correction to measured R_s (5)
Davis, Calif.	16	38.6	121.7	1.02
Fresno, Calif.	85	36.3	120.1	1.05
Gainesville, Fla.	55	29.6	82.4	1.10
North Baltimore, Ohio	240	41.2	83.7	1.00
Logan, Utah	1,350	41.6	111.8	1.04
La Sal, Utah[a]	2,145	37.5	109.3	1.01
Park City, Utah[a]	2,170	40.7	111.5	1.05
Oceanside, Calif.[b]	15	33.3	111.3 7	1.06
Santa Barbara, Calif.[b]	75	34.5	119.8	1.11

[a]High elevation.
[b]Coastal.

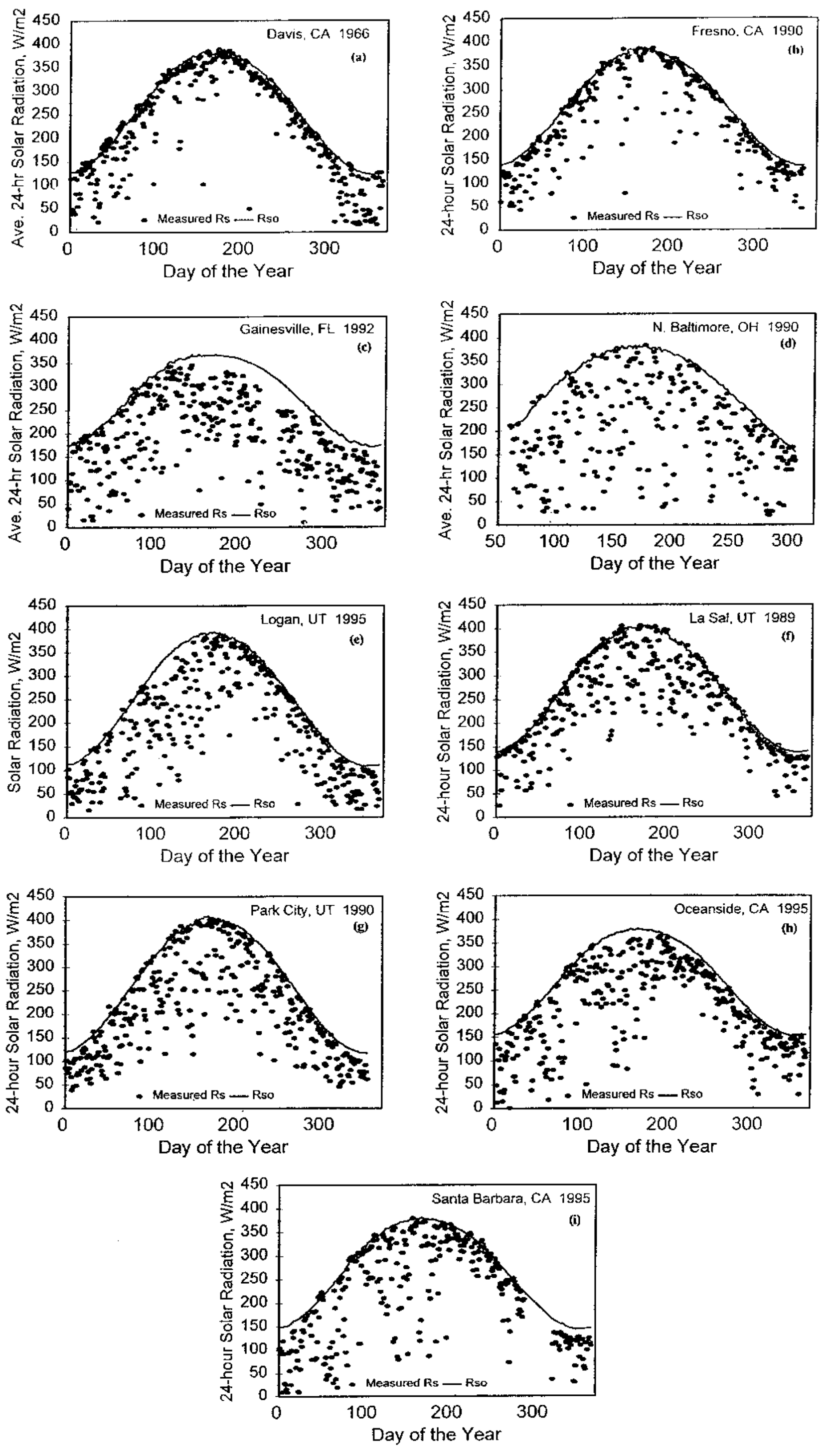

FIG. 2. Measured 24-h Average R_s Adjusted to R_{so} Curve for: (a) Davis; (b) Fresno; (c) Gainesville; (d) North Baltimore; (e) Logan; (f) La Sal; (g) Park City; (h) Oceanside; (i) Santa Barbara

TABLE 2. K_r, Ratios of Estimated R_s to Measured (Corrected) R_s and Standard Errors of Estimate between Estimates and Measurements on Daily and Monthly Time Steps for Self-Calibrating Procedure, Hargreaves Eqs. (1) and (2)

