X. CORRELATIONS BETWEEN DIFFUSE AND GLOBAL IRRADIANCE

For numerous applications, particularly those involving flat-plate collectors and passive solar systems, it is necessary to know both the direct and diffuse components of the incident solar intensity. Because constant care is needed to measure these components, values for direct beam and diffuse irradiance are usually unavailable. However, considerable information is available about the total solar radiation on a horizontal surface. This information can then be used to estimate the relative amounts of direct and diffuse solar radiation in a statistically significant manner by utilizing a procedure developed by Liu and Jordan [1].

The empirical procedure of Liu and Jordan involves a one-parameter correlation between the diffuse to global ratio (often referred to as the diffuse fraction) and the clearness index, K_T[†]. Formally, this quantity is defined as the ratio of the measured total horizontal solar radiation to the corresponding quantity at the top of the earth's atmosphere as calculated from the solar constant. From a detailed statistical analysis, Liu and Jordan discovered that a firm relationship existed between K_T and the diffuse fraction.

The literature abounds with studies attempting to check, improve, and extend this empirical correlation approach. Several authors have compared the original Liu and Jordan results with similar correlations obtained in other geographical areas [2-6]. The influence of the geographic location upon the empirical correlation was suspected, but could not be clearly shown. Both daily and monthly correlations were studied and the interdependence of these has been emphasized [7]. The diffuse fraction has also been correlated with the number of hours of sunshine [8], and with a combination of K_T and cloud cover [9]. Hay [10] developed a sophisticated multi-parameter that included regional data on cloud cover and surface albedo.

Our study examines the validity of the empirical correlation approach using only one free parameter, K_T. The correlations studied include averages over 1, 5, 10, 15, and 30 days. A moving average statistical procedure was utilized to evaluate the diffuse-global correlations averaged over 10 days or more. The traditional method of analyzing monthly averaged solar radiation data is to obtain one data point for each month of information. Using moving averages improves the statistical quality of the analysis. The data base for this study is the hourly global and beam solar radiation values from six University of Oregon sites in the Pacific Northwest along with corresponding data from the Solar Energy Meteorological Research and Training Site (SEMRTS) at Corvallis, Oregon [11]. The material discussed here has been published in a more complete form elsewhere [12].

Data

Data through December 1982 at Burns, Coeur d'Alene, Eugene, Hermiston, Kimberly, and Whitehorse Ranch were used. In addition, data from the SEMRTS site in Corvallis were included to allow comparison with high quality solar radiation information in the region collected by a different group. This affords an independent check on the UO data. Evaluation of the uncertainties associated with solar radiation measurements leads us to believe that the absolute accuracy of our data is ±3% (see section V). The major contributions to this uncertainty come from the deviations from a true cosine response by the pyranometers, the temperature dependence of the sensors, and the uncertainty introduced by the calibration procedures. The contribution from the electronics to the above uncertainty is neg-

[†] *Several names are given to K_T. Liu and Jordan referred to K_T as the cloudiness index, we prefer to call it the clearness index.*

ligible. As described in section V, the relative precision of the results was checked by comparing the measured solar radiation values on clear days at solar noon with the corresponding extraterrestrial values. The relative agreement of all sites from summer clear day values is about +1% when adjusted for altitude.

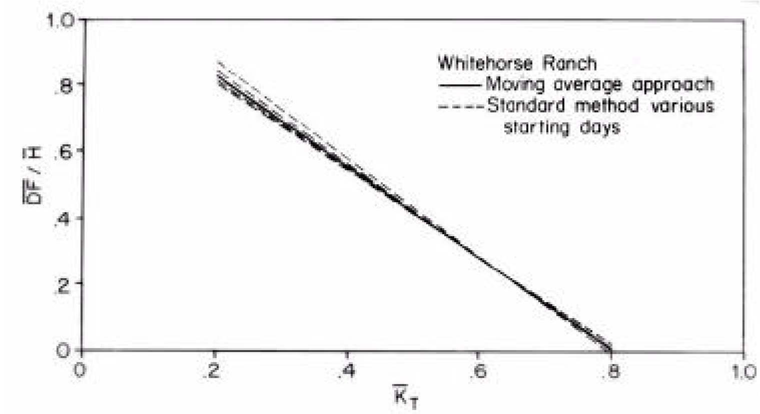


Fig. 25: Comparison of the moving average approach to the conventional procedure for data from Whitehorse Ranch. The averaging period for the correlation was 30 days.

