EVALUATION OF SOLAR RADIATION ESTIMATION PROCEDURES FOR EASTERN SOUTH DAKOTA

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ABSTRACT

Cloudiness observation and maximum and minimum air temperature based methods were used to estimate solar radiation for Brookings and Huron, SD venues. The cloud-based method can be used as a first approximation for estimation of daily solar radiation (standard error of estimates were 3.3 and 6.0 MJ/m2 for Brookings and Huron, respectively). An air temperature methodology had limited utility for time periods of less than seven days.

Keywords

Solar radiation, estimation, cloudiness, air temperature

INTRODUCTION

Solar radiation is the primary energy source used for the evapotranspiration of water from an irrigated crop (Jensen and Haise, 1963). Hence, the availability of solar radiation data is a key to the development of reliable irrigation scheduling programs. Solar radiation data sets are scare in South Dakota as Brookings is the only location having a continuous, long-term record initiated in 1962. Automatic weather stations maintained by South Dakota State University are distributed throughout the State (Figure 1) but have incomplete records going back to the early 1980s for a few sites. Currently the National Oceanic and Atmospheric Administration (NOAA) maintains a data set of sky cover or cloudiness conditions at Aberdeen, Huron, Rapid City and Sioux Falls. There is an interest in

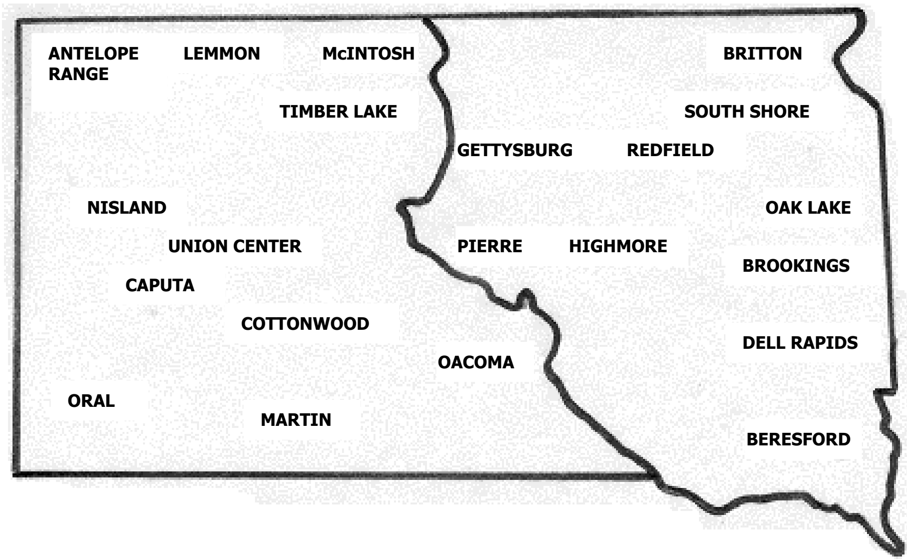

Figure 1. Locations of automatic weather data network (AWDN) stations collecting solar radiation and other climatic data in South Dakota. Contact the Climatologist Office at SDSU for data sets and more details.

the utilization of all available data that can be used to enhance the geographical distribution of solar radiation data sets for South Dakota.

Two indirect methods have been proposed in the literature to estimate solar radiation from climatic data. The first uses cloudiness observations to estimate daily solar radiation and the second employs maximum and minimum daily air temperatures as a basis for radiation estimates. The objective of this paper is to evaluate the adequacy of using the two indirect methods to estimate solar radiation for eastern South Dakota climatic conditions.

METHODS

A procedure similar to that presented by Doorenbos and Pruitt (1977) was used to estimate solar radiation from cloudiness observations. Solar radiation at the surface of the earth is a function of extraterrestrial radiation and the transmission of that radiation through the atmosphere, which is largely dependent upon cloud cover. Doorenbos and Pruitt developed an equation that can be used to convert cloudiness observations to solar radiation.

$$Rs = (0.25 + 0.5*n/N)*Ra \qquad [1]$$

where Rs is solar radiation at the surface of the earth, MJ/m^2 (1 Langley = 0.04187 MJ/m^2)

n/N is the ratio of actual bright sunshine hours to maximum possible sunshine hours

Ra is extraterrestrial radiation, MJ/m^2

Cloudiness observations were recorded, using a scale of zero to ten, which were then converted to n/N values in accord with a procedure proposed by Doorenbos and Pruitt (Table1). It is preferable to use locally derived constants in Equation 1 but such an analysis has not been completed for the Brooking site.