	Self-Calibrating				Hargreaves				$0.17(P/P_o)^{0.5}$			
Subject (1)	K_r (2)	Ratio to measured R_s (3)	Daily SEE (Wm^{-2}) (4)	Monthly SEE (Wm^{-2}) (5)	K_r (6)	Ratio to measured R_s (7)	Daily SEE (Wm^{-2}) (8)	Monthly SEE (Wm^{-2}) (9)	K_r^c (10)	Ratio to measured R_s (11)	Daily SEE (Wm^{-2}) (12)	Monthly SEE (Wm^{-2}) (13)
Davis[a]	0.167	0.95	53	16	0.16	0.91	55	24	0.170	0.97	53	13
Fresno[a]	0.175	1.01	35	13	0.16	0.92	41	23	0.169	0.98	36	14
Gainesville[a]	0.165	1.07	63	18	0.16	1.04	61	14	0.169	1.10	61	22
North Baltimore[a]	0.175	1.10	63	25	0.16	1.01	59	11	0.168	1.06	60	17
Logan[a]	0.150	1.01	39	11	0.16	1.09	42	22	0.157	1.06	41	18
La Sal[a]	0.205	1.01	40	12	0.16	0.78	66	55	0.150	0.73	76	69
Park City[a]	0.190	1.01	45	10	0.16	0.85	57	35	0.149	0.79	66	50
Oceanside[a]	0.160	0.86	59	42	0.19	1.02	47	24	0.170	0.92	53	33
Santa Barbara[a]	0.180	0.91	56	35	0.19	0.95	51	27	0.170	0.85	63	44
Oceanside[a]	0.160[d]	0.95	46	21							-	
Santa Barbara[a]	0.180[d]	0.96	50	23								
Mean[b]	0.175	1.0	48	15	0.16	0.95	53	26	0.162	0.96	56	29
Standard deviation[b]	0.015	0.05	11	5	0.00	0.10	9	13	0.009	0.13	13	20
COV[b] (%)	8.7	4.7				10.4				13.8		

[a]Location.
[b]Without Oceanside and Santa Barbara.
[c]$K_r = 0.17(P/P_o)^{0.5}$.
[d]K_r used for September–April period, with May–August $K_r = 0.20$.

tion (1.04) matched R_s from a precision instrument calibrated against the national standard (National 1992), and is based on observation of incorrect calibrations being used in several large agricultural weather networks (Allen 1996). The statistical results of the total analysis would have been the same if the uncorrected R_s data had been used instead to adjust the R_{so} envelopes by fitting the clarity coefficient, K_{tb} in (6). This latter practice would simulate regional calibration of the R_{so} procedure. Allen (1996) concluded that R_{so} computed following Majumdar et al. (1972) was more correct, on average, then agricultural network pyranometers. Corrected measured R_s is plotted in Fig. 2 for the nine locations.

Estimates of R_s from (1) using the self-calibrated K_r were compared to adjusted measured R_s by calculating a standard error of estimate (SEE) computed as:

$$\mathrm{SEE} = \left(\frac{\sum (\hat{R}_s - R_s)^2}{n - 1} \right)^{0.5} \tag{3}$$

where $\hat{R}_s$ = estimated solar radiation from (1); R_s = adjusted measured solar radiation; and n = number of observations. Eq. (3) was applied with both daily and monthly data.

RESULTS

Comparing the estimated R_s versus time (Fig. 1) with measured R_s versus time (Fig. 2) indicates considerable similarity in the distribution of and variation in daily R_s. Semiarid regions, where skies were often clear, exhibited more variation in estimated R_s and more deviation from R_{so} curves relative to measured values. The $T_{max} - T_{min}$ procedure was unable to exactly predict clear-sky conditions.

K_r values from the self-calibration are listed in Table 2 along with mean ratios of estimated R_s to adjusted measured R_s. Ratios were usually the same for daily and monthly computation time steps, and, with the exception of Oceanside and Santa Barbara, ranged from 0.95 to 1.10, averaging 1.0. The coefficient of variation among ratios was 5%, indicating that the self-calibrations were relatively accurate over the range of climates and elevations. The SEE for daily values without the two coastal locations averaged 48 W m^{-2}, whereas the SEE for monthly values averaged 15 W m^{-2}.

TABLE 3. Percent Difference of Self-Calibrated K_r from Hargreaves Coefficients (0.16 Inland and 0.19 Coastal) and of Estimates from Corrected Measurements

Location (1)	Percent difference from Hargreaves (2)	Percent difference from measured (3)
Davis	4	−5
Fresno	9	1
Gainesville	3	7
N. Baltimore	9	10
Logan	−6	1
La Sal	25	−2
Park City	19	1
Oceanside	−5[a]	−5
Santa Barbara	3[a]	−4

[a]Based on an average of the K_r's required for September–April and for May–August.

Values for K_r ranged from 0.15 at Logan to 0.20 at La Sal, Utah. Differences from the constants proposed by Hargreaves (0.16 for inland locations and 0.19 for coastal locations) are listed in Table 3 and ranged from −6% at Logan up to 25% at La Sal. The average SEE for daily estimates was reduced from 53 to 48 W m^{-2} and the average SEE for monthly estimates was reduced from 26 to 15 W m^{-2} by the self-calibration relative to the fixed constants. The estimates for the two subhumid stations in the eastern United States (Gainesville and North Baltimore) were less accurate following the self-calibration than were the constants proposed by Hargreaves; the self-calibration tended to overestimate K_r for these locations by 7–10%. These comparisons assume that the R_{so} curves generated using Appendix I are accurate.