Method of Analysis

The correlation analysis was done in the following manner. First the daily global and diffuse values were divided by the daily extraterrestrial radiation, normalizing the data and giving K_T and K_{DF} respectively. Next, average values of K_T and K_{DF} were determined for the number of days in the period under consideration (30 days, for example). The diffuse fraction DF/H was then calculated as K_{DF}/K_T. Only days with both global and diffuse irradiance values were included. Averages were calculated for a given period only if more than 80% of the days of the period had good diffuse and global data. For 30 day averages this latter requirement demanded that the data file for the period had 25 or more days of good data present.

The moving average approach was used to enhance the statistical accuracy of the correlations for data averaged over 10, 15, and 30 days. This analysis procedure started by separating the data into groups with the appropriate number of days starting at the beginning of the data set. The diffuse fraction (K_{DF} /K_T) and the clearness index (K_T) were then calculated for the data set. Next, the starting date was shifted 5 days and the entire process repeated. The improvement obtained over the conventional approach for monthly averaged correlations is illustrated in Fig. 25. Each dashed line represents a linear fit to the data obtained by making a single pass through more than two years of data for Whitehorse Ranch (each with a different starting day). This is the conventional approach and results in a straight line determined by approximately 25 points. The solid line shows the monthly averaged correlation using a moving average approach, and was determined with six times the number of points yielding a much better representation of the data.

Results

The correlation between the diffuse fraction and the clearness index was obtained for all seven sites in Oregon and Idaho for periods ranging from one to thirty days. Linear regression fits were sufficient for all but the daily correlations. Higher order fits were statistically indistinguishable from the linear fits. The results are summarized in Table 12. The daily correlations were best fit with a cubic polynomial. The results of the multiple regression calculations for the daily data are summarized in Table 13. (The solar constant used in all calculations was 1370 W/m^2.)

Table 12. Empirical Correlations Obtained with a Linear Dependence on K_T
$K_{DF}/K_T = a + b \bullet K_T$

Station	30 day intervals		15 day		10 day		5 day	
	a	b	a	b	a	b	a	b
Burns	1.212	-1.535	1.171	-1.459	1.177	-1.462	1.198	-1.482
Coeur d'Alene	1.187	-1.535	1.175	-1.496	1.157	-1.441	1.128	-1.371
Corvallis	1.094	-1.290	1.131	-1.358	1.144	-1.368	1.197	-1.457
Eugene	1.099	-1.341	1.113	-1.355	1.141	-1.400	1.169	-1.432
Hermiston	1.041	-1.197	1.038	-1.184	1.047	-1.200	1.122	-1.321
Kimberly	1.165	-1.441	1.078	-1.314	1.078	-1.307	1.133	-1.389
Whitehorse Ranch	1.084	-1.337	1.116	-1.382	1.123	-1.387	1.139	-1.394
All sites	1.108	-1.343	1.104	-1.341	1.118	-1.358	1.155	-1.405

Table 13. Empirical Correlations for Daily Data Using a Cubic Polynomial. $K_{DF}/K_T = a + b \bullet K_T + c \bullet K_T^2 + d \bullet K_T^3$

Site	a	b	c	d
Burns, OR	0.882	1.514	-5.877	3.218
Coeur d'Alene, ID	0.928	1.129	-5.385	3.245
Corvallis, OR	0.943	1.054	-4.980	2.704
Eugene, OR	0.893	1.485	-6.496	4.155
Hermiston, OR	0.943	1.120	-5.498	3.376
Kimberly, ID	0.858	1.669	-6.239	3.532
Whitehorse Ranch, OR	0.911	1.269	-5.777	3.474
All sites	**0.916**	**1.248**	**-5.551**	**3.215**

Over the range of K_T from 0.20 to 0.73 for which there is data, the maximum difference between the diffuse fraction determined by the correlation for any individual site to that determined from the combined correlation is only 0.08. This is nearly twice the standard deviation of the correlation, but is relatively small considering that the seven sites represent quite different climatic conditions ranging from the high desert plateau of Whitehorse Ranch to the verdant Willamette Valley.

