XI. DIFFUSE–GLOBAL CORRELATIONS: SEASONAL VARIATIONS

Estimating the performance of a solar system requires an accurate assessment of incident solar radiation. Ordinarily, solar radiation is measured on a horizontal surface and intensity on the tilted collector surface is calculated via a two-step procedure. First a model is used to estimate the diffuse and direct components from global data. Then each component is projected onto the tilted surface using the appropriate geometrical approximation. Overall accuracy of the result is dependent on the reliability of each step in the above process.

Reliability of the geometrical transformations is an important topic but will not be discussed here. This study focuses on the procedure used for determining direct and diffuse components of irradiance on a horizontal surface. Since these two quantities are seldom measured, empirical correlations are often used to extract beam and diffuse components from measured global values.

Pioneering work of Liu and Jordan [1] related the diffuse fraction (diffuse radiation/total intensity) to the clearness index K_T (total intensity/extraterrestrial radiation). Later studies examined the general validity of this early result. A dependence upon other variables, such as cloud cover, latitude, hours of sunshine, and surface albedo has been suggested [2-7]. Some of the early studies suffered from inadequacies in the data. These older studies often used diffuse data measured with a pyranometer and a shadow band; correction for the latter introduces an unknown uncertainty into the data. The recent use of pyrheliometer data eliminates this problem [8-9].

In the previous section we presented a one-parameter correlation study using direct and global data from our sites in the Pacific Northwest (PNW). Correlations between the diffuse fraction and K_T were obtained for data averaged over 1, 5, 10, 15, and 30 days. Statistical accuracy of correlations obtained by averaging over 10, 15, and 30 days was significantly improved through the use of moving averages. Linear fits sufficed for all but the daily correlations. No dependence upon altitude or climatic conditions was found.

It was noted that the correlation varied throughout the year in a repeated fashion. Seasonal dependence has also been noticed in other recent papers [8,9] reporting correlation studies using high quality solar radiation data. In this section time-dependent variations of diffuse-global correlations for the PNW are examined by studying the residual differences between the measured diffuse fraction and those calculated from the overall best-fit correlation. It is found that these residuals exhibit a pronounced sinusoidal behavior when plotted against the time of year. A simple analytical modification is suggested which significantly reduces the variance from the correlation.

Clear day solar noon transmission values are compared to the seasonal variation in an attempt to understand the physical mechanism responsible. The close match between observed variations and transmission values leads to the assertion that turbidity, water vapor, and air mass are significant factors in the time dependence of the correlation.

Analysis of Correlation Residuals

The seasonal variation in the correlation data is very striking. In Fig. 30, monthly averaged data tends to fall below the best-fit correlation from August through January and above from February through July. Another way to more clearly show the time dependence of the data is to plot the residual differences against the time of year, as in Fig. 31. Daily data points in Fig. 31 have been averaged over all sites but the observed sinusoidal variations are typical of the behavior at each site. The large
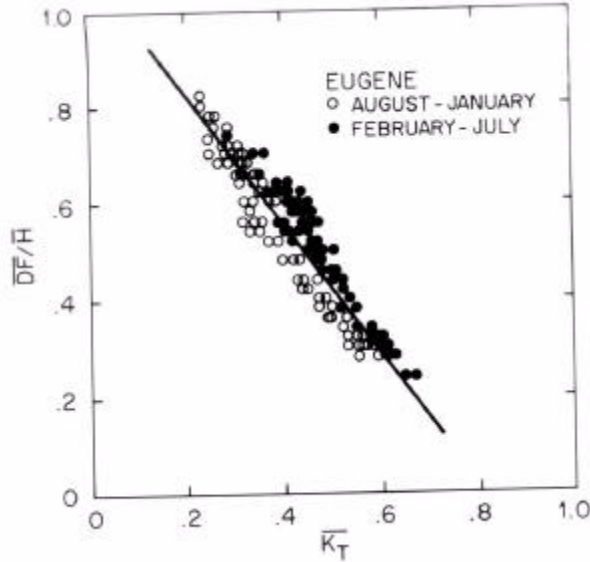
Fig. 30: Seasonal dependence of the monthly averaged correlation data for Eugene, Or. The solid line is the best linear fit to the data.
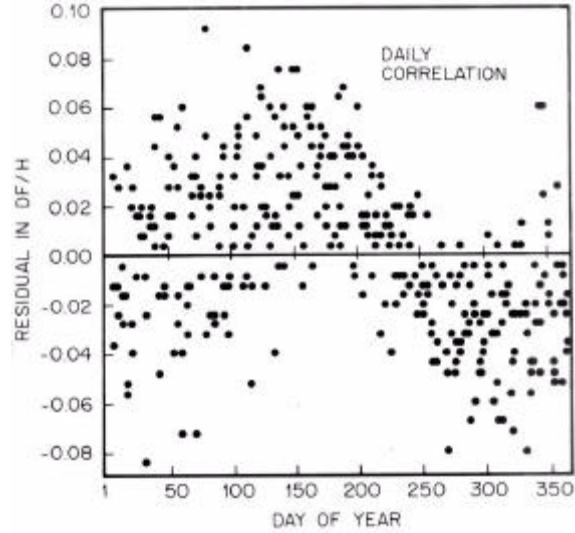