When (2) was used to estimate K_r based on mean atmospheric pressure, the results were less accurate at the high elevation sites of La Sal and Park City; both daily and monthly R_s were underestimated by 27 and 21%. Although the reasoning is correct that the volumetric heat capacity of the atmosphere decreases with elevation and results in a greater change in temperature for a given heat input, the actual amounts of R_s arriving at the surface at altitude are greater because less atmosphere intercepts R_a. Therefore, R_s (and R_{so}) may increase more rapidly than does $(T_{max} - T_{min})^{0.5}$ resulting in an increase in K_r with elevation. At the lower elevation sites, K_r from (2) produced results similar to the self-calibration method and using (1) with K_r from Hargreaves (1994).

Daily R_s from the self-calibration are plotted against measured R_s in Fig. 3. These figures indicate the accuracy of daily estimates. In general, the R_s estimates corresponded with measured R_s, with substantial scatter, especially in the two eastern (subhumid) U.S. locations.

Monthly R_s estimated with monthly average values for T_{max} and T_{min} are plotted against measured R_s in Fig. 4. There was much less scatter than with daily estimates, indicating good accuracy when self-calibrated K_r is used to predict monthly R_s. The linear relationship with measured R_s indicates validity of (1) during winter, spring, summer and fall periods. The coastal locations Oceanside and Santa Barbara required K_r that changed seasonally (September–April and May–August), as described in Table 2 and in the following section.

LOCATIONS INFLUENCED BY OCEAN

Oceanside and Santa Barbara, California, were special cases, i.e., a single value for K_r did not bring R_s estimates up

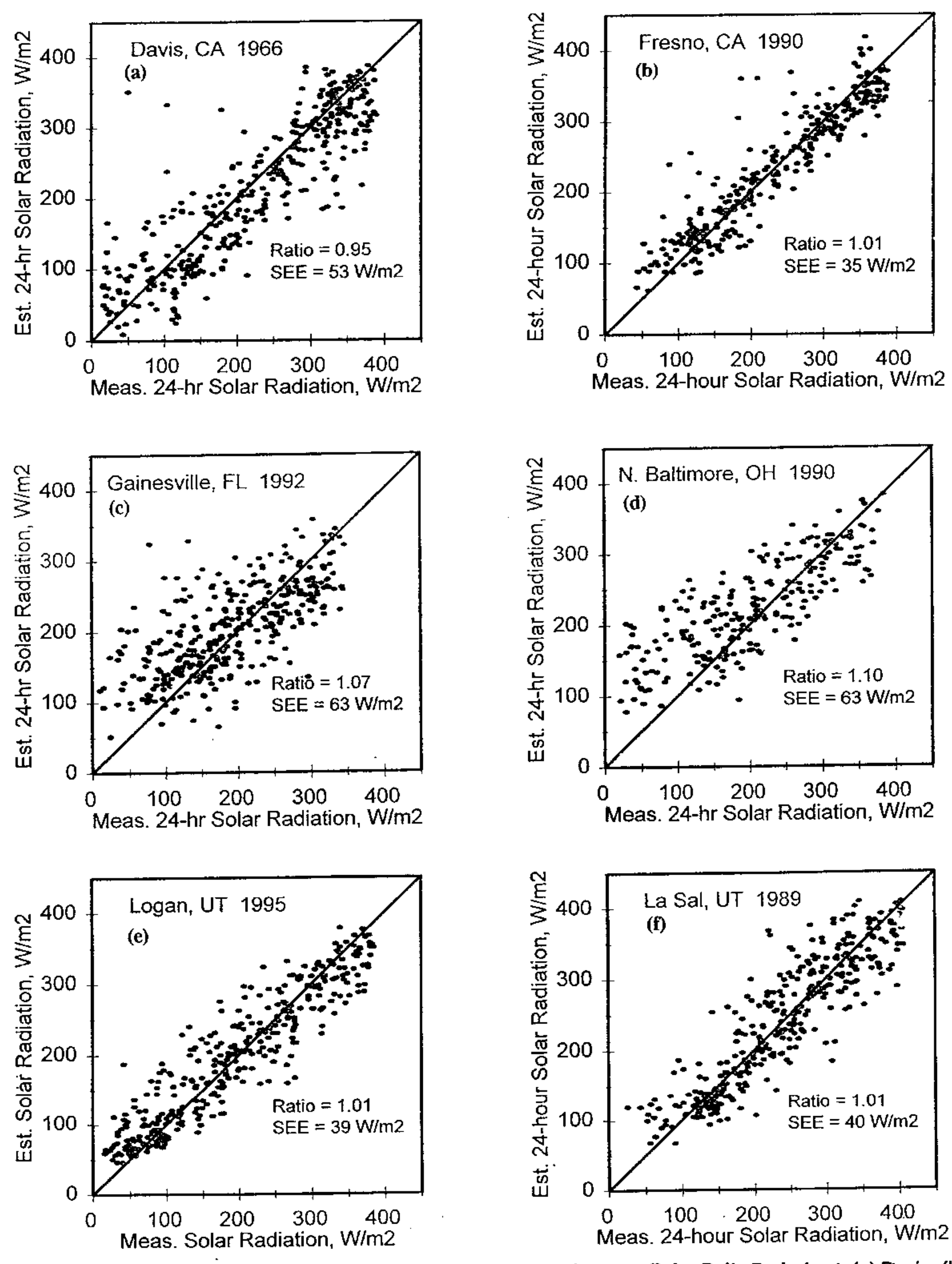

FIG. 3. 24-h Average R_s from Self-Calibrated Eq. (1) versus Measured 24-h Average R_s for Daily Periods at: (a) Davis; (b) Fresno; (c) Gainesville; (d) North Baltimore; (e) Logan; (f) La Sal; (g) Park City; (h) Oceanside; (i) Santa Barbara