The correlations between the daily diffuse fraction and the clearness index are so similar that they do not show up well on a graph. The largest difference between the calculated diffuse fractions at any two sites is 0.035. This is half of the corresponding difference for the monthly averaged correlations and less than half of the standard deviation of the daily correlations.

The diffuse-global correlations for Whitehorse Ranch averaged over 1, 5, 10, 15, and 30 days are illustrated in Fig. 26. Clearly, there is little difference between the correlations obtained with an averaging period of 5 days or greater. Under very close examination, a slight trend towards higher K_{DF}/K_T values as the averaging interval is decreased is discernible, but this trend is not statistically significant. However, the daily regression curve differs significantly from the others.

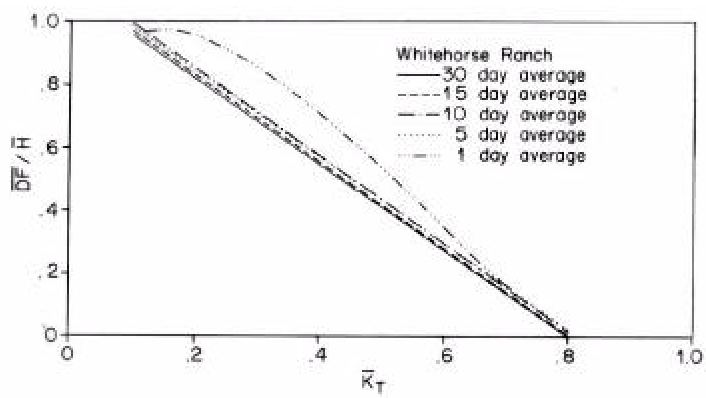


Fig. 26: Comparison of the fits obtained for the solar radiation data from Whitehorse Ranch when the data is averaged over 1, 5, 10, 15, and 30 days.

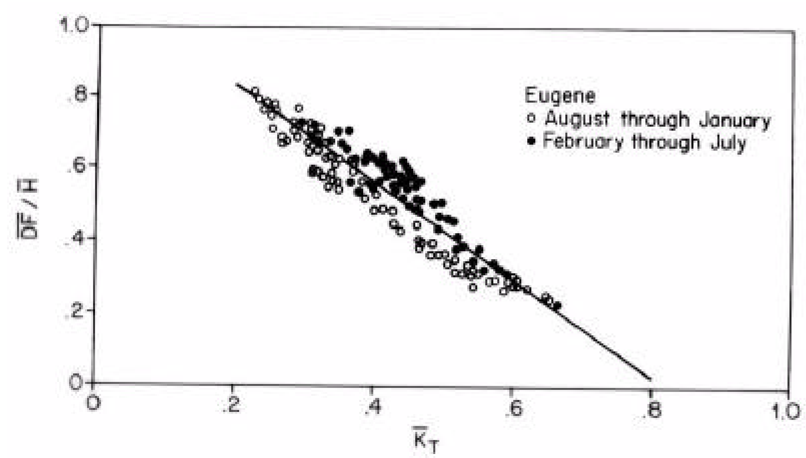


Fig. 27: Comparison of the 30-day averaged data for Eugene from February through July to that for August through January.

An important characteristic of correlation models is the standard deviation of the data from the regression fit. The standard deviation for these fits steadily increased from about 0.05 to 0.09 as the number of days in the averaging period decreased from 30 to 1. However, in all cases, the residuals that make up the standard deviation were not normally distributed, and this lends itself to some ambiguity in determining the best regression fit. The reason for this non-normal distribution can be seen in Fig. 27. This figure compares the monthly averaged data at Eugene for the period from February through July to similar data covering the months of August through January. Clearly there is a distinct difference between the two subsets of the solar radiation data from Eugene. Similar distributions were found for all seven sites.

Discussion

The results illustrated in Fig. 26 (and Tables 12 and 13) show that a linear correlation between the diffuse fraction and the clearness index was obtained for all but the daily correlations. No need was found for a second or higher order term in K_T in any of the correlations with data averaged over five or more days. We believe that the similarity of the fits obtained for sites covering a wide variety of climatic regions was due to the high quality of the solar radiation data used, coupled with the statistical benefits resulting from the use of moving averages. The close agreement between our data and data from the SEMRTS site in Corvallis provides further confirmation of the quality of our data.