Fig. 31: Averaged residuals correlation for all sites plotted against the day of year. Each data point represents the average of the residuals occurring on a given day.

scatter in the residuals is an artifact of the large variation in the daily data. Monthly averaged data that exhibit a much smaller variation give a clearer view of the seasonal effect as shown in Fig. 32. The smooth, almost sinusoidal seasonal pattern is very evident.

The problem is to obtain the best correlation, given the seasonal dependence of the data. We have seen above that the residuals exhibit a time-dependent behavior. What is needed is

to remove this functional dependence on the time of the year. Previous studies [8,9] solved this problem by obtaining one correlation for the winter and another for the rest of the year. In view of the smooth dependence of the residuals upon the time of the year we prefer an analytic approach.
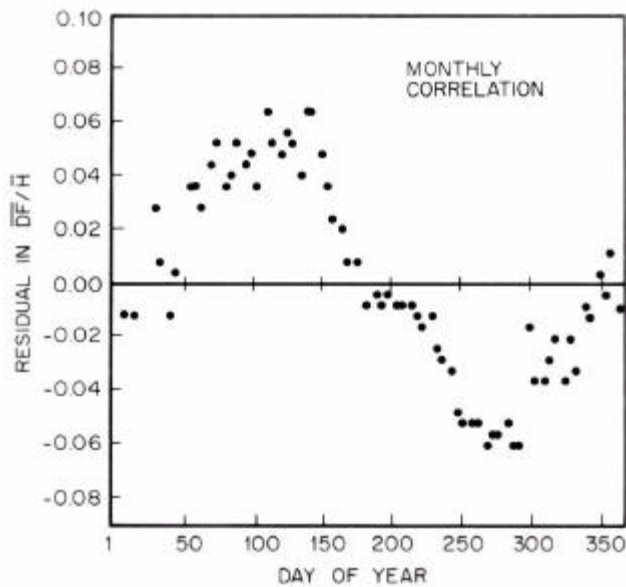

Fig. 32: Average residuals from monthly averaged correlations for all sites plotted against the day of the year. Each data point represents the average of the residuals with the same starting day for the thirty-day interval. The day of the year is the starting day of the thirty-day averaging period.

40

Table 14. Monthly Diffuse-Global Regression Parameters

Site	a	b	c	σ
Burns, OR	1.274	-1.649	0.049	0.036
Coeur d'Alene, ID	1.244	-1.662	0.039	0.030
Corvallis, OR	1.181	-1.489	0.064	0.035
Eugene, OR	1.152	-1.457	0.044	0.038
Hermiston, OR	1.092	-1.297	0.032	0.033
Kimberly, ID	1.222	-1.543	0.033	0.055
Whitehorse Ranch, OR	1.168	-1.490	0.057	0.027
All Sites	**1.162**	**-1.451**	**0.045**	**0.043**
All Sites (no sine term)	**1.108**	**-1.343**		**0.052**

Analytical Modification

One way to improve the correlations would be to fit arbitrary functions to the averaged residuals of Figs. 31 and 32 and then include these functions in the correlation. An almost equal improvement can be made through the use of a simple analytic function involving a sine term that depends only on N, the time of the year (plus a suitable phase). The improvement made through use of this straightforward analytic procedure is described below.