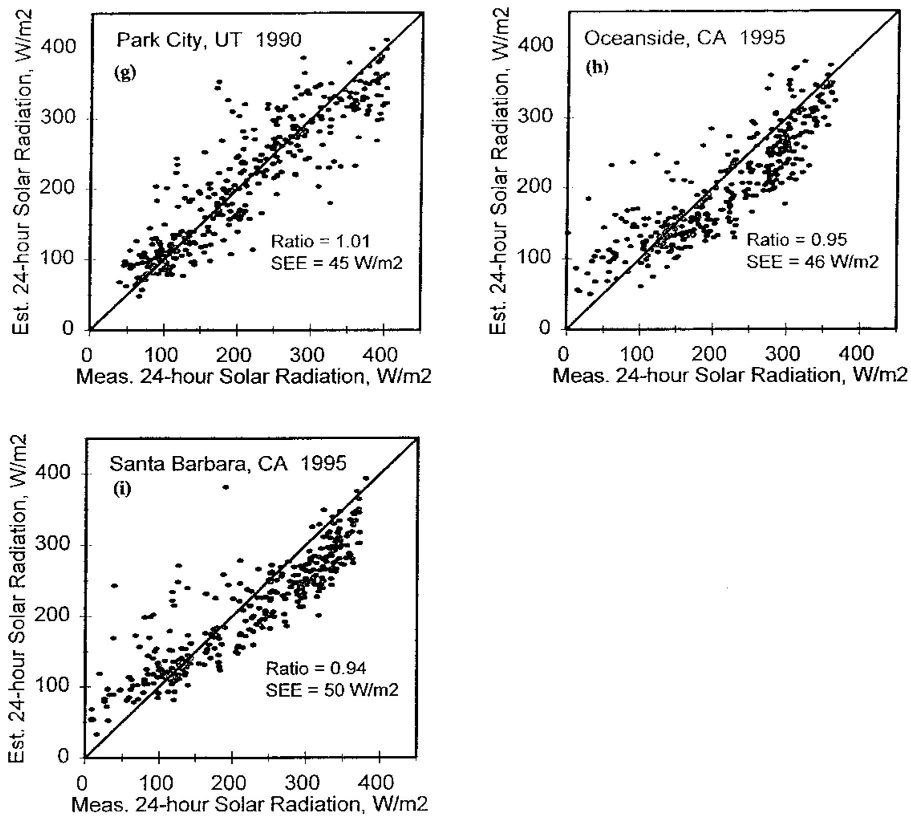

FIG. 3. *(Continued)*

to the R_{so} envelope for the entire year. During the summer, a higher value for K_r, similar to the value 0.19 proposed by Hargreaves for coastal locations, was required, whereas, a lower value for K_r was required for the other seasons. This is apparent when comparing Fig. 5(a) and (b) with Fig. 1(h) and (i), where Fig. 1(h) and (i) used only a single value for K_r.

Weather data were investigated to determine if K_r changed with wind direction and whether prevailing winds came from inland or from the ocean during summer. When $K_r = 0.16$ was applied to days when the predominant wind direction was from inland and $K_r = 0.20$ was applied to days when the predominant direction was from the ocean, R_s was overestimated for many days during fall, winter and spring when winds were from the ocean, as shown in Fig. 6. This was especially true for Oceanside, where $K_r = 0.16$ was required to fit measurements even when winds were from the ocean. Therefore, K_r was less correlated with fetch of wind than with season and frequency of low-altitude cloud banks near the ocean. Splitting the self-calibration into two parts was relatively straightforward, provided that the assumption was made that there were some days during the summer season when skies were cloudless.

COMMENTS ON INDIVIDUAL LOCATIONS

Davis and Fresno, California

Davis and Fresno had an exceptionally large number of clear-sky days [Figs. 2(a)–(b)]. R_s during a number of these clear sky events was difficult to predict. However, predictions were for the most part clustered near the R_{so} envelope [Figs. 1(a)–(b)] and are reasonable, even on a daily basis, as indicated by the scatter plots in Figs. 3(a)–(b).

Gainesville, Florida

Gainesville had many cloudy days throughout the year and especially during summer months, where few clear days were recorded between days 150 and 290 [Fig. 2(c)]. The self-calibrated (1) reproduced trends in the daily data and replicated the cloudy period noted in the measurements. However, many of the predictions on days with the lowest R_s measurements were higher than measured, producing more scatter in Fig. 3(c) as compared to Fig. 3(a) and (b).

North Baltimore, Ohio

North Baltimore had many days when measured R_s values were much lower than predicted daily R_s values [Fig. 2(d)], which raised the monthly averages of estimated R_s enough so that the self-calibrated (1) overestimated monthly R_s by 10%. However, many values for measured daily R_s are below the 0.25 R_a minimum threshold (approximately 0.32 R_s) predicted by most sunshine hour equations under full cloud cover (Doorenbos and Pruitt 1977). Therefore, these lower values would have to represent extremely dark skies over a complete daylight period. If these measurements are not valid, the self-calibration probably was more accurate than indicated by the statistics in Table 2. Only data for days 60–300 were available for North Baltimore.

Logan, Utah

Compared to measured values [Fig. 2(e)], the self-calibration and application of (1) at Logan reduced the daily variation in R_s during the winter and spring [Fig. 1(e)]. There were few high (clear-sky) and low R_s values during this period. After the summer solstice, R_s on clear-sky days was accurately predicted.