Table 1. Factors used to convert cloudiness observations to n/N values.

Cloudiness	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
n/N value	0.95	0.85	0.80	0.75	0.65	0.55	0.50	0.40	0.30	0.15	0.00

Extraterrestrial radiation is only dependent on latitude and time of the year. Integration of irradiance received at the top of the atmosphere for a given time period is given by Duffie and Beckman (1980) as:

Ra = {12*3600*Gsc*[1.0 + 0.33*cos(360*n/365)]/Pi} *
cos(Phi)*cos(Del)*[sin(Omega2) - sin(Omega1)] +
2*Pi*(Omega2 - Omega1)*sin(Phi)*sin(Del)/360 .... [2]

where Ra is extraterrestrial radiation, Joules/m^2
Gsc is the solar constant, 1353 Watts/m^2
n is the Julian date
Phi is latitude, degrees
Del is the declination of the sun, degrees
Omega1 and Omega2 are the angles of the sun from solar noon, degrees (Figure 2).

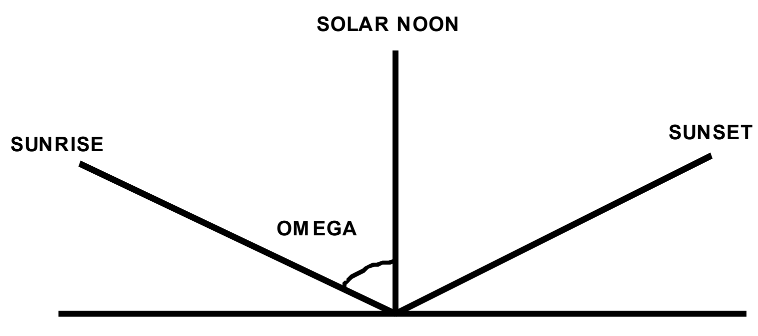

Figure 2. Sunrise solar angle relative to solar noon.

Personnel in the Department of Agricultural and Biosystems Engineering at South Dakota State University recorded cloudiness observations three times per day, morning (8 am) noon, and late afternoon (4 pm) at a Brookings, SD venue. Each day was subdivided into three equal segments and each cloudiness observation was assumed to be representative of the corresponding segment. Daily solar radiation was also measured with an Eppley pyranometer at the Brookings site.

Parameters of Equation 2 were defined as a function of time. Duffie and Beckman (1980) give the declination of the sun as

Del = 23.45*{sin(360 * (284 + n))/365} ....[3]
Declination of the sun constantly changes with time, however the assumption of a constant value for a day produces a negligible error.

Duffie and Beckman (1980) define the hour angle of the sun at sundown as

N = arc cos {-tan(Phi)*tan(Del)} ....[4]

It follows that the hour angle of the sun at sunrise is the negative of the hour angle at sundown. Since Omega1 and Omega2 are defined as the hour angles of the sun for the period of interest, Equation 4 was used to define these parameters as a function of time.

The foregoing equations were incorporated into a PC computer spreadsheet. A six-year data set (1972-1974, 1982-1984) for the months of June, July and August were used in the analysis for calibration purposes. Only dates with three cloudiness observations were included in the data set which caused the removal of about one half of the dates. Cloudiness observations were used to estimate total solar radiation for each date. A second five-year (1985-1987, 1990-1991) independent data set was used for evaluation purposes.

A second venue at Huron, SD was also used for evaluation purposes. Airport personnel collected cloudiness and measured daily solar radiation with a Li-Cor pyranometer during June, July and August of 1991 and 1992.

Air temperatures have also been used as a basis for estimation of solar radiation. Hargreaves and Samani (1982) developed an empirical relationship for this purpose.

