Surface Measurements of Solar Irradiance: A Study of the Spatial Correlation between Simultaneous Measurements at Separated Sites

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ABSTRACT

Pyranometers have been used for many years to measure broadband surface incoming solar irradiance, data that is necessary for surface energy budget, cloud forcing, and satellite validation research. Because such measurements are made at a specific location, it is unclear how representative they may be of a larger area. This study attempts to determine a reasonable spacing between measurement sites for such research by computing the correlation, and standard deviation from perfect correlation, between simultaneous measurements of incoming solar irradiance for a network of surface measurement sites covering a 75 km × 75 km area. Using 1-min data collected from this network of 11 sites during the NASA First ISSCP Radiation Experiment/Surface Radiation Budget Project temporal averages were calculated. The correlation between any two of these sites was determined by comparing simultaneous measurement averages for the 55 possible combinations of site pairs, along with the distances between them. In an attempt to remove the effect of the diurnal cycle, thus leaving clouds as the primary influence on correlation of the radiation field, model results for a clear day were used to normalize measured irradiances and correlations were again calculated.

For individual days, the correlation between sites varied widely, depending primarily on the type of cloud cover the region experienced that day. Removal of the diurnal cycle, as expected, significantly decreased these correlation values. Comparisons using the continuous experiment records from 13 October through 2 November 1986, however, show that a relatively high degree of correlation existed with or without the diurnal cycle removed. Plotting these correlation coefficients versus the distance between sites, the expected trend for a decrease in correlation with increasing distance is observed. Results also confirm that, whether using the complete record for the duration of the experiment or by individual day, the correlation between site station pairs increases with increasing averaging times. Finally, the standard deviation from perfect correlation suggests a predictive relationship within about 6% of clear-sky irradiance for daily averages at a distance of 75 km. Thus, a spacing of 150 km between measurement sites seems reasonable for studies of midlatitude frontal weather regimes using daily averages over periods of weeks or more.

1. Introduction

The principal source of energy for the earth–atmosphere system is solar radiation. This energy is mostly absorbed at the planetary surface, then enters the atmosphere through latent and sensible heat transfer and net emission of longwave radiation. To study these energy exchange processes, measurements of incoming broadband solar irradiance at the surface are essential. Yet the aerial coverage of these measurements, compared with the earth's surface area, is meager at best. Thus, great effort is being expended to develop and refine algorithms to determine the surface solar radiation field using the global coverage afforded by satellite observations. In this case, given point measurements from a standard instrument such as an Eppley pyranometer used to verify these algorithms, it is essential to know how representative they are of a larger area.

The following research attempts to ascertain this aerial coverage by studying the correlation between simultaneous measurements from a network of 11 broadband solar instruments deployed over a 5600-km^2 area and how this correlation changes with distance. We also attempt to separate the effects of the solar diurnal cycle from atmospheric effects (primarily cloud cover) through the use of modeled clear-sky data. Finally, the standard deviation from perfect correlation is used to help quantify the predictive relationship between station pairs for various time averages. Through this approach it is hoped that the results will provide guidelines, depending on the applications for which the data is to be used, for reasonable spatial instrument density.

2. Data

An incoming shortwave irradiance dataset was gathered by the NASA First ISSCP Radiation Experiment/

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Surface Radiation Budget (FIRE/SRB) Project. The dataset includes surface measurements from 12 October through 2 November 1986 at 17 sites in central Wisconsin. These measurements were taken, using Eppley model PSP and Kipp and Zonen CM5 instruments, as 1-min averages. The 17 site records were then adjusted both to conform with the National Oceanic and Atmospheric Administration/Environmental Research Laboratory (NOAA/ERL) standard and to offset small differences between the clocks at the various field sites (Whitlock et al. 1990).

The FIRE/SRB shortwave dataset was used as the basis for this research. Due to various equipment and measurement problems, some data were missing from the station records. For this reason, 11 of the 17 stations were chosen that either had no missing data periods or, as for stations 7 and 8, where the missing data amounted to less than 1% of one daylight period for the entire record. Station 7 is missing 0.9% of the 655-min record for 17 October while station 8 is missing 0.2% of the 461-min record for 12 October. Since 12 October was the initial day of the FIRE/SRB project, the data collection start times on the 12th were highly varied. Consequently, only data from 13 October through 2 November were used, and the record for station 8 is complete for our purposes. For the missing station 7 data, linear interpolation was used to fill in any lost time periods. Table 1 lists the latitude and longitude of the 11 stations (numbered 7–17) from which the collected data were used.

