ANALYSIS OF SATELLITE DERIVED BEAM AND GLOBAL SOLAR RADIATION DATA

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ABSTRACT

Images from the GOES 8 satellite were used along with auxiliary information such as snow cover to produce an hourly solar radiation database on a 0.1° grid for the Pacific Northwest from 1998 through 2002[1]. Both global and beam irradiance values were derived from the satellite images and diffuse values were calculated from the beam and global values. Data from the University of Oregon Solar Radiation Monitoring Network were used to help refine and validate the model used to produce the database from the satellite images.

When compared to ground-based measurements, the mean bias error of the global and beam irradiance values were small, on the order of 2 to 5%. The standard deviation varied from about 20% for global values to nearly 40% for beam values. High quality data from one site, not used to validate the satellite model, is used to examine the potential sources of errors. The largest discrepancies occur on clear winter days when it is difficult to distinguish between frost on the ground and low lying fog and/or clouds. It is suggested that ground-based measurement or visibility measurements are needed to augment the satellite cloud cover data to reduce errors that occur during these cold winter days.

1. INTRODUCTION

Ground-based measurements and satellite-derived solar radiation data complement each other and are necessary to build a comprehensive solar radiation database. It is impractical to have a high density ground-based solar radiation monitoring network that would give anywhere near the coverage capability of a satellite-derived solar

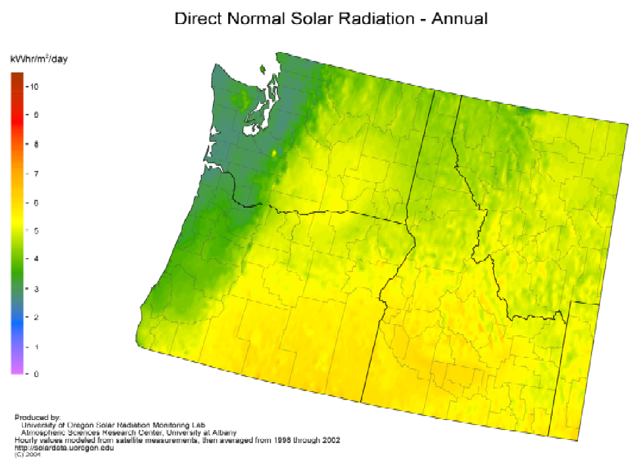

Fig. 1: Annual Pacific Northwest direct normal irradiance from satellite derived solar radiation database.

radiation database (Fig. 1). In addition the uncertainty of interpolated data between sites becomes unacceptable as the distance between stations increases (typically in the 20 to 50 kilometer range). Satellite data can produce a reliable database over large regions on a 0.1° grid (about 10 by 10 kilometers in the Pacific Northwest). However, satellite measurements lack the accuracy and short time interval data necessary for engineering and site specific studies. Taken together, ground-based and satellite-derived solar radiation measurement create a comprehensive solar radiation database.

Testing satellite-derived solar radiation data is not straightforward since satellite images over large areas (10 square kilometers in this example) and ground-based measurements are at a specific location. Nevertheless, it is possible to use averages and statistics to compare, contrast and evaluate these two diverse of databases.

The article is organized in the following manner. First, the quality of, and uncertainties in, the data are discussed. Next, the satellite-derived irradiance data are compared with ground-based measurements. A problem with satellite-derived data in the winter is identified for this specific location and the probable source of this problem is discussed. This is followed by a more detailed comparison between the data sets in a search for possible systematic tendencies in the modeling process. Only when examining the diffuse irradiance can systematic differences be clearly spotted. Possible reasons for these differences are discussed. Conclusions about the utility and accuracy of the satellite-derived data set are then presented.

2. ABOUT THE DATA

The satellite-derived database came from models being developed at the Atmospheric Science Research Center by Richard Perez. The model is based on monitoring the dynamic range for the satellite image pixels and assigning irradiance values corresponding to the relative brightness of the pixels. This cloud index acts as a quasi-linear modulation of a clear sky model. The modulating function was fitted to ground-based measurements grouped together with the data normalized by extraterrestrial irradiance. A comprehensive discussion of the model used to obtain irradiance values from satellite images is found elsewhere [1].

