TRENDS IN DIRECT NORMAL SOLAR IRRADIANCE IN OREGON FROM 1979-2003

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ABSTRACT

To better understand the characteristics of the region's solar resource, a preliminary study was undertaken of trends in direct normal irradiance from three sites around Oregon over a period of 25 years. An overall increase of about 13-16% over the 25 years was found. Seasonal as well as yearly trends were studied. During the summer months an increase was observed while during the winter months a decrease was observed. Changes in clear noon values are also examined. This article analyzes direct normal data unlike other recent studies which find decreasing trends in global radiation data worldwide. The data analysis in this study is the first step in testing and refining regional climate models in the Pacific Northwest. A better understanding of the regional climate models can be achieved by utilizing long-term solar radiation data trends with changes in cloud cover, aerosol optical depth, and other meteorological changes.

1. INTRODUCTION

Understanding long-term changes and trends in solar resource characteristics is important for assessing the risks and reliability of power generated from solar energy facilities. This article studies the trends in direct normal beam irradiance at three locations in Oregon. These sites have been part of the University of Oregon Solar Radiation Monitoring Laboratory (UO SRML) solar monitoring network for 25 years.

All three sites show an increase in beam irradiance of 13-16% over the last 25 years. This high quality database has the potential to offer a new test of and insight into regional climate models.

Recently published articles on total (global) surface irradiance have reported decreases of about 2% per 10-year period over large sections of the world [1] and between 4%-10% decreases per decade during the years 1961-1990 in the Liepert study [2]. These studies also show a few regions with trends that increase or are not significant for some or all temporal ranges. These calculations rely in large part on the data provided by the Global Energy Balance Archive. Additional data from the United States National Solar Radiation Data Base (NSRDB) in the Liepert study contributes to some variation. The NSRDB includes data from Oregon. Stanhill and Cohen review regional and larger network measurements of global radiation between 1950 and 2000 and find a similar overall decrease [3]. At special sessions of the May 2004 Joint Assembly of the American and Canadian Geophysical Unions addressing this "global dimming," there was some evidence presented that since 1990 irradiation may be decreasing less or even increasing [4]

The global dimming studies primarily analyzed global irradiance data while this analysis uses direct normal beam irradiance data. Direct normal, or beam, instruments have fewer systematic errors than global irradiance instruments and their calibrations are more stable. The trends found in the Oregon data suggest that here, at least, global dimming does not seem to be occurring; rather, the summers are getting sunnier. While there is also an increase in the global irradiance measured by the UO SRML, the uncertainties are much higher and considerable work still is needed to track the changes in global instrument calibration.

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This article reports on the initial evaluation of the data and the trends observed and identifies further steps to be taken to develop a stringent test of regional climate models. The initial phase of the project is to fully characterize this change over time and to specify the magnitude and uncertainty of this change. In a future phase, changes in cloud cover and aerosols will be examined and the final phase will be to test regional climate models to see if these observed changes can be matched by the model.

This paper contains the preliminary analysis that examines the seasonal variations and trends in the yearly and monthly averaged beam irradiance. As a check on the uncertainties in the data and the consistency of calibrations, trends in the clear day solar noon values are also evaluated. In future work, clear day values during the morning and evening hours will be studied to check for any changes in aerosol and water vapor over the 25 year period. Once the consistency of the calibrations has been established, future work will extract changes in aerosols and water vapor.

Section 2 begins with a summary of the instruments and methods used to collect the data. Section 3.1 gives a preliminary analysis of trends in yearly averages and monthly averages from winter and summer. In section 3.2, data from the National Solar Radiation Data Base (NSRDB) are used to extend and test the trend observed in UO SRML data. The final analysis in section 3.3 uses clear day irradiance values determine the consistency in the calibrations. A summary of the results and the next steps in the project are discussed in the concluding section.

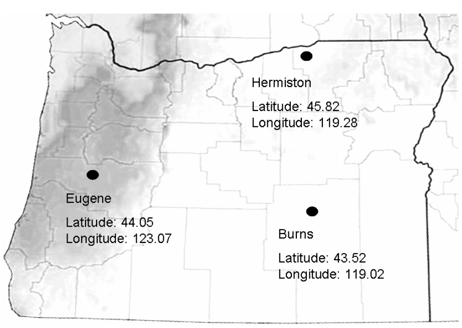

Fig. 1: Sites used in this study.