The monthly diffuse fraction was fitted to the following function of K_T and N,

$$K_{DF}/K_T = a + b \cdot K_T + c \cdot \sin(2\pi(N-40)/365). \quad (1)$$

A value of 1370 W/m^2 was taken for the solar constant in all calculations. For this monthly average case, N is the year day corresponding to the median day of the 30 day period. The results of this fitting process are summarized in Table 14.

Note that $c/|b|$ is only about 0.03, so that the correction made is small. Another way to see the effect of the additional term is by comparing the correlation with and without this term and looking at the reduction in the standard deviation from the best fit. A comparison for all sites is shown in the last two lines of Table 14. The overall reduction in the standard deviation (σ) is about 25%, while in the range of K_T between 0.4 and 0.6 the standard de-

K_T between 0.4 and 0.6 the standard deviation is reduced by about 50%. For K_T above 0.6 the effect on the correlation is small because most periods with high values of K_T in the Pacific Northwest occur during July through August when the contribution from the sine term is small. For $K_T<0.4$, the period contains many days when the diffuse fraction is almost 1 and the adjustment is expected to be small. The improvement to the correlation is shown clearly in Fig. 33. This shows the same data that was used to plot Fig. 30 except that the individual data points in Fig. 33 have been changed by $c \cdot \sin(2\pi(N-40)/365)$. The solid straight line represents the linear portion of the improved correlation. A similar procedure has been applied to the daily correlation analysis, with a corresponding improvement
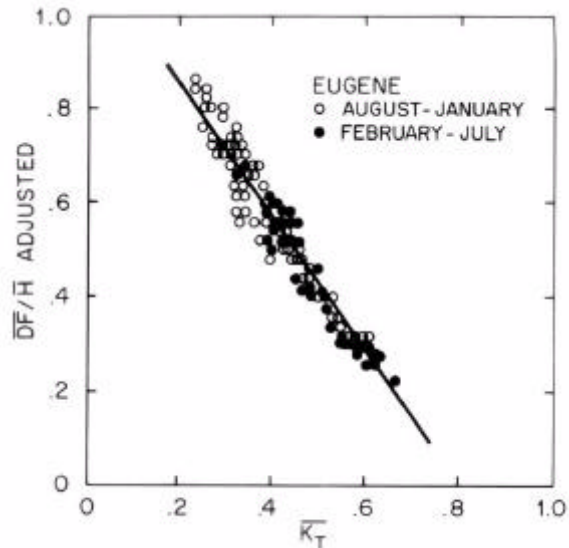

Fig. 33: Seasonal dependence of the monthly averaged correlation data for Eugene after shifting the diffuse fraction data points by the sine term in the modified correlation. The line through the data is the linear portion of the modified correlation fit.

in the scatter of both the correlation data and the residuals.

Conclusions

The diffuse fraction-clearness index correlations are found to vary systematically over the year. Examining the residuals of the one-parameter empirical correlations best demonstrates this variation. The variation shows a sinusoidal behavior over the year. Any correct description of this relationship should take these seasonal changes into account. For the seven Pacific Northwest sites under study, inclusion of a dependence on the sine of the year day in the empirical correlation accounts for the annual variation and significantly improves the daily and monthly averaged correlations. The improvement in the daily fit is manifested primarily in the distribution of the residuals that no longer show a sinusoidal dependence on the time of the year. For the monthly correlations the variance of the diffuse fraction about the correlation is also significantly reduced.

It is instructive to look at the effect of the modification to the correlation in another way. By using Eqn. 1, the relative change in K_{DF}/K_T due to the modification can be determined. It is

$$\Delta(K_{DF}/K_T)=c \cdot \sin(2\pi(N-40)/365)/[a + b \cdot K_T]. \quad (2)$$

This can be as large as 50% for K_T near 0.70, which is about as large as the monthly averaged clearness index gets. However, the size of this correction is misleading. Of greater importance is the relative change in K_{DF} divided by the clearness index, K_T. Thus,

$$\Delta(K_{DF})/K_T = c \cdot \sin(2\pi(N-40)/365). \quad (3)$$

The maximum change in this quantity is now only 0.045. This means that the change in the diffuse radiation due to the modification to the correlation divided by the global radiation is only about 5%. Nevertheless, as we have

seen, it is important to make this correction to eliminate systematic effects.