It was noted previously that a value of K_{DF}/K_T was computed whenever good data existed for more than 80% of the days in the averaging period. The justification for this is shown in Fig. 26 that compares the fits obtained as the averaging period varied from one to thirty days. It is clearly impossible to significantly distinguish between any of the plots except for the daily average. Thus, missing up to 20% of the data for any given time period does not alter the results.

We find a significant systematic seasonal effect, in that all seven sites have their data grouped into two semi-annual periods, as illustrated graphically in Fig. 27. This bears resemblance to seasonal effects found in other studies [5,6]. We feel this is due to the combined effects of the amount of atmosphere through which the sunlight has to travel and the turbidity of the atmosphere. How to take these seasonal variations into account is discussed in the next section.

Many comments have been made in the literature about the differences between various empirical correlation models. Our present monthly averaged fit for all sites combined is compared to those of several other authors in Fig. 28. Our own overall empirical fit agrees best with the results of Page [13]. We are in substantial disagreement with the curve labeled Tuller [3], but it should be noted that this is also their overall best fit, and several of their sites had empirical correlations that were much closer to ours. The stations used for the correlations derived by Collares-Pereira and Rabl [5] have an average latitude of about 36 degrees while our sites have an average latitude of about 44 degrees. Comparisons of the different monthly averaged correlations suggest there is a possibility of a latitude dependence. This difference would be most evident in the summer where higher latitudes have longer days, and the sun is lower in altitude. The affects of air mass and turbidity would be most apparent during this time of year.

Comparison of the daily correlations is shown in Fig. 29. Again, our overall regression fit falls below that of Collares-Pereira and Rabl [5] (not shown) and Erb[6], both of whom used the same database. The winter fit of Erb falls almost on top of our best fit. There is some evidence of a latitude dependence, but the differences between the correlations are small enough to be caused by uncertainties in instrument calibration.

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. D. W. Ruth and R. E. Chant, The Relationship of Diffuse Radiation to Total Radiation in Canada. **SOLAR ENERGY** 18, 153-154 (1976).
3. S. E. Tuller, The Relationship Between Diffuse, Total, and Extraterrestrial Solar Radiation. **SOLAR ENERGY** 18, 259-263 (1976).
4. N. K. D. Choudhury, Solar Radiation at New Dehli. **SOLAR ENERGY** 7, 44 (1963).

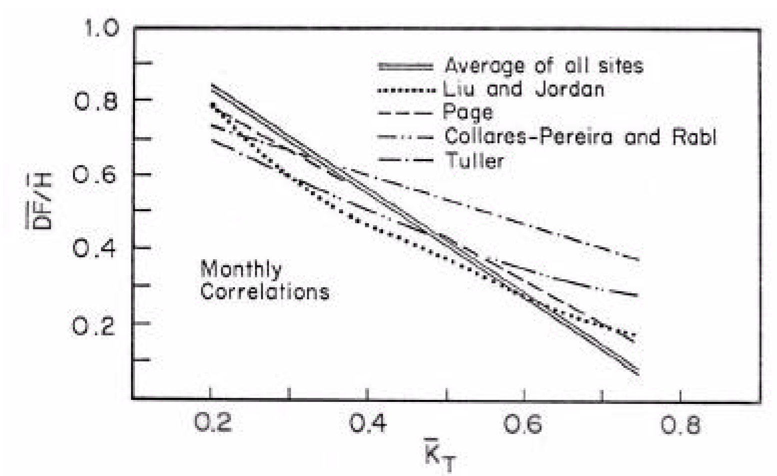


Fig. 28. Comparison of various monthly averaged empirical correlations. Page's fit is fairly similar to the fit obtained for our PNW sites.