2. DATA COLLECTION METHOD

The University of Oregon Solar Radiation Monitoring Laboratory collects solar radiation data around the Northwest. Since 1978, it has operated high quality pyranometers and pyrheliometers to collect global and direct normal radiation data at the sites used in this study. In the years since its founding, the UO SRML has maintained a number of other monitoring sites around the Northwest.

However, Eugene, Burns, and Hermiston (shown in figure 1) have the longest continuous records of direct normal measurements. Of the sites, only Hermiston is missing data for a significant period of time: this gap is from 1990-1992. All three stations utilize Eppley Normal Incident Pyrheliometers (NIPs) to collect direct normal radiation data. The stations also measure global radiation with Eppley Precision Spectral Pyranometers (PSPs).

Burns, Hermiston, and, until recently, Eugene, have NIPs mounted on Eppley Solar Trackers which must be manually adjusted frequently for changes in declination. In 1997, the NIPs in Eugene were moved to an automatic tracker which aligns the pyrheliometer with the sun throughout the day and through the seasonal changes in declination. Each site is maintained by a station maintenance operator who cleans the instruments and adjusts the trackers as needed. When the trackers are not aligned properly, the measurements made with NIPs mounted on them are not correct. These values are removed from the dataset. Because the Eppley Solar Trackers are manually adjusted, there are gaps in the data occasionally when the tracker was not properly aligned. Future plans call for filling in the data gaps using global data and beam-global correlations.

Normal Incident Pyrheliometers (NIPs) are high quality instruments with an absolute calibration accuracy of 3% and a relative accuracy of 2%. They are initially calibrated against absolute cavity radiometers. The NIPs used at these sites were recalibrated every few years, as funding allowed. Most of these calibrations were relative, using another NIP as a reference, although they were also occasionally calibrated against absolute cavity radiometers. NIPs are much less prone to calibration error compared to PSPs whose sensitivity tends to decrease over time [5]. NIPs also don't have the same cosine response problems as PSPs, making their irradiance measurements dependent on zenith angle. Because pyrheliometers are pointed directly at the sun, there is no cosine response problem, and the calibrations of the instruments vary slowly over time. The better accuracy, fewer systematic errors, and calibration consistency make direct normal data a more accurate gauge of long term trends than global data.

The SRML direct normal data, however, has gaps because of the previously mentioned alignment problems, as well as a problem in the early 1980's with moisture in the NIPs resulting from a poor window sealant. As with alignment problems, data identified as bad because of moisture problems is removed from the dataset, but this leaves gaps. Fortunately, global irradiance measurements are more complete than beam irradiance measurements and beam values can be estimated using correlations dependent on the global values.

Preliminary efforts have begun to unify calibrations over time. This is especially true with the global data where the method of calibrating the instruments changed in 1995 when the UO SRML switched from calibrations obtained around solar noon to calibration values obtained when the zenith angle was between 45 and 55º. Instruments also changed slowly over time as problems were encountered and equipment had to be sent back to the factory for repair and/or re-calibration.

A record of clear day solar noon values has been maintained to help ensure that instrument calibration remained relatively steady over time and did not drift or make dramatic changes.

3. DATA ANALYSIS

3.1 Complete Dataset

Figure 2 is a plot of the yearly average direct normal irradiance for each site. All three sites show very similar trends throughout the 25 year period. Table 1 shows the regression analysis for these trends. All three sites show trends which are clearly increasing, with a 95% confidence level. Note that the total percent increase in Eugene was over 26 years, while Burns and Hermiston only have data for 24 year spans. Also, the total percentage increases differ not only because of different rates of increase, but also because average insolation at the sites differs. While Eugene has about the same average annual increase as Hermiston, the percentage change at the two sites is quite different because the average insolation in Eugene is lower than that in Hermiston.