Global and direct normal (beam) irradiance values were produced by the satellite model. Diffuse values were obtained by subtracting the beam irradiance projected onto a horizontal surface from the global irradiance values.

In January 2002, a high quality solar radiation data monitoring station was installed at Kimberly Idaho as part of an upgrade to the University of Oregon Solar Radiation Data Monitoring Network. Global, beam, and diffuse irradiance are measured at this station. The diffuse irradiance is obtained from a star-type Schenk pyranometer mounted on an automatic tracker. The beam data are obtained from an Eppley Normal Incident Pyrheliometer (NIP) and the global measurements are made with an Eppley Precision Spectral Pyranometer (PSP). The global values used in this study are calculated by adding the measured diffuse values to the beam data projected onto a horizontal surface. This method produces the best global values available and eliminates the cosine response and re-radiation problems associated with typical global measurements. This is especially true on clear days.

TABLE 1: Overall bias and deviation between satellite-derived values and ground-based measurements for Kimberly, Idaho 2002

Irradiance\Measure	Average W/m^2	MBE %	σ W/m^2	σ %
Global	413	-4.9	84	21.5
Beam	481	2.0	200	40.9
Diffuse	132	15.4	60	54.2

Calibration of the instruments is traceable to the National Renewable Energy Laboratory, and hence, to the international standard. Data are integrated 5-minute values that are downloaded and inspected on a daily bases. The instruments are maintained and cleaned 5 days a week.

3. COMPARISONS BETWEEN SATELLITE-DERIVED AND GROUND-BASED DATA

It is always important to test and validate models with data that were not used in the original development of the dataset. The high quality Kimberly data became available after the model was finalized and hence serve an independent check on the satellite-derived solar radiation database.

While ground-based solar radiation measurements do not measure the same area of sky as seen by a satellite, the statistical means should be similar and the

TABLE 2: Typical comparison of MBE and RMSE for Oregon sites used in verification of the satellite model in the region

Site	Irradiance \Measure	Average W/m^2	MBE %	σ W/ m^2	σ %
Burns	Global	387	-2	70	18
Burns	Beam	480	-4	180	38
Eugene	Global	311	1	53	17
Eugene	Beam	305	2	112	37
Hermiston	Global	358	-1	44	12
Hermiston	Beam	460	1	155	34
Klamath Falls	Global	357	4	50	14
Klamath Falls	Beam	493	6	174	35

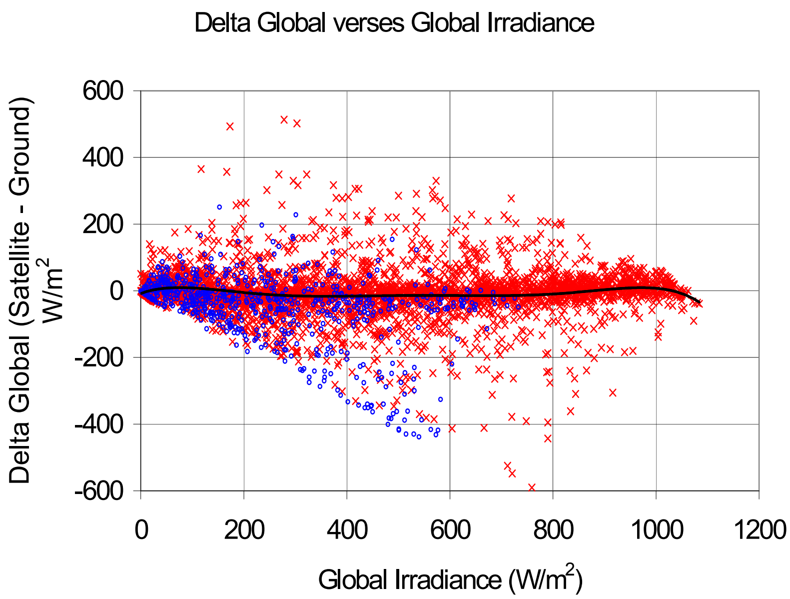

Fig. 2: Difference between hourly global irradiance obtained from satellite modeling and ground-based measurements. Blue circles December, January, and February. Red Xs rest of year.

