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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 [Perez, R., Ineichen, P., Moore, K., Kmiecik, M., Chain, C., George, R., Vignola, F. 2002. A new operational satellite-to-irradiance model. Solar Energy 73(5), 307–317]. 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.

This article presents new and independent tests of this satellite database from one year with high quality data from Kimberly, Idaho that was not used in the original development and testing of the satellite model. The mean bias error of the satellite-derived global and beam irradiance values were 5% and 2% respectively. The standard deviation ranged from 22% for global values to 41% for beam values. The largest discrepancies occur on clear winter days when it is difficult to distinguish between frost or snow on the ground and low lying fog or clouds. It is suggested that ground-based solar or visibility measurements or auxiliary satellite data are needed to augment the satellite cloud cover and snow cover data to reduce errors that can occur during 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 radiation database (Fig. 1). In addition the uncertainty of interpolated data between sites becomes unacceptable as the distance between stations increases (typically in the 20–50 km range). Satellite data can produce a reliable database over large regions on a 0.1° grid (about 10 by 10 km in the Pacific Northwest). However, satellite measurements lack the accuracy and short time interval data necessary for many 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 ($100\ km^2$ in this example once an hour) and ground-based measurements look at only a small portion of the sky and the data are averaged over an hour. Therefore averages and statistics are typically used to compare and contrast these two diverse databases (Zelenka et al., 1999).

The article is organized in the following manner. First, the quality of, and uncertainties in, the data are briefly 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

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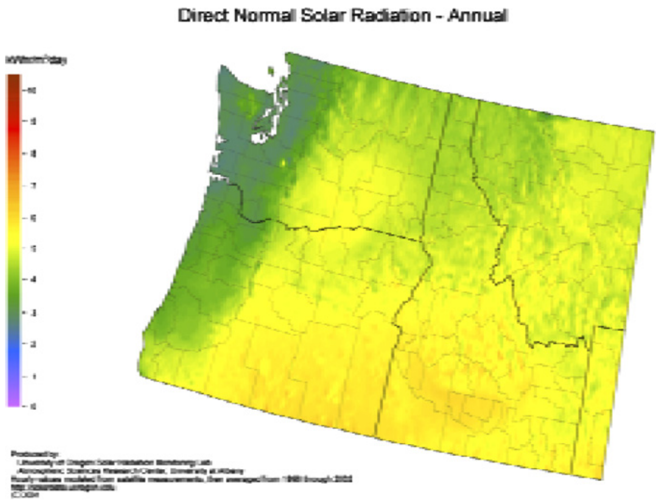

Fig. 1. Annual average direct normal irradiance for the Pacific Northwest from satellite derived solar radiation database (1998–2002).

between the data sets in a search for possible systematic differenced caused by 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 hourly irradiance values from satellite images is found elsewhere (Perez et al., 2002).

Global and direct normal (beam) irradiance hourly values were produced by the satellite model. Diffuse hourly 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.

Calibration of the instruments is traceable to the National Renewable Energy Laboratory, and hence, to the international standard. Data are integrated 5 min values that are downloaded and inspected on a daily bases. The instruments are maintained and cleaned five 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 as an independent check on this 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 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.

The mean bias error (MBE) is less than 5% for global and beam irradiance and about 15% for diffuse irradiance. The standard deviation or root mean square error (RMSE) is about 21% for global irradiance, 41% for beam irradiance, and approximately 54% for 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 variance in the datasets comes from the fact that the ground data are based on one point averaged over a hour as compared to the large area view by a satellite once an hour. One might think that this makes it pointless to make hour by hour comparisons, especially on partially cloudy days. However, with a perfect model, the distribution of the differences should be normal and the averages should be the same. Deviations from a normal distribution and systematic differences identify areas where improvements might be possible.

Figs. 2 and 3 plot the difference between the ground-measured and satellite-derived values against the ground-based measured data. Global data offer the best match.