TABLE 1. Station records used in this study.

Station	Latitude (°N)	Longitude (°W)	Station
7	43.33	89.37	Arlington
8	43.56	89.48	Portage
9	43.53	89.97	Reedsburg
10	43.28	90.04	Plain
11	43.21	90.19	Tri-County
12	42.99	90.15	Dodgeville
13	43.00	89.74	Mt. Horeb
14	43.16	89.91	Arena
15	43.30	89.74	Sauk City
16	43.11	89.53	Middleton
17	43.13	89.32	Madison (Traux)

3. Methods

All averages used in this study refer to an arithmetic average. The radiometers used in the FIRE/SRB Wisconsin experiment have a given accuracy of about 5–10 W m^{-2} (Whitlock et al. 1990). To ensure that the probable error in the measurements is less than 5% of expected clear sky irradiance (i.e., clear-sky irradiance greater than 200 W m^{-2}), averages were calculated only from 800 to 1600 local standard time. The distances between stations were calculated using the station latitude and longitude coordinates. Correlations between stations and standard deviations were computed using typical methods (Young 1962). The trends were determined by a sum-of-least-squares linear fit to the data (Walpole and Myers 1989).

The calculated diurnal cycle for a clear day was computed using the AFGL midlatitude winter model atmosphere for 44°N as climatological input into a delta-two-stream model incorporating the numerical scheme of Toon et al. (1989). Since no aerosol or cloud optical depth was included in the model, solar attenuation in these clear-sky calculations is due only to gaseous absorption by H_2O vapor, CO_2, O_3, and O_2, and molecular scattering. Thus, the calculated values represent the theoretical maximum curve of the clear-sky irradiance for a plane-parallel atmosphere.

The fact that the sun rises and sets produces a certain amount of correlation between nearby stations. In an effort to remove the influence of the diurnal cycle from the data and the correlations, each 1-min value of the measured irradiance was divided by the corresponding value of the calculated clear-sky irradiance. Thus, clear sky conditions produce ratio values of near unity and deviations from unity are due primarily to the influence of the cloud field. These "normalized" values of the irradiance were then used for correlation, standard deviation, and trend calculations in a manner identical to that applied to the measured irradiance.

4. Results

a. *Correlations using entire record*

Using the daily averages of measured irradiance, the correlation coefficients between station pairs were computed. These results were plotted versus the corresponding distances and the sum-of-least-squares trend was calculated (Fig. 1a). The correlation is greater than 0.97 in all cases and the trend indicates an expected tendency for a decrease in correlation with increasing distance.

Correlation coefficients were then computed for simultaneous 30-, 15-, 5-, and 1-min time averages of the measured irradiance. Again, these results were plotted versus distance and the trends computed. An example of this is given in Fig. 1b for 15-min averages (note the change in vertical scale from Fig. 1a), which again shows that correlation decreases with distance. The correlation versus distance trend lines for all the time averages (Fig. 2a) indicate that the trend of the correlation is displaced toward lower correlation values as the time interval decreases. All trends exhibit a decreasing correlation with increasing distance.

Results similar to those above were obtained with the diurnal cycle removed from the data. A plot of the trends calculated from the normalized irradiance values is shown in Fig. 2b. All trends, with the exception of daily averages, are displaced toward lower correlation values compared with those in Fig. 2a. Again, the nor-