The improvement in estimating the diffuse and hence the direct horizontal component becomes significant when accurate knowledge of the direct component is important. Testing of various modeling techniques and estimating the performance of concentrating collectors require accurate direct values. However, the magnitude of the improvement is not as significant when estimating solar energy incident on tilted surfaces. Any error in estimating the direct component is partially offset by the opposite error in the diffuse component when the two components are combined on a tilted surface. This was shown in reference [9] when predictions of tilted irradiance were compared for various diffuse-global correlations. Fortunately, the present refinement to the correlation is simple, and its use allows better seasonal estimates.

There are a number of possible explanations for the observed seasonal variation. One is a systematic error in the calculation of the extraterrestrial radiation due to approximations in the analytic expression for the declination. This possibility was eliminated through the use of an equation for the declination that gives values in close agreement with those listed in the ephemeris table. Another possibility is a systematic error in the calculation of the diffuse component. The method we have used to calculate the diffuse solar radiation [10] uses a weighed average of the cosine to calculate the horizontal direct component, reducing the uncertainty in the diffuse data from this effect to less than 1%. In addition, our studies of beam-global correlations [11] yield the same seasonal variation. We conclude that the observed seasonal variation is an intrinsic property of the data.

In principle the temperature and cosine dependence of the sensors could also effect the data in a systematic way, giving rise to sea-
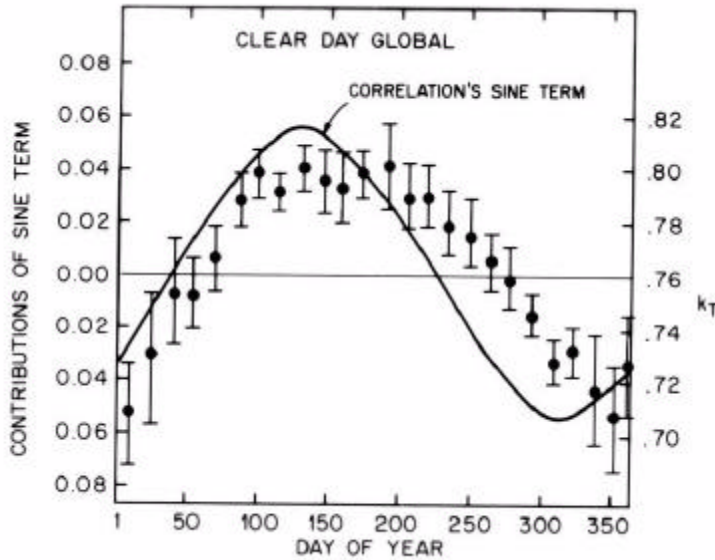
Fig. 34: Clear day solar noon transmission values for Whitehorse Ranch and Burns plotted against time of year. On clear days the instantaneous solar noon global value was divided by the equivalent extraterrestrial value. Transmission values were then averaged over a 15-day period and then averaged over all years for which there were data. The scale for k_T is given on the right of the graph. The solid curve is the contribution of the monthly averaged sine term plotted against the year day.

sonal variations. The temperature characteristics of our Eppley monitoring instruments are such that the sensitivity decreases at both high and low temperatures (with respect to 0°C). The maximum effect from this contribution is less than 1% during the few days of the year when extreme temperatures are experienced. Deviations due to the cosine dependence are significant only during the winter months. Even then, when the sun's elevation angle is small, the maximum effect for the daily values is probably less than 2%. In addition, even a 2% effect on the monthly average global radiation during the winter months would cause only minor changes in K_{DF}/K_T. We conclude that the observed seasonal variation is also not due to these effects.

