Using Satellite-Derived Solar Radiation to Create Weather Files of Unprecedented Accuracy and Reliability

Yu Joe Huang¹

¹White Box Technologies, Inc., Moraga CA USA

Abstract

The biggest weakness of weather files has always been the solar radiation, which alone of all the climatic parameters are not measured but calculated using various solar models. The advent of geosynchronous weather satellites has now provided an uninterrupted record of cloud conditions over the entire world for up to two decades. Furthermore, interest in solar power around the world has spurred research in the accurate estimation of solar radiation from satellite observations and support by governmental organizations to make this information freely available or at low cost on the Web. The availability of such solar radiation data, coupled with the concurrent availability of standard weather data, provides the simulation community with a golden opportunity to create weather files of unprecedented accuracy for many more locations than previously possible.

This paper will give an overview of how satellite-derived radiation is obtained, and its accuracy compared to detailed ground measurements and older modelling methods. The paper will also describe practical aspects such as the currently available public Web resources, including their coverage and resolution over space and time, and how to avoid pitfalls in merging that data with data from standard weather reports.

Introduction

Weather data is an unavoidable part of building energy simulations. Ever since simulations were first done, modellers have relied on weather data from public sources, primarily national meteorological bureaus in the early years and more recently, government agencies in charge of renewable energy or solar power. Although reporting weather conditions has always been the core mission of national meteorological bureaus, compiling detailed weather data to be used in building energy simulations, i.e., hourly records of weather conditions for an entire year, was a new development that only began in the 1980s, so that the availability of such data varies greatly from country to country.

Although the primary focus of this paper is on the availability of satellite-derived solar radiation and how to incorporate it into standard weather files, the increased availability of weather station data will also be mentioned, as both are needed in order to create a usable weather file.

Public Sources of Weather Station Data

It is beyond the capability, nor the intent, of this paper to describe the availability of weather data in countries around the world, whose meteorological bureaus can have very different policies about making their data accessible to the general public. What this paper can describe are several public weather data sources that are accessible through the Internet and most often free of charge, or at a nominal subscription rate.

The first of these, which still remains the first go-to web site for weather station data, is the Integrated Surface Database (Lott and Baldwin 2001) that was launched in 2006 and continues to be maintained by the US National Climatic Data Center or NCDC, since 2016 called the National Centers for Environmental Information (NCEI 2019). From 2006 through 2011, the ISD was free only for US government, academic, and non-profit organizations, but since 2012, it has been free for everyone. This database contains up to 40 years of weather data contributed by nearly 20,000 weather stations around the world under a World Meteorological Organization (WMO) agreement, of which over 8,000 stations (roughly 2,000 US and 6,000 non-US) have data of sufficient resolution and period-of-record for developing annual hourly weather files.

Since the ISD is an archive of weather data reported by stations in the participating nations, the data should be the same as that reported by the national meteorological bureaus, unless there is intentional data masking. The benefit provided by the ISD is not only making so much weather data accessible to all, but also in converting data from different places and time periods into a standard DSI-3505 format, so that once software has been developed to read that format, all that weather data becomes readily usable. Furthermore, the DSI-3505 format is well documented, containing 105 columns in fixed-field format for mandatory data elements including wind speed and direction, sky condition, visibility, dry-bulb temperature, dew point temperature, and atmospheric pressure, followed by optional additional data elements in free-field format (NCDC 2003).

For use in building energy simulations, the most useful of these additional data elements is the cloud cover which is used by many solar models to calculate solar radiation. Other additional data elements of potential use in building energy simulations are Liquid Precipitation

(or Rainfall), Visibility, Ceiling Height, and Present Weather.¹

There are now numerous commercial weather web sites that provide weather data from Personal Weather Stations (PWS), of which the Weather Underground (WU 2019) is the largest and best-known. As of January 2019, Weather Underground claims to have a network of over 250,000 weather stations around the world, although they're mostly distributed in North America, Europe, Japan, and Australia (see Fig. 1).

Figure 1: WU weather station network around the world.