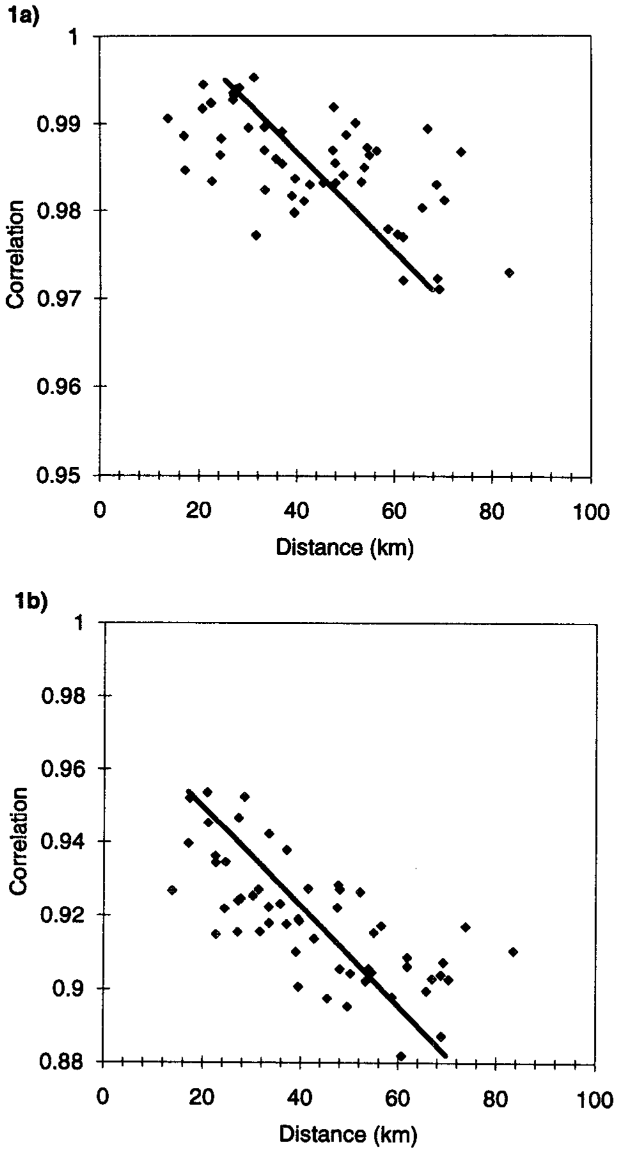

FIG. 1. (a) Correlation vs distance using daily averages of measured irradiance from 13 October to 2 November 1986. (b) Same as (a) but for 15-min averages.

malized irradiance trend is displaced toward lower values with a decrease in averaging time, and the correlation decreases with distance.

To compare these various results, as well as correlations calculated for each day of the experiment (see the following section), the correlation mean and standard deviation from the mean were calculated. For example, according to the plot of correlation of the measured daily averages versus distance in Fig. 1a, the correlation coefficient ranges between 0.97 and 0.997. The mean of these values (regardless of distance) is 0.985, with a standard deviation of 0.006. These values of mean and standard deviation can be used to obtain a sense of the range of the correlation values determined for all station pairs.

Figure 3 compares the results using all days of the experiment for both the normalized irradiance and the measured irradiance. For daily averages there is virtually no difference in correlation between measured and normalized values. Since taking a daily average in effect removes the influence of the diurnal cycle, this result serves as verification for using the clear-sky model results to produce normalized values. For time averages of shorter duration, removing the diurnal cycle causes a decrease in correlation for each case, as well as a slight increase in standard deviation. However, even

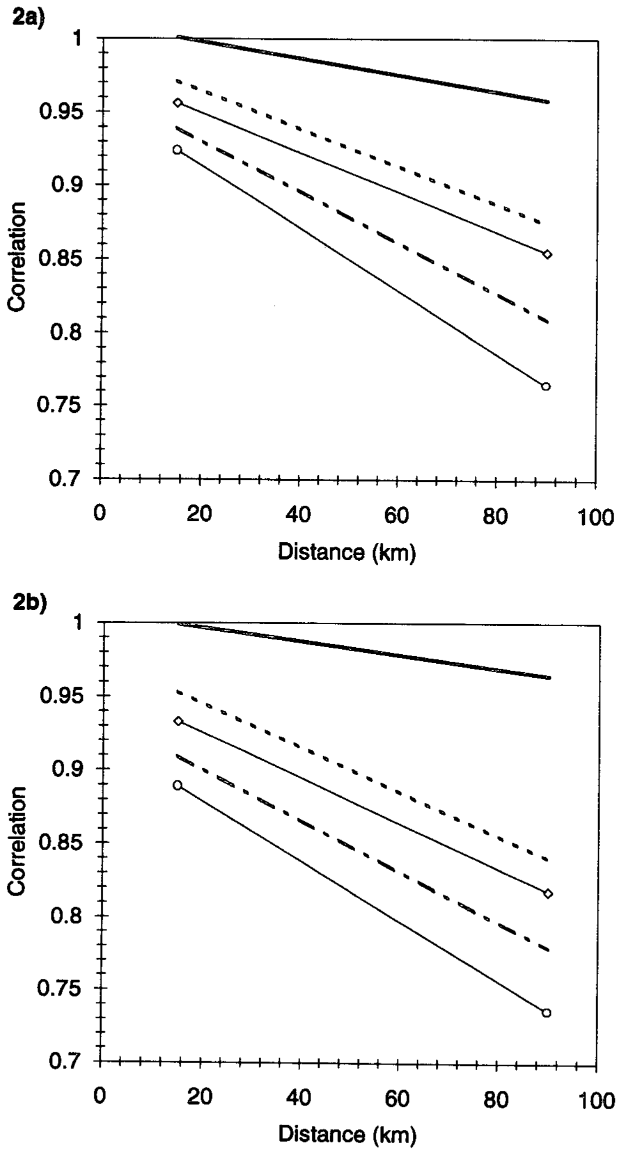

FIG. 2. (a) Comparison of measured trends of correlation vs distance using all days for daily average (solid), and 30- (dashed), 15- (solid, diamonds), 5- (dot dashed), and 1-min (solid, circles) averages. (b) Same as (a) but for normalized irradiance.