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 (%)	RMSE (W/m^2)	RMSE (%)
Global	413	−4.9	84	21.5
Beam	481	2.0	200	40.9
Diffuse	132	15.4	60	54.2

Table 2
Typical comparison of MBE and RMSE for Oregon sites used in verification of the satellite model in the region (Vignola and Perez, 2004)

Site	Irradiance/ measure	Average (W/m^2)	MBE (%)	RMSE (W/m^2)	RMSE (%)
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

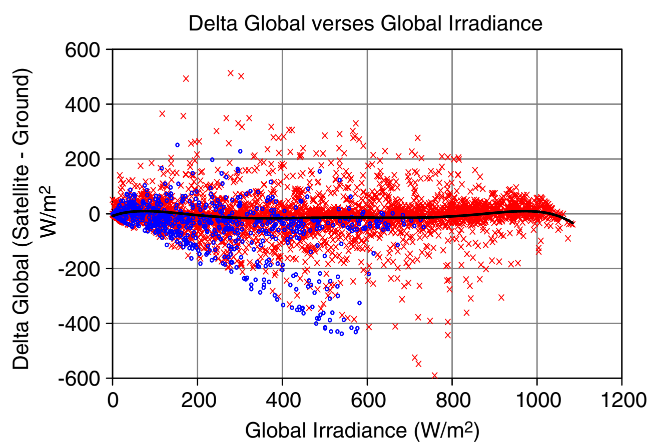

Fig. 2. Difference between hourly global irradiance obtained from satellite modeling and ground-based measurements. Blue circles are for December, January, and February. Red ×s rest of year. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

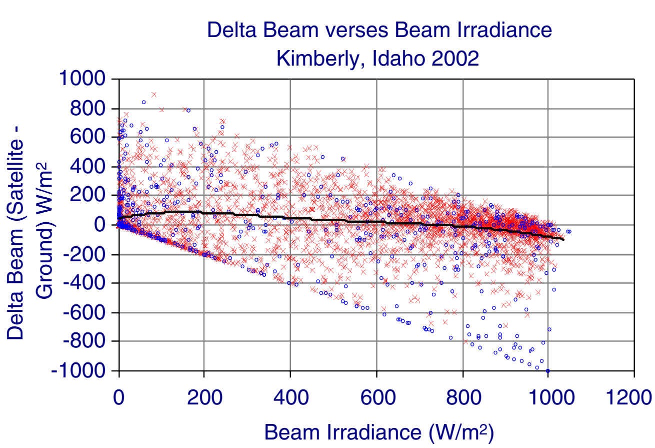

Fig. 3. Difference between hourly beam irradiance obtained from satellite modeling and ground-based measurements. Small blue circles are for December, January, and February data points. The red ×s are data from the rest of the year. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Most differences are in a ±50 W/m^2 band. However, there is a considerable scatter in the data. Some of this is 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 beam data plot (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 29 there is a very poor correlation between the satellite-derived database and the ground-based beam data. Snow days were identified on the 18th, 23rd, and 29th. Snow or frost on the ground has an albedo close to fog or clouds. The Perez satellite model adjusts for the increased albedo, but this leaves a very small dynamic range to distinguish between clear sky with snow on the ground and fog or clouds, especially on flat harvested ground. 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. 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.

It is a 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

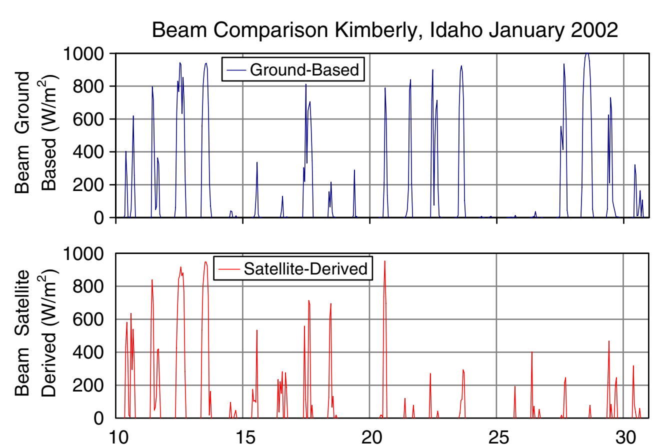

Fig. 4. Ground-based and satellite-derived beam values for January, 2002 at Kimberly, Idaho. Big differences exist on days 21–29 where satellite-derived data indicates little beam irradiance and ground-based measurements show several extremely clear days.

way to examine the data from a different perspective and to evaluate the relative accuracies of the satellite-derived global and beam irradiance. 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 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 type 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 accentuate the systematic errors that are in the measured global data. These systematic errors can be significant (on the order of 10% or 20% of the diffuse values on a clear day) and it would be difficult separate problems associated with the satellite modeling from errors in the calculated diffuse values.