Rs = Kt*Ra*$TD^{0.5}$ ....[5]

where Rs is global solar radiation, MJ/m^2

Kt is a calibration coefficient

Ra is extraterrestrial radiation, MJ/m^2

TD is air temperature difference (Tmax - Tmin), degrees C

Daily maximum and minimum air temperature data (NOAA) along with solar radiation data values from the calibration data set were used to determine calibration constants, Kt values, on a daily basis. Daily values were then averaged over seven-day periods to obtain weekly values. Calibration constants were used with air temperature data to generate independent estimates of daily and weekly solar radiation values for comparison purposes. Note that equation 5 was originally developed for the estimation of long-term values such as mean monthly radiation values.

RESULTS AND DISCUSSION

Cloudiness-Based Procedure

A linear regression relationship was developed for the daily measured and estimated solar radiation data based on cloudiness observations for the calibration data set (Figure 3). Three hundred and fifty four daily values were used to develop the following mathematical relationship

MEAS = -1.27 + 0.943*EST ....[6]

where MEAS is a measured daily solar radiation value, MJ/m^2

EST is an estimated daily solar radiation value based on cloudiness observations, MJ/m^2

The relationship with an R^2 value of 0.71 and a standard error of estimate of 3.1 MJ/m^2 can now be used to make predictions of future daily solar radiation values if cloudiness data sets are available to make EST values.

An independent data set consisting of 204 daily values was used to evaluate the adequacy of Equation 6 for prediction purposes at the Brookings site (Figure 4). The data have a similar scatter to those in Figure 3 but tend to center about the line of equality (1:1 line) with a standard error of estimate of 3.3 MJ/m^2, similar to the Equation 4 value. A trendline relationship representing the data in Figure 4 has the following form

PRED = 5.10 + 0.720*MEAS ....[7]

where PRED is a predicted daily solar radiation value based on cloudiness observations and Equation 6, MJ/m^2

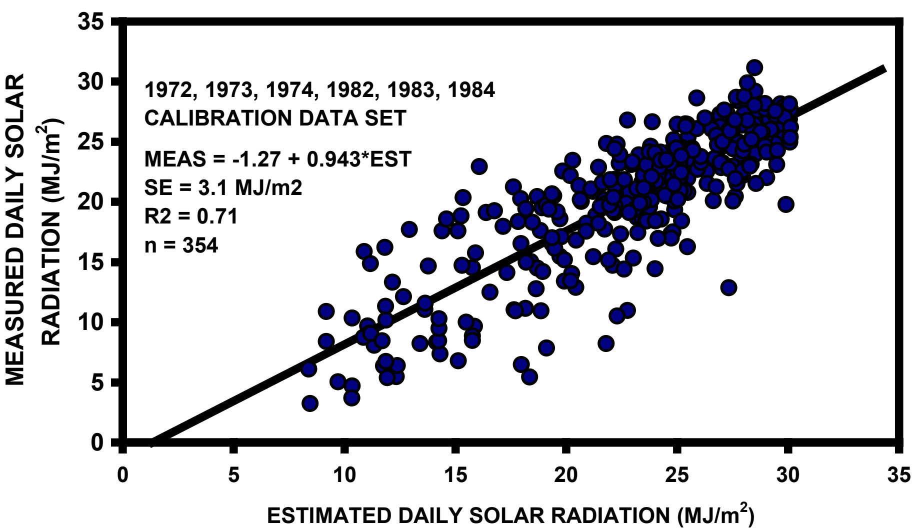

Figure 3. Measured versus estimated daily solar radiation for the calibration data set at Brookings, SD.