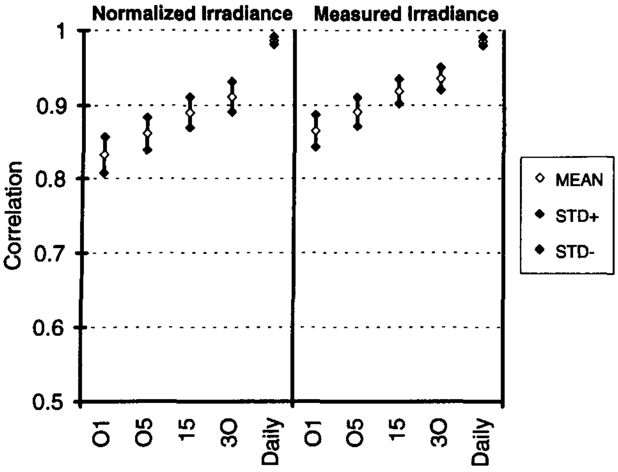

FIG. 3. Correlation means plus/minus one standard deviation using all days from 13 October through 2 November 1986. Averages shown are 1-min (01), 5-min (05), 15-min (15), 30-min (30), and daily (Daily) of both normalized irradiance and measured irradiance.

for the 1-min averages of normalized irradiance, the correlation mean minus the standard deviation (STD−) still remains greater than 0.8 when using the entire three weeks of experiment data.

b. Individual day correlations

Correlations and standard deviations were calculated for each individual day of the experiment records. For example, the correlation between station pairs was determined using only the data from 24 October for the various time averages (Fig. 4). The mean of the correlation values was determined, as well as the standard deviation from the mean and the trend. This was done for each of the 21 days of the experiment. Figure 4a shows the results plotted for the 15-min averages of measured irradiance for 24 October. Figure 4b shows the same results, but for normalized irradiances. Note the difference in scale of the correlation axis between the two figures.

For individual days, the calculated correlation versus distance plots were highly scattered for all time averages. Thus, the calculated trends lose significance in determining the tendency of the correlation to change with distance. For this reason, little can be inferred, with or without the diurnal cycle removed, except to say that for clear sky conditions, correlation decreases with increasing distance.

Removing the diurnal cycle causes a decrease in correlation mean and an increase in standard deviation for each case. Both of these tendencies are much more pronounced for individual days compared to the aggregate dataset. Figure 5 shows the correlation means and standard deviations by day from 24 October through 2 November for (a) measured irradiance and (b) normalized irradiance. Note the difference in correlation axis scale between the two.

In these plots 27 October, 30 October, and 2 November show the highest correlation means and smallest standard deviations of the measured irradiance. For these days, the lowest value of the mean and mean minus one standard deviation is about 0.94 and 0.92, respectively, for the 1-min averages on 30 October. With the diurnal cycle removed, these terms decrease rapidly as the time interval is decreased. The corresponding 1-min average values are 0.51 and 0.37.

Figure 6 shows 15-min averages of the measured irradiance recorded at station 7 from 24 October to 2 November inclusive. In a general sense, this plot is representative of all 11 station records for this period. The days of 27 October and 2 November were mostly