TABLE 1: TREND REGRESSION ANALYSIS

	Burns	Hermiston	Eugene
Years Spanned by Data	24	24	26
Total Increase ($kWhr/m^2/day$)	.71	.59	.61
Total Percent Increase:	12.9	12.3	16.6
Annual Increase ($kWhr/m^2/day$)	.029	.025	.024

Using the correlation between beam and global data, the gaps in beam data can be filled. The dataset for Eugene in 1978 is missing 67 average daily values, the most of any year in the three datasets. Most of the gaps relate to startup problems, as it was the first year beam data was taken. Using beam-global correlation to fill in gaps in this extreme example increased the annual average by 18%. This dropped the overall Eugene trend from a 19% increase to a 16.6% increase over the 26 year period. Other years at all three sites are also missing some data, though no years are as significant as this one to the trends. With global data measurements at each site, there is potential to fill in most of these gaps and decrease the uncertainty in the annual averages. Future work will specify the uncertainties caused by the gaps and the filling of the gaps.

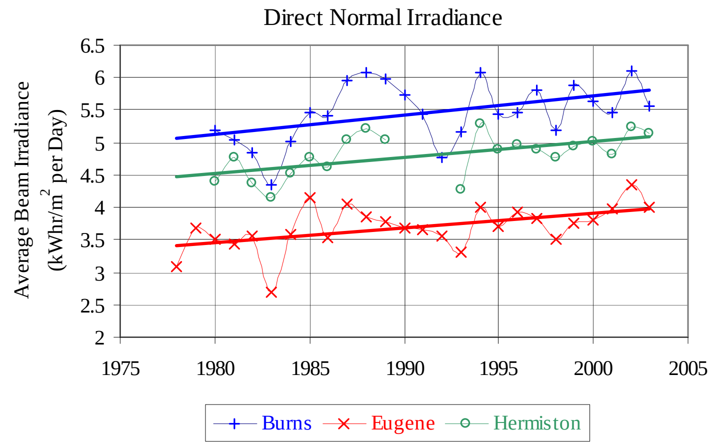

Fig. 2: Annual direct normal averages for Burns, Eugene, and Hermiston. While the effects of the eruption of El Chichón in 1982-1983 and the eruption of Mt. Pinatubo in 1992-1994 can be seen at all locations, these averages also exhibit an increasing trend throughout the 25 year period.

If the years most affected by the volcanic eruptions of El Chichón and Mt. Pinatubo were removed from the dataset (1982,-83, 1992-94) the percentage increase would drop significantly, by 30-50%. However, if those years are removed from the UO SRML and NSRDB data (as discussed in section 3.2) combined, the trend increases slightly.

This data also shows seasonal differences. The winter months show a decrease over the 25 year span, while the summer months show an increase. Figure 3 shows the decreasing trend in January at the three sites. The trend also decreases for the month of December at all three sites. The trend is not decreasing with a high level of confidence. To one standard deviation, Burns does show a reliable decrease, though the other two sites are not significant to that level.

The average monthly beam irradiance in summer increases at all the sites. Figure 4 shows the trend in July. The July increases are statistically significant to a 90% confidence level at all three sites. The higher summer irradiance values dominate the total annual trends so that the overall yearly average trend is positive. These differing seasonal values could indicate a change in cloudiness because clouds are more prevalent in the winter than the summer.

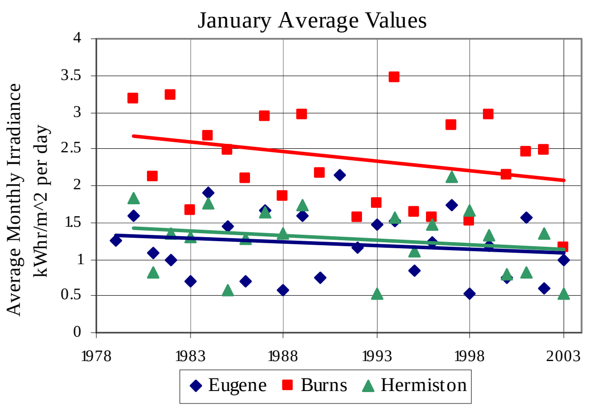

Fig. 3: Average January data at Eugene, Burns, and Hermiston are an example of decreasing winter trends. All three sites show a decreasing trend over the 25 year period in the winter

3.2 Comparison to NSRDB Data

The National Renewable Energy Laboratory (NREL) has created a National Solar Radiation Data Base from 1961-1990 for sites around the United States utilizing cloud cover and meteorological data along with some measured solar radiation data. Included in the dataset is direct normal radiation for both Eugene and Burns. For these two sites, the NSRDB includes data from the UO SRML for the years 1979-1990 in Eugene, and 1980-1988 at Burns. For these two sites, the NSRDB includes some data from the UO SRML for the years 1979-1990 in Eugene, and 1980-1988 at Burns. Most of the data in the data base were obtained by using cloud cover observations to estimate the incident solar radiation.