La Sal and Park City, Utah

Estimates with the self-calibrated (1) were relatively accurate at these high-elevation sites especially on clear days. R_s on very cloudy days was generally too high, although monthly estimates were accurate.

Oceanside and Santa Barbara, California

Daily R_s during late spring and early summer was substantially underpredicted by (1) at Oceanside when only a single K_r was used for the entire year [Fig. 1(h)]. However, estimates improved when a separate K_r value was self-calibrated for May-August (Fig. 5). Estimates and self-calibration at Santa Barbara did not require a second K_r value as much as at Oceanside, but the additional coefficient slightly improved estimates. Estimated values for R_s on days with very low R_s/R_a

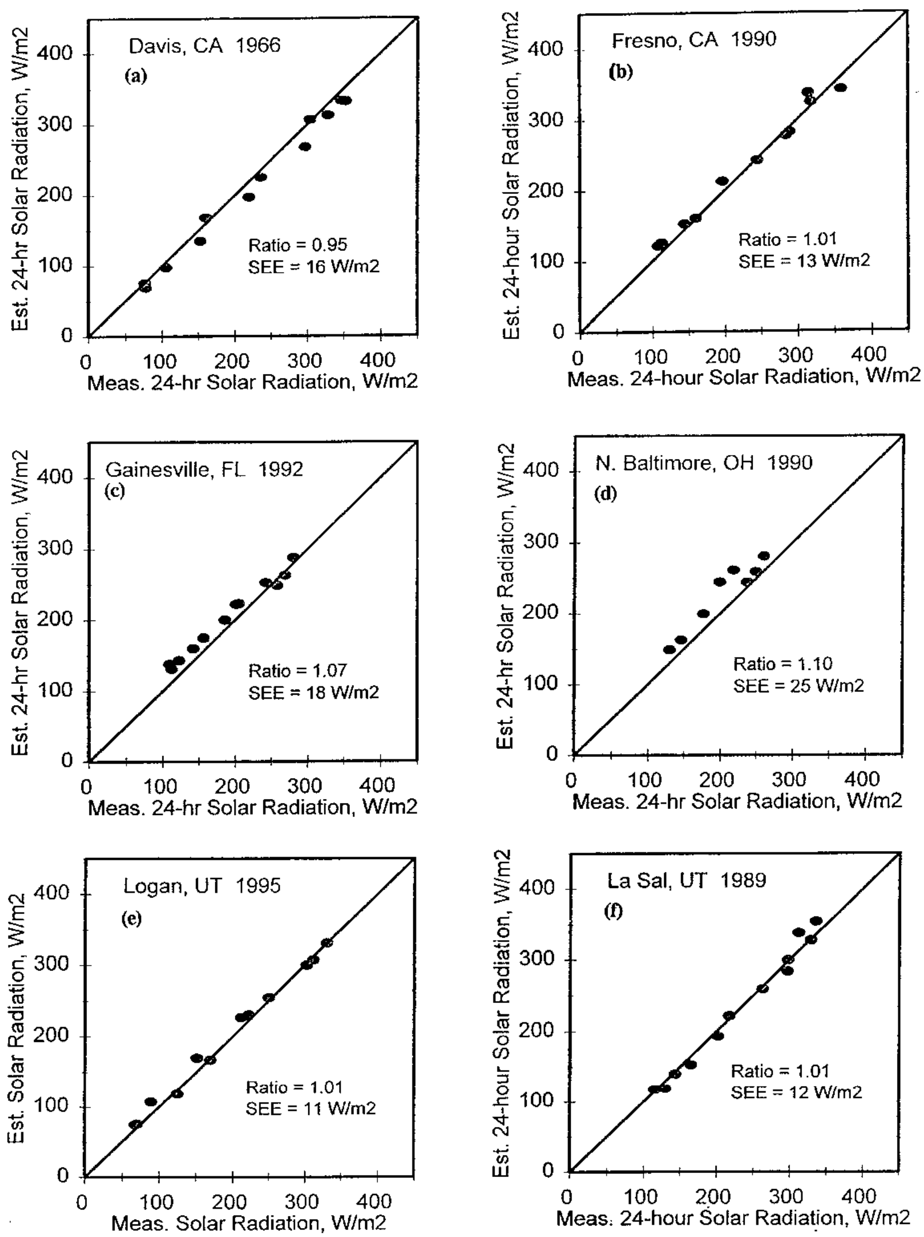

FIG. 4. R_s from Self-Calibrated Eq. (1) versus Measured R_s for Monthly Periods at: (a) Davis; (b) Fresno; (c) Gainesville; (d) North Baltimore; (e) Logan; (f) La Sal; (g) Park City; (h) Oceanside; (i) Santa Barbara