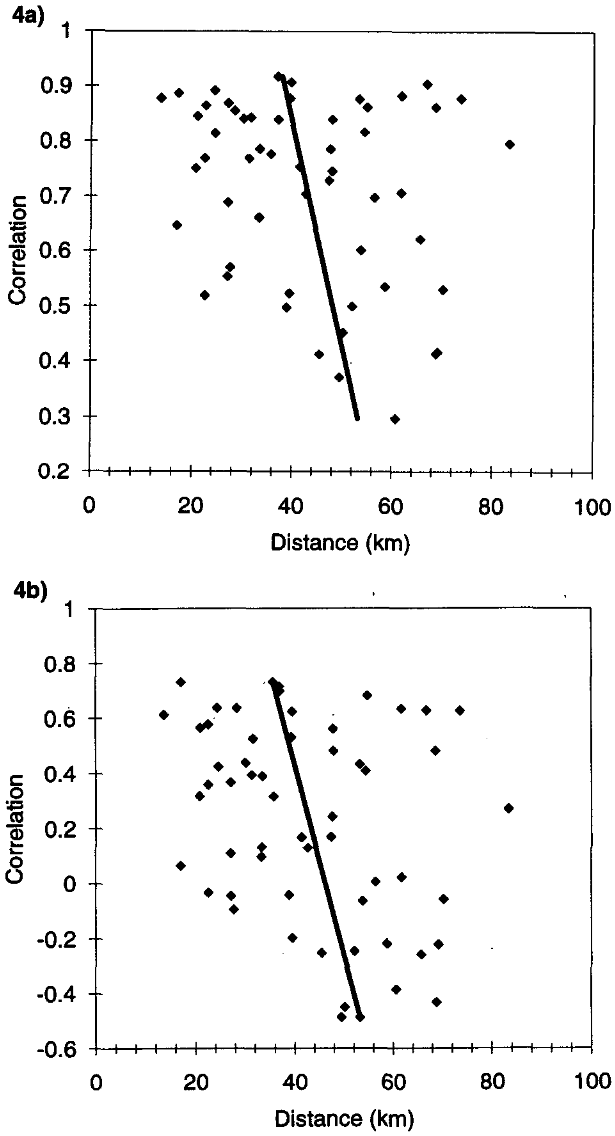

FIG. 4. Correlation vs distance using 15-min averages of (a) measured irradiance and (b) normalized irradiance for 24 October 1986 only.