One way to test for systematic differences is to plot the difference between the measured and calculated values against the ground-based measured data, as in Figs. 2-3. Global data offer the best match. Most of the data is in a band with 50 W/m^2. However, there is a considerable scatter in the data. Some of this is to be expected and results from the different ways in with the values were obtained. However, there are a considerable number of extreme values that occur during the winter months (December, January, and February) that are plotted as blue circles in these figures. This difference is even more visible in the plot beam data (Fig. 3). These extreme differences in winter occur when the ground-based measurements show a clear day values but the satellite values indicate a very cloudy period with no direct sunlight.

A plot of the satellite-derived and ground-based beam irradiance data, for January, is shown in Fig. 4. From January 21 through January 28 there is a very poor correlation between the beam irradiance from the satellite-derived database and the ground-based

distribution about the mean should be normal with a perfect model. A comparison of the ground-based measurements at Kimberly, Idaho and the satellite-deriver data corresponding to the station's location are given in Table 1.

Mean bias error (MBE) is less than 5% for global and beam irradiance and about 15% for diffuse irradiance. The standard deviation (Route Mean Square Error) is about 21% for the global irradiance, 41% for the beam irradiance, and approximately 54% for the diffuse irradiance. These statistics are typical of values seen at ground stations used to test and validate the satellite model in the region (Table 2).

Again, much of the difference in standard deviation comes from the fact that the ground data is based on one point in the area seen by the satellite. A true measure of the difference between satellite-derived and ground-based data are in the MBE.

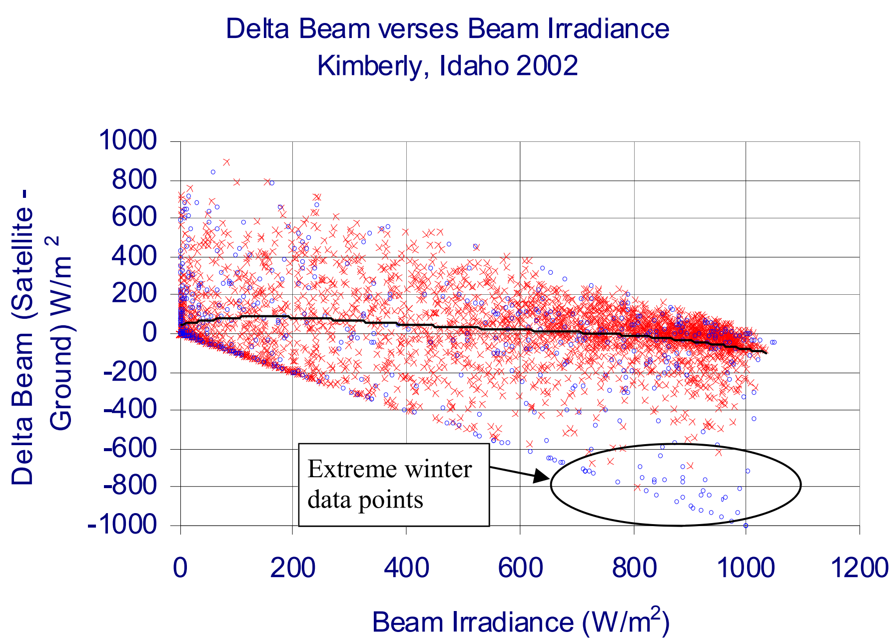

Fig. 3: Difference between hourly beam irradiance obtained from satellite modeling and ground-based measurements. Small blue circles are December, January, and February data points. The red X's are data from the rest of the year.