The NSRDB data has greater uncertainty than the measured direct normal data. NREL estimates the error in calculated

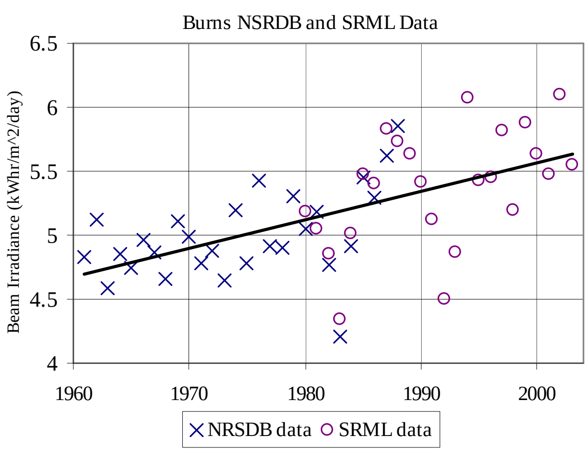

Fig. 5: Burns direct normal irradiance trend using NSRDB data and UO SRML data together.

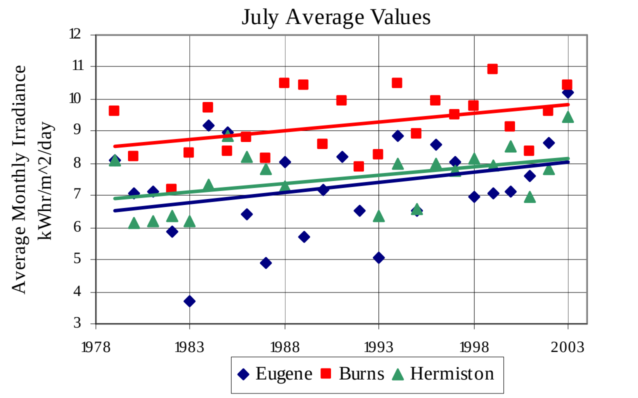

Fig. 4: The trends in average July direct normal values are an example of the increasing summer beam irradiance at Eugene, Burns, and Hermiston, in contrast to the decreasing winter data.

hourly direct normal data in the NSRDB at ±9%, while the error in the measured data is ±3%. More information on this data can be found in the National Solar Radiation Data Base *User's Manual* [6]. Figures 5 and 6 are plots combining the NSRDB yearly average data and the UO SRML yearly average data. The values were calculated from daily totals from each dataset. Some of the years that have NSRDB and UO SRML data have different values annual average beam irradiance. The main difference is due to NREL having a complete record while the UO SRML data has some gaps.

For Burns, regression fits for trends in both the NSRDB data alone and the composite dataset (NSRDB and SRML data together) increase with a 95% confidence level. In Eugene, the regression fit for just the NSRDB data is more

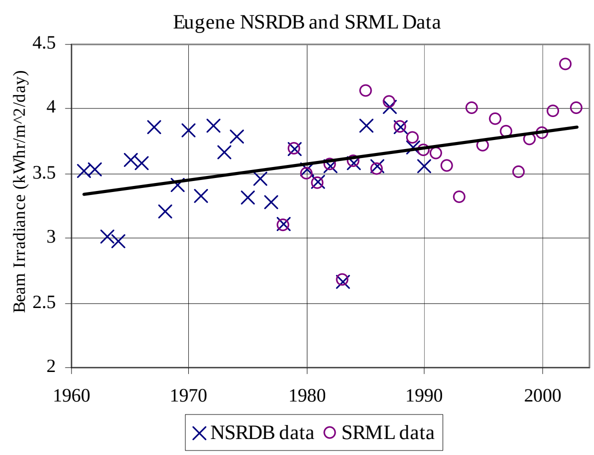

Fig. 6: Eugene direct normal irradiance trend using both NSRDB data and data from the UO SRML. Both Eugene and Burns data show significant increasing trends to a 95% confidence level using both NSRDB and UO SRML data together.