Comparisons of the differences between the two data sets verses zenith angle were carried out, but no systematic difference were 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.

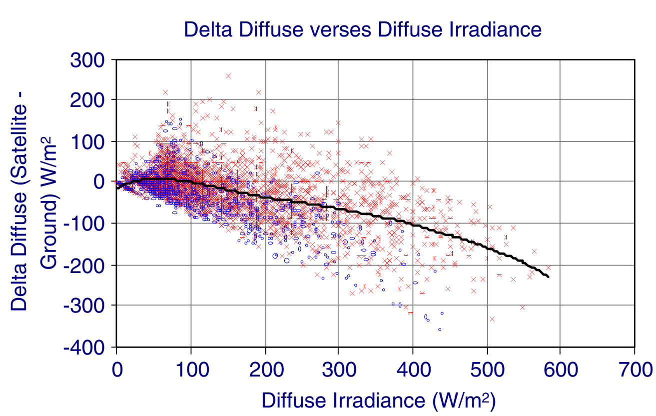

Fig. 5. Plot of the difference between satellite-derived and ground-based diffuse measurements plotted against diffuse intensity.

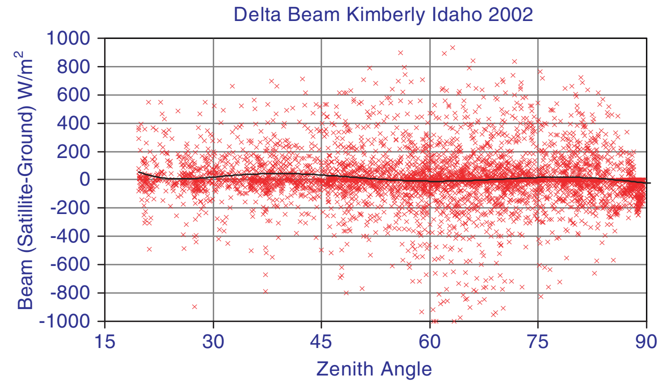

Fig. 6. Plot of the difference between ground-based and satellite-derived beam irradiance verses zenith angle. The trend line show there is little or no systematic deviation about the zenith angle.

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 day, and is highest at noon and is relatively symmetric around solar noon, puts constraints on the possible sources for this 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

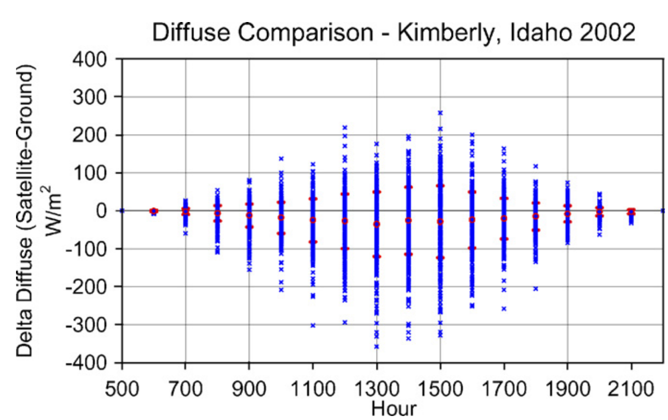

Fig. 7. Difference between diffuse irradiance from satellite-derived values and ground-based measurements plotted as ×s against time of day. The red bars are median and standard deviation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

as the re-radiation into the sky by first class pyranometers. However, it is hard to see how this would get 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 blocks the morning sun (Vignola and Perez, 2004). At both sites the satellite-derived data was higher than observed and possibly 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.

Confidence in using satellite-derived data between ground stations is boosted because the satellite-derived data matches the average Kimberly data so well.

Of course there is the large root mean square error between the ground-based and satellite based measurements, but much of this difference is related to the fact that ground-based data sample one small area of the sky while satellites-derived data are based on 100 km^2 averaged satellite image pixels.

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 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 suggests 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.

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