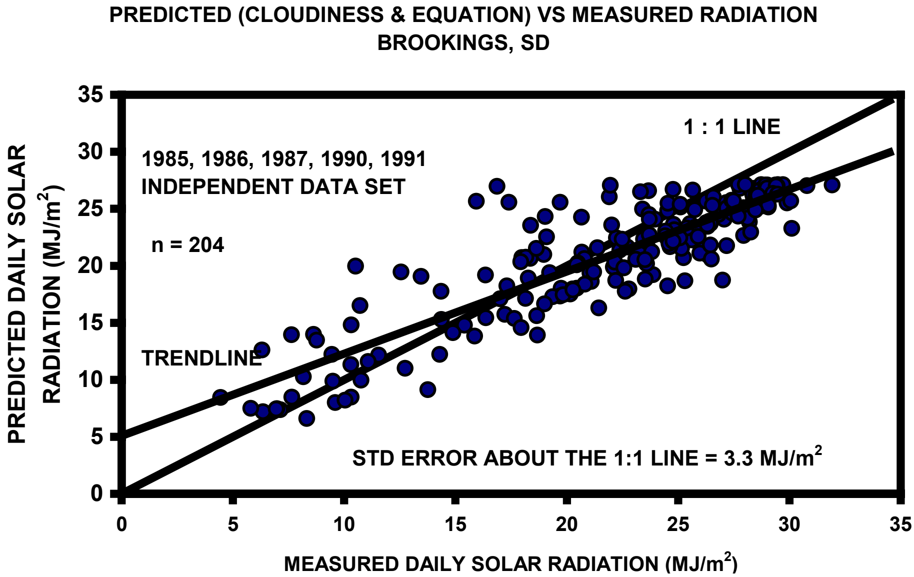

Figure 4. Predicted (based on cloudiness observations and a calibration equation) versus measured daily solar radiation values for an independent data set at Brookings, SD.

Equation 7 indicates that the proposed prediction procedure produced values that were too large for the cloudiest days (small measured values) and tended to be too small for the clear days with the most solar radiation.

The same procedure was used to make predictions for the Huron site using the independent Huron data set (Figure 5). It is readily apparent that the proposed prediction procedure produces daily radiation values that are smaller than measured values as most of the plotted values are below the line of equality (1:1 line). The standard error of estimate for the line of equality is 6.0 MJ/m^2. A trendline relationship for the data values in Figure 5 is as follows

PRED = -0.300 + 0.784*MEAS ....[8]

with a standard error of estimate of 3.1 MJ/m^2 and an R^2 of 0.73. The intercept is about zero, which is desirable, but the slope of the line shows an under prediction for all daily values. Again there is a rather large spread in the plotted data which indicates that the estimation and prediction procedures are marginally accurate.

The proposed prediction procedure did a better job for the independent Brookings data set than for the Huron data set. One possible reason is that those making the cloudiness observations at the two venues were different people. There is an element of subjectivity relating to the visual interpretation of a given cloudiness condition. Hence it would be recommended that each venue data set would contain a calibration period before the cloudiness observations would be used for prediction purposes. Another possible reason for the differences is that two different solar sensors were used at the two venues, but both were checked

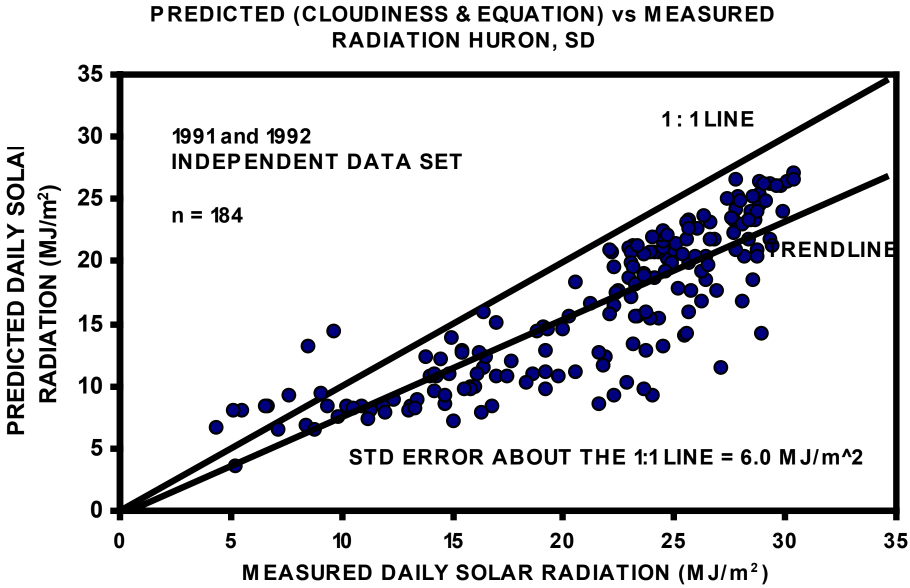

Figure 5. Predicted (based on cloudiness observations and a calibration equation) versus measured daily solar radiation values for an independent data set at Huron, SD.

for calibration and found to be satisfactory. Any difference in sensor accuracy would have minimal impact in explaining the lack of fit for the Huron data set.