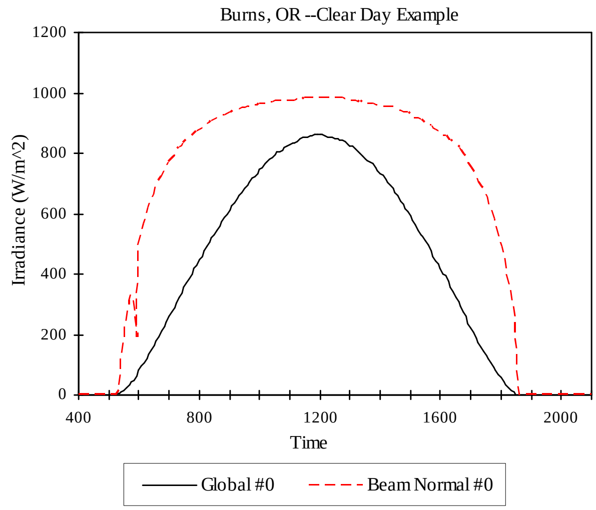

Fig. 7: Example of a clear day graph from Burns OR. These plots were used to identify clear noon periods for the clear day studies.

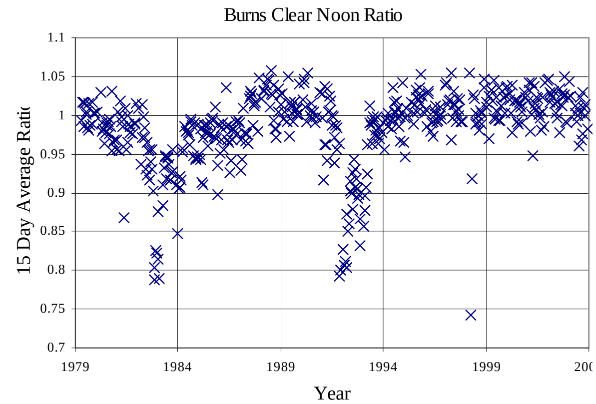

Fig. 8: Plot of the 15-day average clear noon values for Burns. Data were normalized using averages for each 15-day bin from the 25-year period, excluding unusually low values after the eruptions of El Chichón and Mt. Pinatubo.

uncertain. However, when combined with the UO SRML, the composite dataset increase is significant with a 95% confidence level. The trend lines shown in figures 5 and 6 are for the composite dataset at each site. This extension of the dataset further validates the increasing trend in the UO SRML dataset.

3.3 Description of Clear Day studies

Clear day studies are used to check for consistency within calibrations and will be used to differentiate between changes in cloudiness and aerosol concentrations. Clear days were chosen based on the smoothness of the data charts. Direct and global radiation are plotted continuously by chart recorders as a backup to electronically collected data. The charts were then examined for smoothly curved peaks. Figure 7 shows a clear day. The clear solar noon periods (when the sun is highest in the sky) are fairly easily distinguishable from cloudy periods by visual inspection. The peak value within 10 minutes of solar noon was recorded from the five minute average data. In this way clear day solar noon irradiance values for the three stations were collected for the 25 year period.

These results are represented graphically in figure 8 for the Burns site. To improve statistics, clear noon values were grouped into 15-day intervals or bins. The average of all clear noon values in each 15-day interval was used to determine the average clear noon value for the interval. What is plotted in figure 8 is the ratio of the 15-day value from each year to the average 15-day value for all 25 years. This method facilitates comparison of summer and winter periods. Note the dips in 1982 and 1992 due to the eruptions of El Chichón and Mt. Pinatubo respectively. The aerosol effects of these volcanic eruptions are well documented. (See, for example, the *Pacific Northwest Solar Radiation Data Book* [7].) As they are atypical values, the low values from the years of the volcanic eruptions were not included in the average 15-day values used to normalize the data.

Linear regression lines were fit to the clear day data. If you ignore the low values from volcanic years, Burns shows about a 4% increase over the whole time period. Including the volcanic periods, there is about a 5.5% increase over the 25 years. The other sites likewise show a 5-6% increase in the full datasets. It is not clear at this point whether the increase is related to affects from the volcanic eruptions or changes in instruments or calibrations. A thorough examination of the instrumentation and calibration records along with studies of clear day records during the morning and evening hours will help identify the source of this increase. Clearly the overall trend of the annual averages with its 12-16% increase cannot be due solely to calibration changes. This further suggests that there may be changes due to cloudiness.