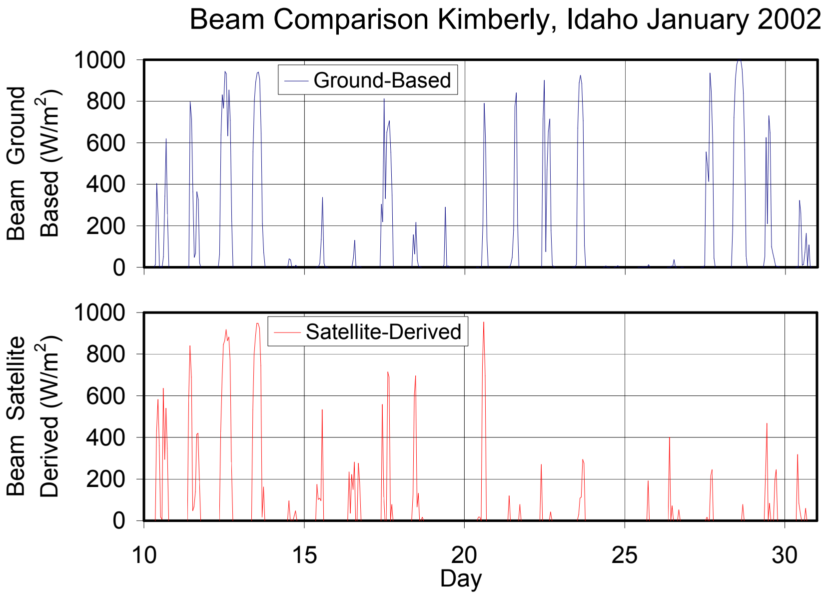

Fig. 4: Ground-based and satellite-derived beam values for January, 2002 at Kimberly, Idaho. Big differences exist on days 21-29 where satellite-derived data indicates little beam irradiance and ground-based measurements show several extremely clear days.

measurements. Clearly there is some phenomenon causing this problem. It is postulated that frost on the flat harvested ground mimics the appearance of fog or low cloud cover. If one flies over this area in winter, the frosted ground is a dirty gray-white color, and it is easy to see why it is difficult for satellite images to distinguish between the two situations. The small brightness range in the satellite image during these periods makes it very difficult to determine the exact situation. This is one area where improvements in modeling or the addition of another measurement is needed. For example, information from ground-based measurements from specific locations could be used to verify satellite produced data and if there is a consistent large difference the data could be flagged and potentially a correction could be applied to the region near the data site. This would probably have to be done by observation first before developing an algorithm to handle this automatically. At a minimum, this would enable the expanded model to distinguish between totally cloudy and totally sunny periods.

While a vast majority of the data points are well matched, there is still a considerable scatter between the two data sets. The challenge is to distinguish natural scatter between two diverse data sets and effects that systematically skew the satellite-derived data. Diffuse irradiance values offer a way to examine the data from a different perspective and a way to see how well the global and beam models work together. The diffuse irradiance is sensitive to factors not easily discernable from comparisons between global and beam irradiance.

Fig. 5 plots the hourly difference between the diffuse values from the satellite model data and the ground-based measurements. This plot shows a systematic underestimation of the diffuse irradiance calculated from the satellite-derived global and beam irradiance values. High diffuse values typically occur when there are thin or scattered clouds. One possible cause is light reflected from the ground to the clouds and back again to the location. Comparison from other areas are needed to determine if this is a systemic problem or a problem seen at specific sites. This is an area where

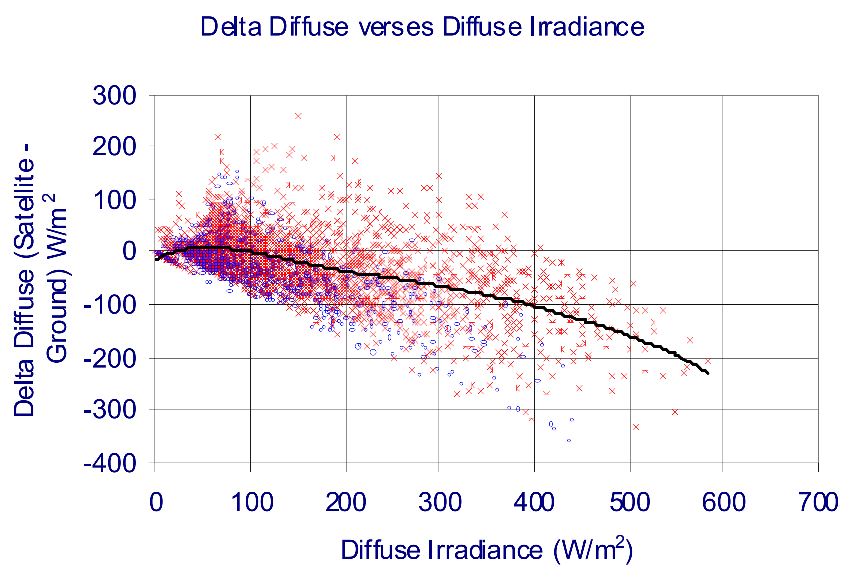

Fig. 5: Plot of the difference between satellite-derived and ground-based diffuse measurements plotted against diffuse intensity.