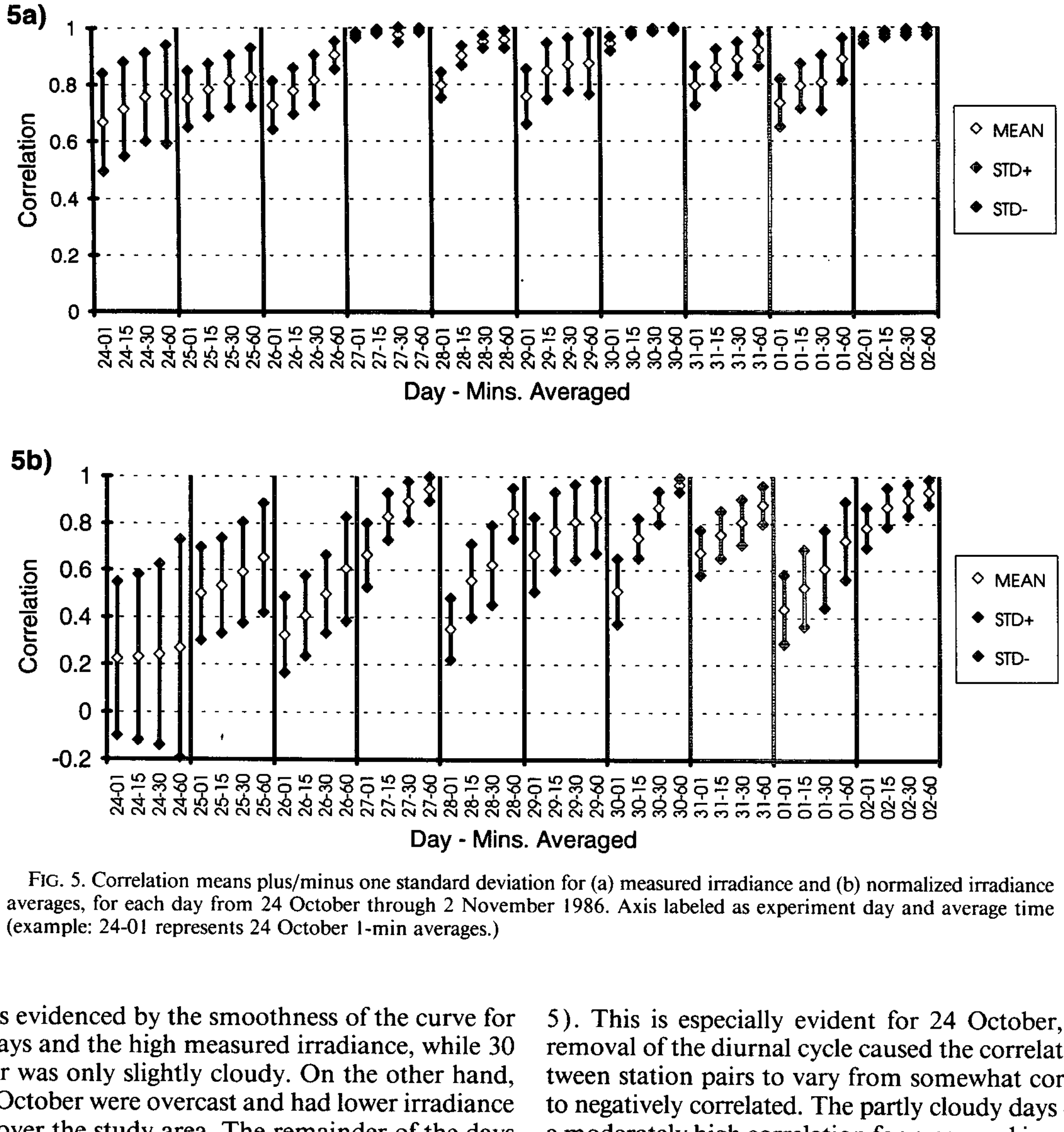

FIG. 5. Correlation means plus/minus one standard deviation for (a) measured irradiance and (b) normalized irradiance averages, for each day from 24 October through 2 November 1986. Axis labeled as experiment day and average time (example: 24-01 represents 24 October 1-min averages.)

clear, as evidenced by the smoothness of the curve for these days and the high measured irradiance, while 30 October was only slightly cloudy. On the other hand, 24–26 October were overcast and had lower irradiance values over the study area. The remainder of the days were partly cloudy to varying degrees.

The correlation means for the overcast days are relatively low, compared with the means for mostly clear days, both for measured irradiance and normalized irradiance and exhibit large standard deviations (Fig. 5). This is especially evident for 24 October, where removal of the diurnal cycle caused the correlation between station pairs to vary from somewhat correlated to negatively correlated. The partly cloudy days display a moderately high correlation for measured irradiance, but the normalized irradiance in these cases gives varying results. These differences indicate that the diurnal cycle is the primary factor in the similarity between station records on a cloudy day. This is due to the smaller-scale variability in a cloudy environment compared to the approximately 8-h daylight timescale.

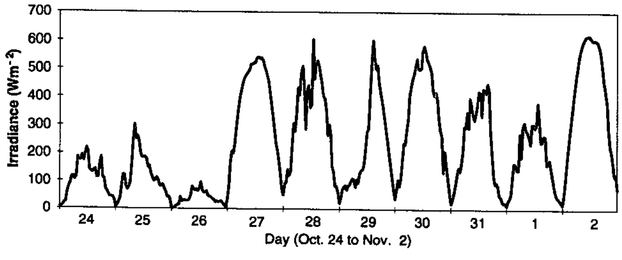

FIG. 6. Measured irradiance record from station 7 using 15-min averages, 24 October–2 November 1986.

c. Pairwise regression statistics

Although the value of the correlation coefficient computed for station record pairs indicates the degree of similarity between the two time series, a quantification of the predictive relationship between station pairs is needed. As one approach to this quantification, we calculated the standard deviation of the measured irradiance values about the $X = Y$ line (perfect correlation) for each station pair for all time averages ($\Delta t = 1$, 15, 30, and 60 min, and daily). Thus, given an