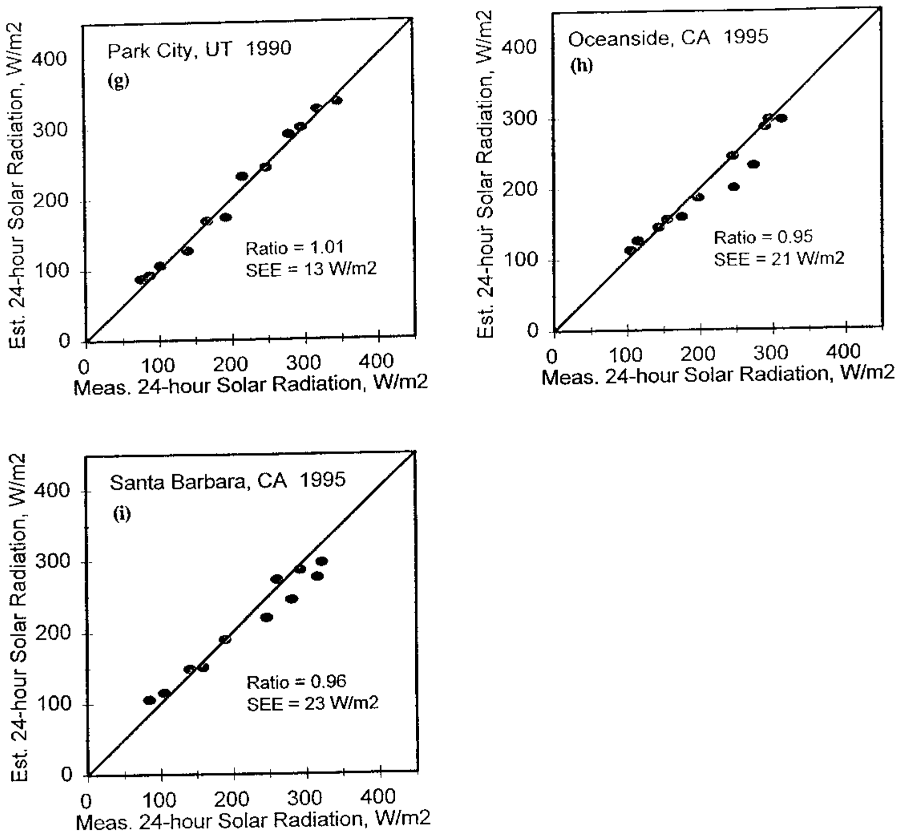

FIG. 4. ***(Continued)***

were too large, similar to the results at the Florida and Ohio sites.

COMPARISON WITH USING R_s/R_a FROM NEARBY STATION

R_s data were available for the same year for La Sal and Park City, Utah, (high-elevation sites) and for Oceanside and Santa Barbara, Calif. (coastal sites). La Sal and Park City are located 340 km (210 mi) apart and Oceanside and Santa Barbara are located 270 km (170 mi) apart, well beyond the 30 km suggested by Hubbard (1994) for daily estimates. R_s was predicted by multiplying R_s/R_a computed daily or monthly at one station by R_a for the same day or month at the neighboring station. Ratios of R_s/R_a were used, rather than R_s only, to account for differences in sun angle and day length between locations.

Estimates using the regional R_s/R_a approach are shown in Fig. 7 for La Sal, Utah, with (a) based on R_s/R_a at Park City, and for Oceanside, Calif., and (b) based on R_s/R_a at Santa Barbara. The estimated daily R_s tended to follow a 1:1 line, but with substantial scatter. Standard errors of estimate were 57 and 58 W m^{-2}, higher than the 40 and 46 W m^{-2} obtained using the self-calibrated (1). R_s during clear periods was estimated fairly accurately, especially at Oceanside, but R_s during periods of cloudiness was not. The paired stations were too distant to consistently have the same R_s/R_a ratios on the same day, so that the self-calibrated (1) provided superior results.

Monthly R_s estimated using the regional R_s/R_a approach is shown in Fig. 8 for La Sal, with (a) based on R_s/R_a at Park City, and for Oceanside, and (b) based on R_s/R_a at Santa Barbara. In both cases, there was little deviation from measurements. Standard errors of estimate were 17 and 14 W m^{-2}, compared to 13 and 21 W m^{-2} with the self-calibrated (1). For monthly time steps, using R_s/R_a from a similar, neighboring weather station within about 400 km and using the self-calibrated (1) both resulted in accurate predictions.

SUMMARY AND CONCLUSIONS

Procedures were introduced to self-calibrate an equation used to estimate solar radiation using maximum and minimum air temperature and extraterrestrial radiation. The self-calibration is based on computed solar radiation on cloudless days. The resulting calibration can be used to predict both daily and monthly R_s. The method was tested at nine locations in the United States representing low, medium, and high elevations, semi-arid and subhumid climates and ocean locations.

The self-calibration procedure was generally accurate over a wide range of climates and elevations, especially when predicting monthly R_s. Prediction of daily R_s was less accurate, but tended to follow actual R_s. The self-calibration procedure has about the same accuracy on a monthly basis as obtained using a nearby regional station that is within about 400 km and was more accurate than using R_s/R_a from regional stations on a daily basis when the regional stations were about 300 km distant. It appears that a single value for K_r can be used to predict R_s for an entire year, with the exception of coastal areas where estimates were improved when K_r was determined separately for two different portions of the year.