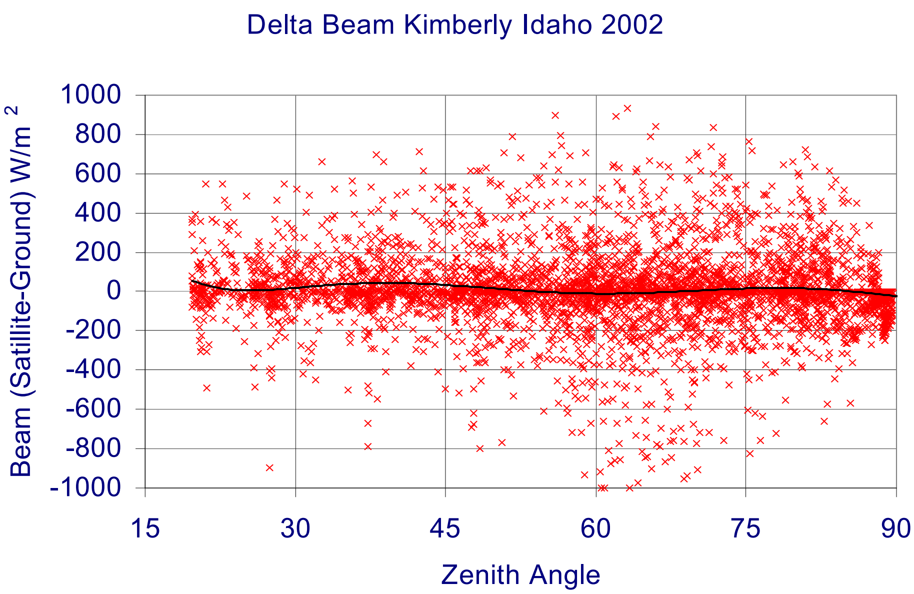

Fig. 6: Plot of the difference between ground-based and satellite-derived beam irradiance verses zenith angle. The trend line show there is little or no systematic deviation about the zenith angle.

Comparisons of the differences between the two data sets verses zenith angle were carried out, but no systematic difference was observed (see Fig. 6 for an example). The methodology used to develop the satellite model was basically independent of zenith angle, grouping all data together and normalizing it to extraterrestrial irradiance. This result helps to validate the methodology.

Another way to evaluate the difference between satellite-derived and ground-based measurements is to plot the difference against time of day. When this is done for global and beam irradiance, no discernable trend can be seen. However, when the difference in diffuse irradiance is plotted against time of day (Fig. 7), the satellite-derived values systematically underestimate the measured values. There are several possible causes for this discrepancy. It is possible that this difference is related directly to the same systematic underestimated diffuse values that are shown in Fig. 5. However, the fact that this difference varies over the

further effort might lead to improvements of the satellite models.

Only ground-based sites with high quality data should be utilized when trying to develop improved satellite models. The best sites measure both direct normal and diffuse irradiance with black and white or star based pyranometers shaded by a disk. Global measurements have systematic errors caused by poor cosine response and re-radiation into the sky. These systematic errors associated with global measurement are of the same magnitude as the differences seen in the diffuse data. Diffuse values obtained by subtracting measured beam irradiance from ground-based measured global values enhance the systematic errors that are in the measured global data. These errors can be significant (on the order of 10 or 20% on a clear day) and it would be difficult separate problems associated with the satellite modeling from errors in the measured data.