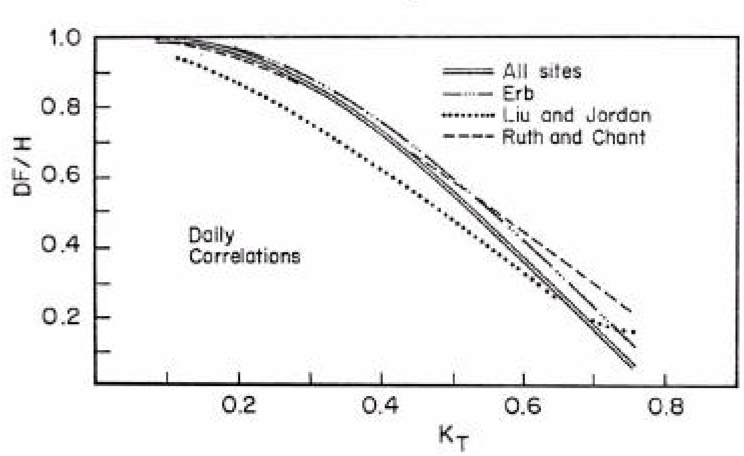
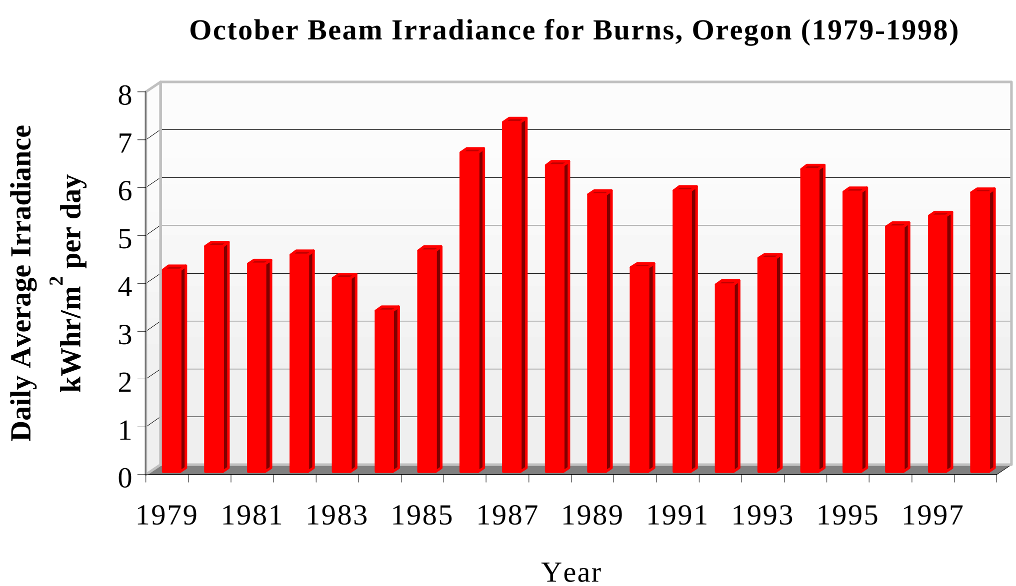


Fig. 29. Comparison of various daily averaged diffuse-global correlations. The curve labeled Erb is for spring to fall data only, and is almost identical to that found in reference 6. The winter curve of Erb is practically identical to ours.

5. 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).
6. 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).
7. S. A. Klein and J. A. Duffie, Estimation of Monthly Averaged Diffuse Radiation. **Proceedings of the American Section of ISES** Vol. 2.2, 672-675 (1978).
8. M. Iqbal, Estimation of the Monthly Average of the Diffuse Component of Total Insolation on a Horizontal Surface. **SOLAR ENERGY** 20, 101-106 (1978).
9. M. L. Wesley and R. C. Lipschutz, A Method for Estimating Hourly Averages of Diffuse and Direct Solar Radiation Under a Layer of Scattered Clouds. **SOLAR ENERGY** 18, 467-474 (1976).
10. J. E. Hay, A Revised Method for Determining the Direct and Diffuse Components of the Total Shortwave Radiation**. Atmosphere, Q**u. 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).
11. C. R. Nagaraja Rao, et al., Solar Radiation and Related Meteorological Data for Corvallis, Oregon -- 1981. April, (1982).
12. F. Vignola and D. K. McDaniels, Correlations Between Diffuse and Global Insolation for the Pacific Northwest. **SOLAR ENERGY** 32, 161-168 (1984).
13. 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).



Long-term variation of beam radiation. More data are needed to identify any possible pattern.