Temperature-Based Procedure

Calibration coefficients, Kt, were derived from measured daily solar radiation and maximum and minimum air temperatures using a six-year (1972-1974, 1982-1984) Brookings data set with 552 individual days. Daily coefficient values were quite variable, so seven-day mean values were determined beginning on June 1 and continuing through the end of August (Table 2). Even the mean seven-day values for the six-year calibration period varied from 0.133 to 0.158 with an overall mean of 0.145. Since there was no consistent trend in coefficient values over the three-month period of interest, the overall mean value was used for prediction purposes. Samani and Pessarakli (1986) recommended a value of 0.156 for the Sioux Falls, SD area which would increase all predicted values by 7.6% if used in place of the 0.145 value.

The temperature-based procedure for predicting daily solar radiation values did not generate satisfactory results (Figure 6). Predicted values tended to be insensitive to corresponding measured daily values, as indicated by a near horizontal trendline with a slope of 0.213 representing the data values. The complete trendline equation is

PRED = 15.5 + 0.213*MEAS ....[9]

Table 2. Mean 7-day Kt coefficient values for Brookings, SD.

	7 DAY PERIODS STARTING ON JUNE 1												
YEAR	1	2	3	4	5	6	7	8	9	10	11	12	13
1972	0.124	0.151	0.129	0.147	0.146	0.150	0.136	0.144	0.128	0.136	0.157	0.099	0.145
1973	0.150	0.131	0.142	0.139	0.134	0.158	0.136	0.142	0.153	0.139	0.146	0.103	0.141
1974	0.150	0.147	0.153	0.165	0.152	0.147	0.130	0.135	0.128	0.128	0.173	0.164	0.155
1982	0.164	0.144	0.164	0.150	0.135	0.149	0.161	0.158	0.180	0.147	0.138	0.152	0.126
1983	0.141	0.108	0.145	0.130	0.149	0.172	0.155	0.161	0.136	0.136	0.153	0.152	0.160
1984	0.119	0.117	0.140	0.185	0.174	0.172	0.135	0.139	0.145	0.122	0.147	0.172	0.156
AVERAGE	**0.141**	**0.133**	**0.146**	**0.153**	**0.148**	**0.158**	**0.142**	**0.147**	**0.145**	**0.135**	**0.152**	**0.140**	**0.147**

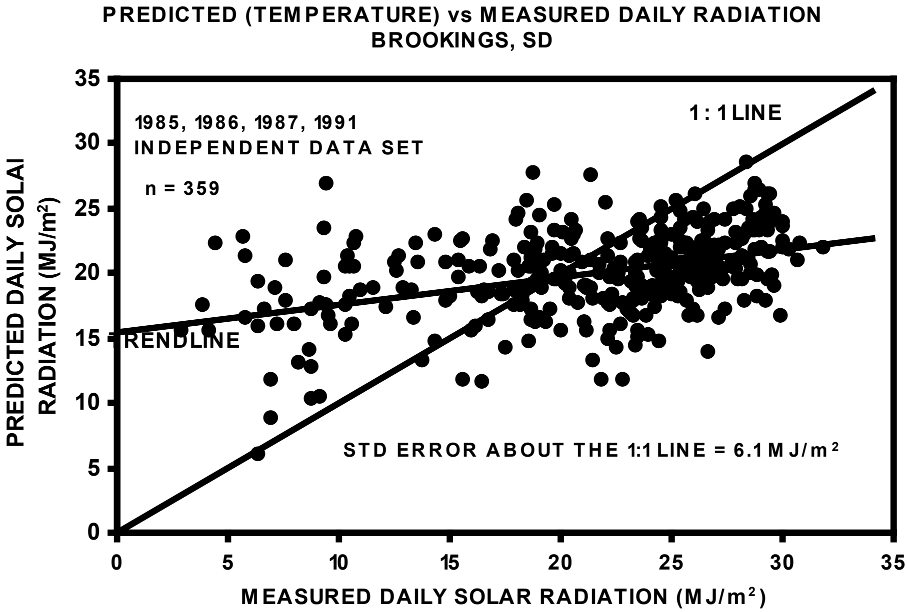

Figure 6. Predicted (based on air temperature) versus measured daily solar radiation values for an independent data set at Brookings, SD.