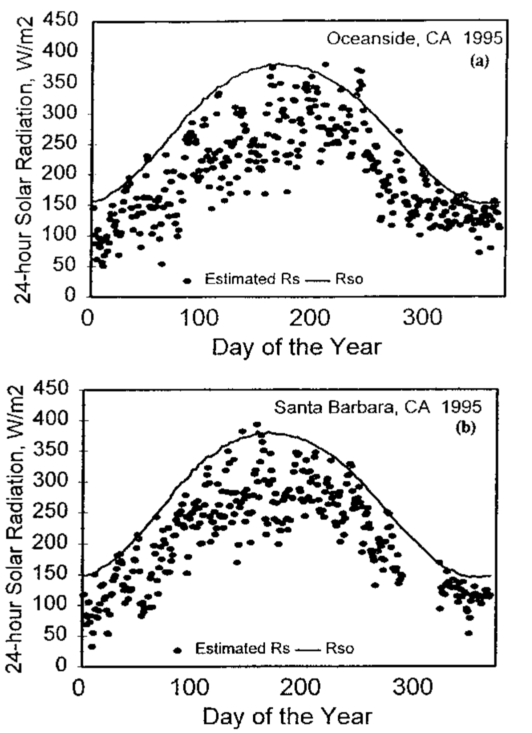

FIG. 5. 24-h Average R_s from Self-Calibrated Eq. (1) Using Two Seasonal Values for K_r (September–April and May–August) for: (a) Oceanside; (b) Santa Barbara

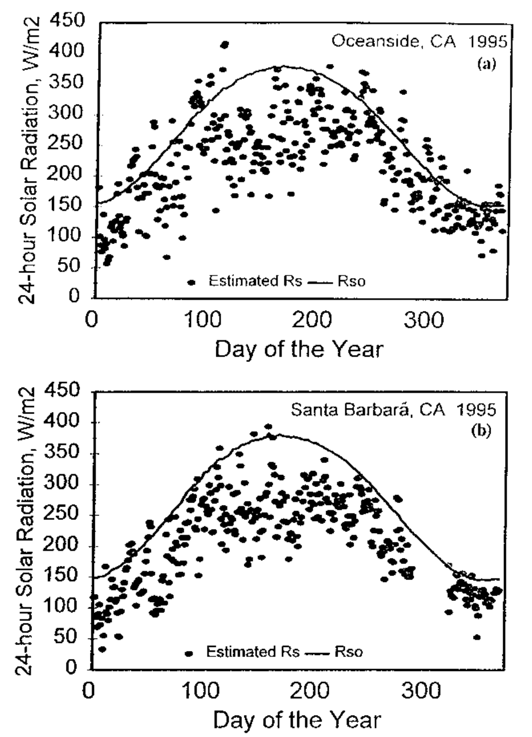

FIG. 6. 24-h Average R_s from Self-Calibrated Eq. (1) Using Two Values for K_r Based on Wind Direction for: (a) Oceanside; (b) Santa Barbara

The self-calibration procedure was more accurate than fixed calibration coefficients suggested by Hargreaves (1994) and Allen (1995a, 1996), especially at semi-arid and high elevation sites. The procedure was more accurate and valid than an atmospheric-pressure–based method proposed by Allen (1995a, 1996). The latter method (2) is no longer recommended. Standard errors of 30 to 60 W m^{-2} can be expected when using the self-calibration procedure for daily R_s and standard errors of 10 to 25 W m^{-2} can be expected when using the self-calibration procedure to estimate monthly R_s. Mean prediction accuracy was within 5% in the majority of cases.

The self-calibration method requires only daily maximum and minimum air temperature data and is simple and conservative (it is constrained by computed clear sky solar radiation curves). The method should be useful in estimating evapotranspiration in hydrologic and agricultural applications. Estimation errors in daily R_s predictions would dampen out and prediction accuracy would improve in applications where ET is used in daily soil water balance computations where the soil water reservoir acts as a buffer.

In locations having precipitation records, the accuracy of R_s may be further improved by including correlations with precipitation. This was not evaluated in this study and would not have affected the general approach of self-calibration, especially for days having no precipitation. Others have added precipitation or "wet" days into R_s prediction models (Walker et al. 1995). This tactic warrants additional analysis.

ACKNOWLEDGMENTS

This research was supported by the Utah Agricultural Experiment Station, Utah State University, Logan, Utah 84322-4810 and approved as journal paper no. 96-91-HE. Acknowledgment is given to George Hargreaves, Professor-emeritus at Utah State University, for pioneering work in this area and for stimulating the work in the present study. Kurt Gutknecht, editor for the Utah Agricultural Experiment Station, improved the clarity of the manuscript.

APPENDIX I. CLEAR-SKY SOLAR RADIATION

Global solar (short wave) radiation ($0.3 - 3 \times 10^{-6}$ m wavelength) under clear-sky conditions (R_{so}) and incident to a horizontal plane can be computed as

$$R_{so} = K_T R_a \tag{4}$$

where R_a = extraterrestrial radiation; and K_T = transmission index. R_a is a function of latitude and day of the year. Calculation procedures by Duffie and Beckman (1980, 1991) are included in Allen et al. (1989, 1994, 1996) and Jensen et al. (1990). For 24-h data, K_T may range from 0.7 to 0.8, depending on atmospheric clarity (dust, pollution, humidity, etc.), elevation and sun angle.

Majumdar et al. (1972), Boes (1981), Allen (1996) and others have estimated K_T as the sum of transmission coefficients for beam and diffuse radiation:

$$K_T = K_B + K_D \tag{5}$$

where K_B = transmission coefficient for direct beam radiation (short wave radiation flux density coming directly from sun's beam) incident to a plane parallel to earth's surface; and K_D = transmission coefficient for diffuse short wave radiation (short wave radiation flux density coming from scattered sunlight).