4. CONCLUSION

This preliminary analysis shows a 13-16% increase in the annual direct normal irradiance at three sites in Oregon. On closer examination, this “increase” varies seasonally, with a summer increase and an actual decreasing trend during the winter months. Any decrease during the winter months would have a minimal effect on the annual average because the average irradiance during December is about 1/4- to 1/5 of the average irradiance during July. The fact that there is a winter decrease and a summer increase suggests that the change are related to changes in cloud cover and not calibration or instrument effects.

As mentioned earlier, other analyses of surface solar radiation have reported decreases in global irradiance of about 2% per 10-year period or about 5% over a 25 year period [1] which is consistent with a between 4%-10% decreases for a three decade period found in another study[2]. These studies cover many stations worldwide and do find a few regions where the change in global irradiance is not significant or where the global irradiance actual increases. These calculations rely in large part on global data provided by the Global Energy Balance Archive. Additional data from the United States National Solar Radiation Data Base (NSRDB) are used in the Liepert study. The NSRDB data are mainly from cloud cover observations and the methodology used to develop the database [6] could obscure long-term trends as changes in aerosol optical depth were removed.

The beam data in the UO SRML database has a well documented calibration and instrumentation history. In addition, the instruments used to measure beam irradiance do not have many of the problems associated with instruments used to measure global irradiance. Therefore it should be possible to more accurately pin down the trend observed in the northwest. The beam data are also 5-minute data and this information has been and will be used to determine broadband aerosol optical depth.

More research needs to be done to fully characterize the increase in beam irradiance seen in Oregon. The monthly and yearly average values will continue to be refined by filling in gaps in the data and thoroughly checking calibration changes to reduce uncertainties in the measurements. Further, the impact of aerosols will be studied by using clear periods to monitor changing aerosol optical depth over the period of record. The morning and evening direct radiation passes through more atmosphere than that at noon so a trend caused by aerosols would be more pronounced in the morning and evening hours. Additionally, narrowband spectral measurements are being monitoring at Eugene along with several other meteorological parameters. These measurements can be used to better characterize the aerosol optical depth and to better define recent observations of broadband aerosol optical depth measurements.

A decrease in cloud cover is expected to be the main cause of the increase in solar radiation. The best way to see this trend is to examine satellite images. Satellite images from 1998-2002 were used to create a database in the Pacific Northwest. Comparison with cloud cover data from the early 1980s would help confirm or disprove this assumption.

This dataset could be very valuable in comparisons with regional climate models, especially because parts of it have not been used as model inputs previously. The precision to which the trend can be defined will also be a stringent test of the regional climate models.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

(1) Gilgen, H., Wild, M., Ohmura, A., Means and Trends of Shortwave Irradiance at the Surface Estimated from Global Energy Balance Archive Data, Journal of Climate, 1998, **11**, 2042-2061.

(2) Liepert, B.G., Observed reductions of surface solar radiation at sites in the United States and worldwide from 1961 to 1990, Geophysical Research Letters, 2002, **29**, DOI 10.1029/2002GL014910.

(3) Stanhill, G., Cohen, S., Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences, Agricultural and Forest Meteorology, 2001, **107**, 255-278.

(4) Cohen, S., Liepert, B., Stanhill, G., Global Dimming Comes of Age. EOS ,2004,Vol.85,38,p.362.

(5) Vignola, F, Reda, I, Responsivity of an Eppley NIP as a Function of Time and Temperature, Proceedings of the 1998 Annual Conference, American Solar Energy Society, 1998, p. 517-522.

(6) NREL, User's Manual: National Solar Radiation Data Base, Version 1.0, 1992, dist. by National Climatic Data Center, Federal Building, Asheville, NC 28801, 93 pp. <http://rredc.nrel.gov/solar/pubs/NSRDB/ > (December 14, 2004).

(7) Vignola, F., McDaniels, D.K., Pacific Northwest Solar Radiation Data Book, 1999, published by the UO Solar Monitoring Laboratory, Eugene, OR. <http://solardat.uoregon.edu/PacNWSolarRadiationDataBook.html> (January 27, 2005)