with a standard error of 3.0 MJ/m^2 and an R^2 of 0.17. The standard of error about the line of equality (1:1 line) was 6.1 MJ/m^2. These statistics are summarized in Table 3. Seven-day mean predicted values had less scatter than the daily values and were more in agreement with measured seven-day mean values with a standard of error about the line of equality (1:1 line) of 2.6 MJ/m^2 (Figure 7). The slope of the trendline is only 0.501, which is quite different from a desired value of 1.00, and the intercept has a value of 9.33 MJ/m^2 that is far from zero.

A Huron independent data set was also used to evaluate the temperature-based procedure. One hundred and eighty two daily values during 1991 and 1992 indicated similar shortcomings as was found for the Brookings data set (Figure 8). Data were scattered and tended to follow a horizontal trend, similar to the

Table 3. Summary of trendline statistics and standard errors about the 1:1 lines.

LOCATION	DATA	INTER-CEPT	SLOPE	STD ERROR	R^2	STD ERROR OF 1:1 LINE
BROOKINGS	DAILY	15.5	0.213	3.0	0.17	6.1
	7-DAY	9.33	0.501	1.5	0.53	2.6
HURON	DAILY	12.6	0.329	2.3	0.48	5.3
	7-DAY	9.98	0.453	1.2	0.63	2.8

PREDICTED = INTERCEPT + SLOPE * MEASURED

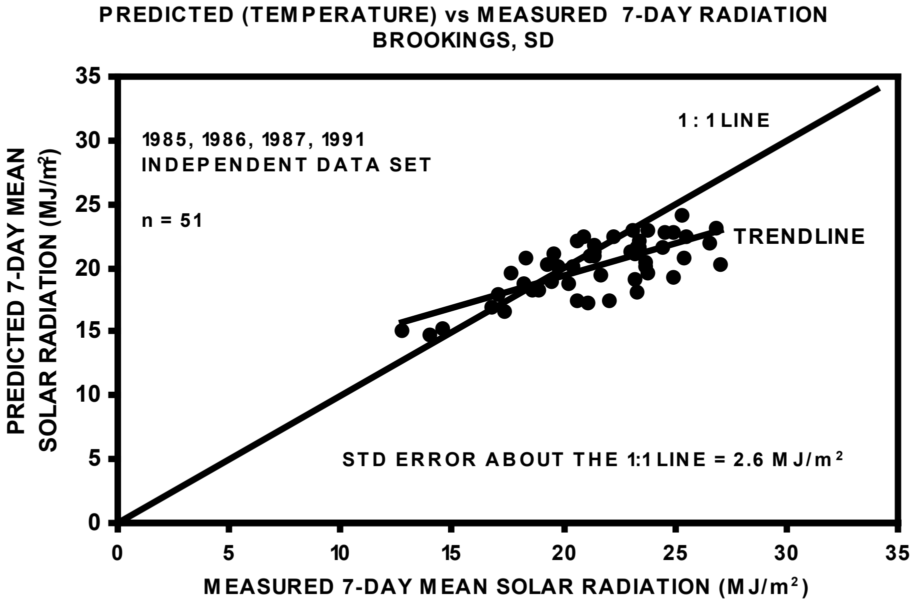

Figure 7. Predicted (based on air temperature) versus measured mean 7-day solar radiation values for an independent data set at Brookings, SD.

Brookings results, and again did not follow the line of equality (1:1 line). Trendline statistics were similar to those associated with the Brookings daily values. Mean seven-day values were also similar to the Brookings data set with a standard of error about the line of equality (1:1 line) of 2.8 MJ/m2 (Figure 9).