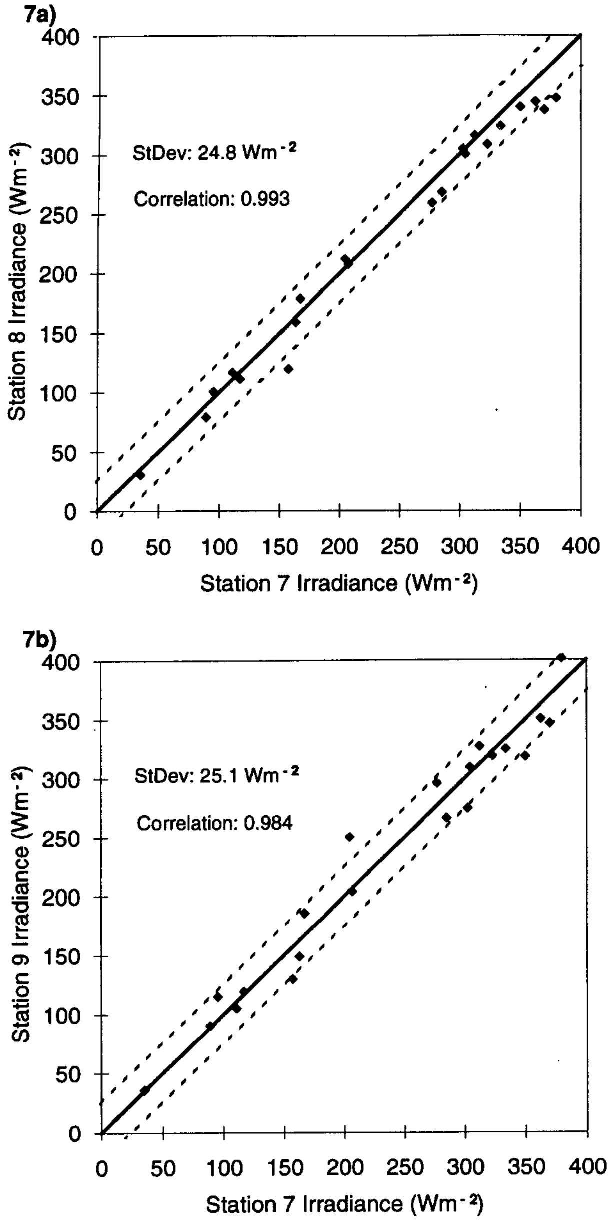

FIG. 7. Daily averages of measured irradiance plotted for (a) station 7 vs station 8 and (b) station 7 vs station 9. Solid line denotes $X = Y$, dashed lines denote plus/minus one standard deviation from the line.

observed irradiance at one station, this standard deviation indicates the precision with which that measurement can be used to predict the irradiance at the second station (and vice versa). As an example, results of this calculation are shown for station pairs 7 and 8 (Fig. 7a), and 7 and 9 (Fig. 7b) for daily averages of irradiance measurements. For these pairs, the correlation coefficients are high (>0.98), but the standard deviation from perfect correlation is about 25 W m^{-2}. Thus, on any given day, knowing the measured irradiance at station 7 allows us to predict the measured irradiance at either station 8 or 9 to within about 25 W m^{-2}.

The standard deviation values computed for all pairs for daily and 60-min averages of incoming irradiance are plotted as a function of the pairwise correlation coefficient in Fig. 8. Not surprisingly, the standard de-

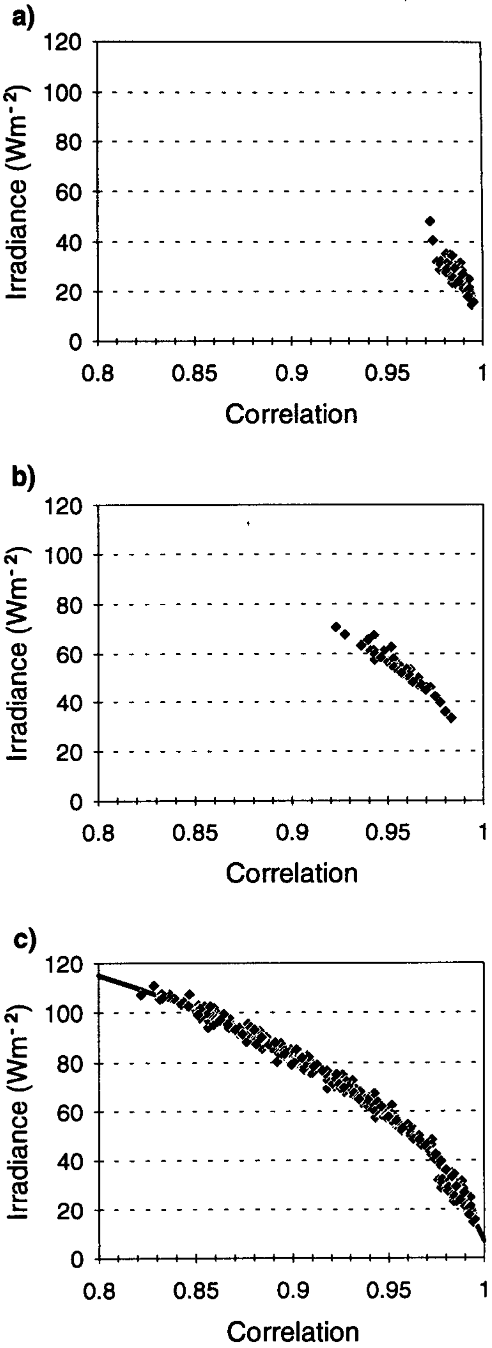

FIG. 8. Correlation vs associated standard deviation of measured irradiance for (a) daily averages, (b) 60-min averages, and (c) all averages combined. Solid line in (c) denotes sum-of-least-squares polynomial fit.