We believe that the combined effects of air mass, water vapor, and turbidity most probably cause the observed seasonal variation. The authors of reference [8] have suggested that changes in air mass might be responsible for the differences between the summer and winter diffuse-global correlations (turbidity effects were also suggested as a possibility). However, no quantitative comparisons were made. If air mass were the only cause, complete symmetry between summer and winter would be expected. Instead, as shown in Figs.

31 and 32, the observed seasonal variation for the PNW is essentially anti-symmetric with respect to the solstices, with the maximum deviations from the correlations occurring near the spring and fall equinoxes. This suggests to us that the observed seasonal variation is due to the combined effect of changes in air mass, water vapor, and turbidity.

A study of the clear day solar noon transmission values supports our contention that the seasonal variation is a function of air mass, water vapor, and turbidity. As a check on the calibration of our instruments a record is kept of the clear day solar noon transmission values. These transmission values show a seasonal variation similar to that of the diffuse-global correlations. In addition, the magnitude of this variation is about the same as the magnitude of the change in the correlations. The observed pattern in the transmission values for Whitehorse Ranch and Burns is shown in Fig. 34. This pattern is typical of all of our PNW sites. The slight difference in phase between the sine term used to improve the correlation and the clear day transmission values is not significant.

the seasonal variation is a function of air mass, water vapor, and turbidity

43

Since turbidity and water vapor as well as air mass play an important role in the transmission values we believe they also play an important role in the seasonal variation of the correlations.

As a further test of the connection between turbidity, water vapor, and air mass and the observed seasonal behavior of the correlations, the transmission values shown in Fig. 34 were utilized directly as a modification to the correlation. The resulting correlation fits were essentially the same as before, with the same striking reduction in the standard deviation for the monthly averaged correlations as was found when the sinusoidal term was included.

References

1. B. Y. H. Liu and R. C. Jordan, The Interrelationship and Characteristic Distribution of Direct, Diffuse, and Total Solar Radiation. **SOLAR ENERGY 4**, 1-19 (1960).

2. J. K. Page, The Estimation of Monthly Mean Values of Daily Total Short Wave Radiation on Vertical and Inclined Surfaces from Sunshine Records for Latitudes 40N-40S. **Proc. of the UN. Conf. on New Sources of Energy** Vol. **4** 378-389 (1964).

3. D. W. Ruth and R. E. Chant, The Relationship of Diffuse Radiation to Total Radiation in Canada. **SOLAR ENERGY 18**, 153-154 (1976).

4. S. E. Tuller, The Relationship Between Diffuse, Total, and Extraterrestrial Solar Radiation. **SOLAR ENERGY 18**, 259-263 (1976).

5. N. K. D. Choudhury, Solar Radiation at New Dehli. **SOLAR ENERGY 7**, 44 (1963).

6. M. Iqbal, Estimation of the Monthly Average of the Diffuse Component of Total Insolation on a Horizontal Surface. **SOLAR ENERGY 20**, 101-106 (1978).

7. J. E. Hay, A Revised Method for Determining the Direct and Diffuse Components of the Total Shortwave Radiation**. Atmosphere, Qu. Publication of the Canadian Meteorological Society 14**, 278 (1976); J. E. Hay, Climatologically Related Problems in Determining the Potential for Solar Energy Utilization in Canada**. Proc. WMO/UNESCO Symposium on Solar Energy**, Geneva (1976).

8. M. Collares-Pereira and A. Rabl, The Average Distribution of Solar Radiation-Correlations Between Diffuse and Hemispherical and Daily and Hourly Insolation Values. **SOLAR ENERGY 22**, 155-164 (1979).

9. D. G. Erbs, S. A. Klein, and J. A. Duffie, Estimation of the Diffuse Radiation Fraction for Hourly, Daily and Monthly-Averaged Global Radiation. **SOLAR ENERGY 28**, 293-302 (1982).

10. F. Vignola and D. K. McDaniels, Correlations Between Diffuse and Global Insolation for the Pacific Northwest. **SOLAR ENERGY 32**, 161-168 (1984).

11. F. Vignola and D. K. McDaniels, Beam-Global Correlation in the Pacific Northwest. **SOLAR ENERGY 36**, 409-418 (1986).