Daily solar radiation predicted values were not reliable. Data scatter and insensitivity to changes in daily solar radiation (function of clouds) makes application of the temperature-based method for use in the estimation of daily evapotranspiration very questionable. Weekly or seven-day predicted values are associated with smaller errors of estimate but have limited utility for daily irrigation scheduling purposes. They could be used for periods of a week or more with a reasonable degree of confidence.

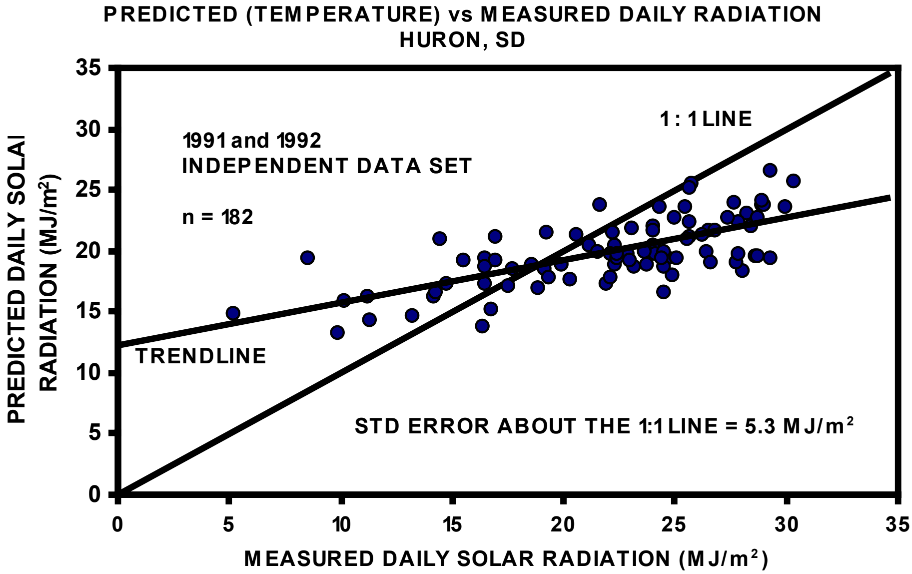

Figure 8. Predicted (based on air temperature) versus measured daily solar radiation values for an independent data set at Huron, SD.

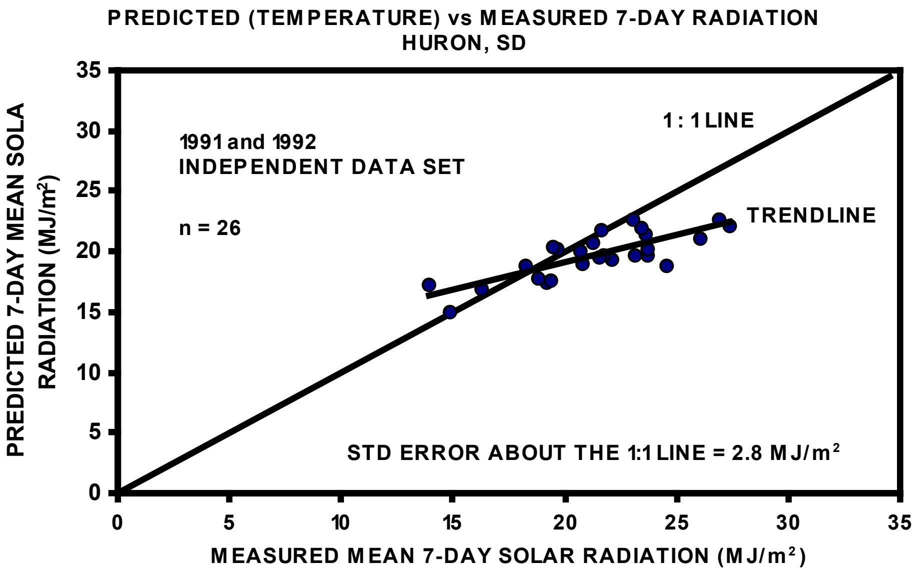

Figure 9. Predicted (based on air temperature) versus measured mean 7-day solar radiation values for an independent data set at Huron, SD.

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