Some absorption and scattering of direct beam radiation is caused by water vapor. Therefore, transferability of K_T functions are improved when precipitable water is a variable in the extinction function for direct beam radiation. A function proposed by Majumdar et al. (1972) and Boes (1981) and modified by Allen (1996) is

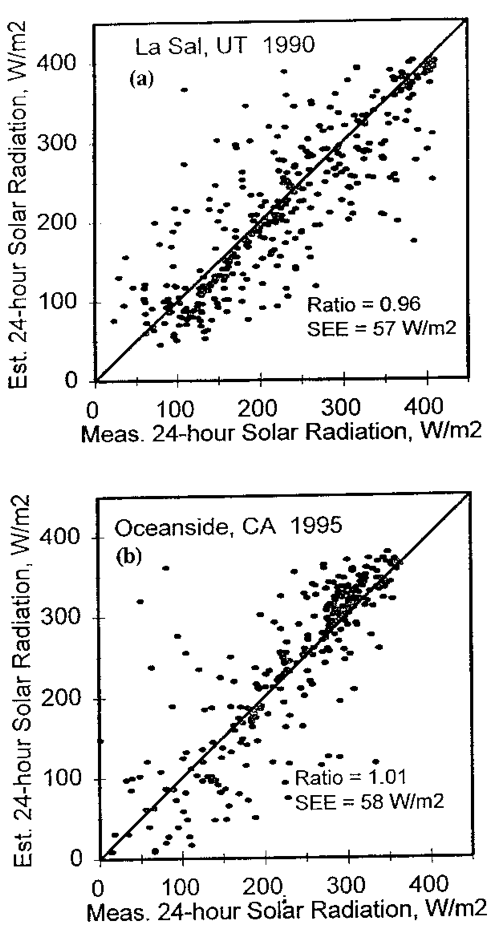

FIG. 7. 24-h Average R_s at: (a) La Sal Estimated Using Measured R_s/R_a at Park City; (b) Oceanside Using Measured R_s/R_a from Santa Barbara

$$K_B = 0.98 \exp\left[\frac{-0.00146P}{K_{tb}\sin\phi} - 0.091\left(\frac{W}{\sin\phi}\right)^{0.25}\right] \quad (6)$$

where P = atmospheric pressure (kPa); W = precipitable water in atmosphere (mm); K_{tb} = clarity coefficient; and ϕ = angle of sun above horizon (solar altitude) (rad). Generally, $0.5 < K_{tb} \leq 1.0$, where $K_{tb} = 1.0$ for clean air and K_{tb} = about 0.5 for extremely turbid or dusty air. K_{tb} is usually taken as 1.0 to predict the upper limit on K_T for agricultural areas and was the value used in the present study. W is approximated using an equation by Garrison and Adler (1990)

$$W = 0.14e_dP + 2.1 \quad (7)$$

where e_d = vapor pressure near surface (kPa); and W is in mm.

The diffuse radiation transmission index, K_D, is estimated from K_B using expressions by Allen (1996) that were based on work by Boes (1981)

$$K_D = 0.35 - 0.33K_B \quad \text{for } K_B \geq 0.15 \quad (8a)$$

$$K_D = 0.18 + 0.82K_B \quad \text{for } K_B < 0.15 \quad (8b)$$

When applying (6) for 24-h time steps, mean 24-h solar altitude, weighted according to instantaneous R_a, is calculated following Allen (1996) as

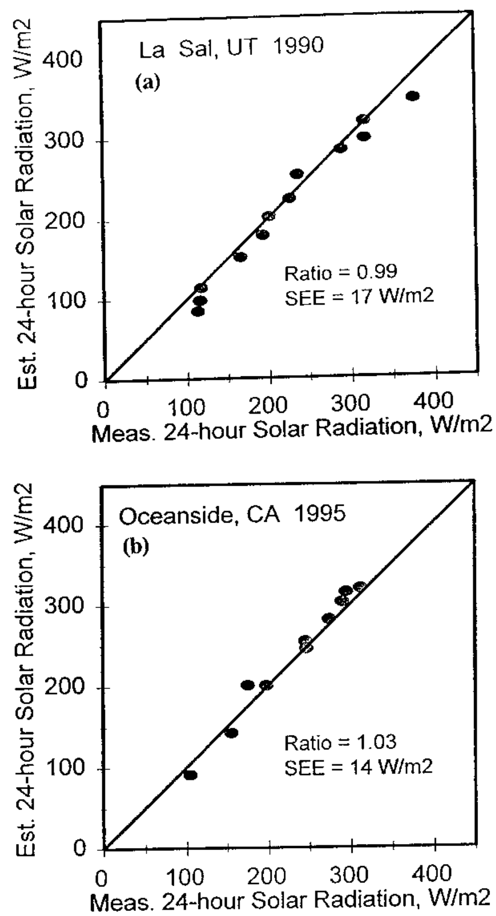

FIG. 8. Monthly Average R_s at: (a) La Sal Estimated Using Measured R_s/R_a at Park City; (b) Oceanside Using Measured R_s/R_a from Santa Barbara

$$\phi = 0.85 + .3\varphi \sin\left(\frac{2\pi}{365}D - 1.39\right) - 0.42\varphi^2 \quad (9)$$

where D = day of year (1 to 366); and φ = latitude in radians. Calculation of instantaneous or hourly ϕ is given in Duffie and Beckman (1980, 1991), Allen et al. (1989, 1994, 1996), and Jensen et al. (1990).

A once-per-day humidity reading can be used to estimate W when investigating hourly and 24-h data, since e_d and precipitable moisture in the atmosphere do not normally change substantially during the course of a day. When humidity data are lacking, e_d can be approximated as the saturation vapor pressure at minimum daily air temperature (T_{min}), although the accuracy of the R_{so} estimate will degrade slightly.

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