viation increases as the correlation coefficients decrease. More interestingly, when the points for all the time averages are plotted on the same graph, the points resemble a somewhat smooth curve. This is, of course, related to the definition of the correlation coefficient. However, by fitting a smooth curve to these points, we can provide a rough estimate of the relationship between any correlation coefficient for any time-averaging period and the related predictive value of an irradiance observation. The smooth line in Fig. 8c represents the functional relationship:

$$Y \approx 150 - (22.3X^{51.1} + 120.7X^{5.55})\ \mathrm{W\ m^{-2}}, \quad (1)$$

where Y is the standard deviation and X is the pairwise correlation coefficient. This relationship implies that shorter averaging periods, with their corresponding lower correlation coefficients, have considerably poorer predictive capability. While this result is intuitively obvious, quantification of the relationship is useful for understanding the actual predictive value of individual irradiance measurements.

5. Conclusions

The FIRE/SRB Wisconsin experiment, by nature of the time and place of its occurrence, is a limited representation of a midlatitude frontal weather regime. Caution must be exercised in applying these results to other regimes, such as those dominated by deep convection. Also, this study does not include orographic effects. In hilly terrain, a distance of 50 km can produce a significant shift in the microclimate. The correlations calculated in this study would not necessarily apply to such dissimilar environments. Nonetheless, some interesting conclusions regarding typical midlatitude weather regimes can be drawn from this study.

When performing comparisons using all experimental data from 13 October through 2 November, a relatively high degree of correlation exists between station records. This is especially true using daily averages of measured irradiance, where the correlation mean minus one standard deviation is still roughly 0.98. This correlation value is associated with a standard deviation of irradiance of approximately 30 W m^{-2} (Fig. 8a), which is about 6% of the calculated diurnal clear-sky daily irradiance mean. Figure 1a gives a correlation trend value of slightly less than 0.97 at a distance of 75 km. The associated standard deviation of the measured irradiance is then roughly 40 W m^{-2} using the calculated polynomial fit equation (1) (Fig. 8c), which is about 9% of the clear-sky daily mean.

It should be noted that these deviations from perfect correlation are randomly distributed (Figs. 7a and 7b). Thus, over time, they tend to cancel out. This indicates that weekly time averages over a period of months would give higher correlation coefficients than that for daily averages. Although the 3-week duration of the Wisconsin experiment precludes the study of weekly averages over periods of months, it can be inferred using the predictive equation that the associated standard deviations of measured irradiance would approach the accuracy of the instruments (10 W m^{-2}) at a correlation of about 0.998.

Using the normalized irradiance, the daily averages still maintain a very strong correlation. For shorter time averages, a moderate loss of correlation occurs, although again removing the diurnal cycle has only a slight effect. This indicates that the study area as a whole experienced roughly the same type of large-scale cloud cover changes over this 3-week period. This is not surprising in view of the synoptic weather scales during this period. It is for this reason that such high correlation coefficients were obtained. These results likewise confirm the assumption that the correlation between site records increases with increasing average times (e.g., a higher correlation is found for 30-min averages than for 15-min averages). An expected tendency for a decrease in correlation with increasing distance is also observed.

For individual days, the correlation between sites varies widely, depending primarily on the type of cloud cover that the region experienced that day. On relatively clear days (Fig. 6), the lowest correlation mean is about 0.94 for the 1-min averages of 30 October (Fig. 5a). The correlation means for the 60-min averages of the same days are all greater than 0.98. For the overcast days, the correlation means range from a low of roughly 0.67 (24 October, 1-min averages) to 0.9 (26 October, 60-min averages). The significant decrease in correlation due to the removal of the diurnal cycle suggests that smaller-scale cloud features play a more important role on any given day. This is also indicated by the failure of the trend analysis to produce meaningful results in this part of the study.

In conclusion, based on this data, a coverage radius of about 75 km is quite reasonable for studies using daily averages of incoming solar irradiance over a period of weeks or longer. This would give a spacing of 150 km between measurement sites. Indications are that even greater distances would still yield good results for uniform terrain. If a particular study (still over a period of weeks) requires shorter time averages, then perhaps a more dense array should be considered. For detailed studies focusing on limited temporal durations and small spatial extent, pyranometer observations must be considered as point measurements limited to the field of view of the instrument unless the particular day being studied had mostly clear skies.

The largest drawback of this study is the limited time duration of the Wisconsin experiment data. A similar analysis should be carried out for a much longer time sample in order to examine the validity of these conclusions for different synoptic regimes. The establishment of the Atmospheric Radiation Measurement (ARM) site in Lamont, Oklahoma, may allow such an analysis to be performed.

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