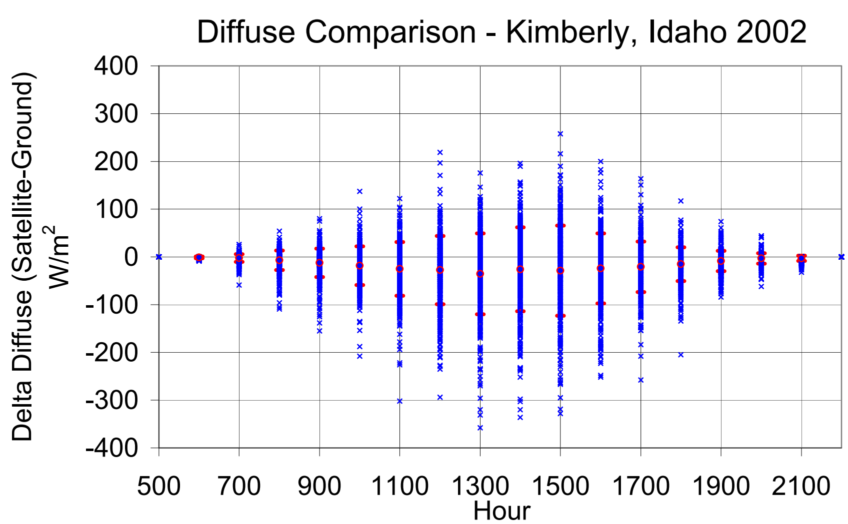

Fig. 7: Difference between diffuse irradiance from satellite-derived values and ground-based measurements plotted against time of day. The red bars are median and standard deviation.

day, and is highest at noon and is relatively symmetric around solar noon, adds another constraint to the problem.

Again, a possible explanation is that the satellite model underestimates the magnitude of the ground reflected irradiance that is reflected by the sky. Evidence for this possibility is that the diffuse irradiance is systematically underestimated under thin or scattered cloud conditions as shown in Fig. 5.

This is a small difference and does not show up in the global data. It also is about the same order of magnitude as the re-radiation into the night sky by first class pyranometers. However, it is hard to see how this problem got incorporated into the satellite model. This is an example of the usefulness of evaluating the diffuse component and of the necessity of having high quality diffuse measurements available for the comparison.

Comparisons at more locations are necessary to adequately characterize this difference and to ensure that it is not a problem specific to one location.

4. CONCLUSION

Modeling satellite images to derived solar radiation values is the best way to obtain irradiance values over large areas. Yearly mean bias values are extremely small, typically 5% or less with a few exceptions. The two stations with the worst fit in Oregon are Gladstone, which has shading by nearby trees and Klamath Falls, which has a hill to the east that block the morning sun [2]. At both sites the satellite-derived data was higher than observed and probably represents a more accurate annual average. Considering the effort necessary to obtain absolute accurate ground base measurements of 5% or better, this is quite a feat.

This also means that interpolating average irradiance values between locations is better done with satellite-derived data than typical methods.

Of course there is the large root mean square error between the ground-based and satellite based measurements, but much of that is related to the fact that ground-based sample one small area of the sky while satellites are imaging larger areas (on the order of 1 kilometer square but averaged over 10 square kilometers).

Of course on clear days or totally overcast days, the values should be similar to ground-based measurements. However, this is not always the case. While examining data from Kimberly, Idaho, examples were found where the satellite-derived data indicated a completely cloudy day and the ground-based measurements showed that it was a completely clear day. Indications point to frost or a small covering of snow on the ground that mimicked visual patterns of fog or low lying clouds. One solution to this problem would be to incorporate ground-based measurements into the satellite analysis package that will help distinguish between sunny periods or low lying clouds in the winter months. Eliminating these errors could significantly impact the size of the RMSE.

A small systematic difference was found when examining diffuse irradiance. When diffuse values were calculated from the satellite modeled global and beam values, they were below the high quality measured diffuse values. This was particularly true during periods of high diffuse values. Also, evaluating the diffuse irradiance over the day also showed the small but systematic underestimation of diffuse values.

A possible source for this difference is that reflection between the ground and clouds amplifies the diffuse irradiance more than assumed in the model. Of course this difference could be associated with particularities with the site studied. This calls for further studies in diverse areas where high quality diffuse irradiance values are available.

While satellite models may use some tweaking their accuracy is approaching the limits of the current technology. Satellite-derived database are fast becoming the standards and will be augmented by ground-based databases that will be used for engineering and scientific studies.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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