For the US, there are roughly 50 times as many WU as there are ISD weather stations. Whereas a typical urban area may have less than a handful of ISD stations, there would be from 50 up to 100 or so WU stations. Like the ISD, the data from the WU network are also in a consistent METAR² reporting format, which makes it easy to be processed into weather files for use in building energy simulations. The main limitations of WU PWS data are (1) more frequent data gaps as compared to ISD stations, (2) shorter periods of record, and (3) absence of cloud cover reports needed to calculate solar radiation. This last deficiency can be addressed by “borrowing” cloud cover data from the nearest ISD station, or better yet, using satellite-derived solar radiation when available, in which case this limitation becomes moot.

Public Sources of Satellite-Derived Solar Radiation Data

Until the advent of weather satellites and the development of irradiance models to derive solar radiation from satellite imagery, the solar radiation seen in practically all weather files have been calculated using analytical models for clear sky irradiance and empirical models for all sky irradiance based on the reported cloud cover and in some models other weather parameters. A good summary of such modelling techniques can be found in Iqbal (1983). Although measured solar data were often used in the development of solar models,

¹ Present Weather refers to weather conditions such as rain, drizzle, snow, etc., reported by a 2-number code.

² METAR or METeorological Aerodrome Report, is the most common format in the world for transmission of observational weather data that has been standardized through the International Civil Aviation Organization (ICAO). Although the format is standardized, the weather data can be transmitted in either SI or IP units.

such data are too rare for their direct use in weather files, which have used models as the only practical way to estimate the amount of solar radiation.

Since solar radiation is the only parameter on weather files that is not measured but rather calculated, it has become one of the most contentious and challenging aspects in the development of weather files. For example, the technical reports for the TMY2, TMY3, IWEC, and IWEC2 weather files have all devoted the most extended discussion to how the solar radiation has been derived (Marion and Urban 1995, Wilcox and Marion 2008, Thevenard and Brunger 2001, Huang et al. 2011).

There are numerous difficulties in modelling solar radiation due to limitations in both the models and the input data. A review of Iqbal (1983) indicates that modelled solar are generally more reliable for the domain (location, time of year. etc.) for which the model was developed, but much less so when applied to other locations and times (Dutton 2006). This is not an indication of bias, but the use of limited measured data to develop the solar models meant that, *ipso facto*, the models are calibrated to that measured data. Another problem in modelling solar radiation is the reliability of the inputs for Cloud Cover, which tend to be reported less regularly than temperature, humidity, or wind, and can also reflect the subjectivity of human observation. The author recalls a station in Africa that reported the Cloud Cover as 0.80 for over 85% of the year.

The use of satellite imagery to calculate solar irradiance has many advantages. The data are comprehensive, uninterrupted, and objective, leading to an unusual situation where solar irradiance can flip from being the least to the most readily available weather parameter of all.

The technology for deriving the incoming solar radiation at the surface from a satellite imagery of the cloud cover and reflected surface radiation has been under development in several countries around the world for almost twenty years (see Perez et al. 2002 as an early example).

Much of the interest and governmental support for such work is due to the needs to the solar power industry, for which having an accurate assessment of solar resources affects the siting and economic evaluation of a solar power plant as much as having a good geological map of oil reserves is to the oil industry.

Starting in the early 2000's there have been commercial companies that have provided satellite-derived solar and weather data to the solar industry, such as Clean Power Research (CPR 2019) and Solargis (2019). Through collaborative agreements with governmental agencies or financial institutions, these companies have made some of their data public, such as CPR's SolarAnywhere portal with hourly solar for the US from 1998-2012 (CPR 2019b) or SolarGIS's solar maps showing average annual irradiance anywhere in the world (SolarGIS 2019b). However, outside of those, their commercial data, e.g., hourly time-series of solar irradiance, costs

from several hundred to several thousand EUR or dollars per site per year.

Starting in the early 2010's, several government-supported national or international agencies have been established to provide satellite-derived solar irradiance for different parts of the world for free or at a low price.

Four Web-based satellite-derived solar data bases or services have been identified covering more than 90% of the world's land area: (1) the National Solar Radiation Database (NSRDB) maintained by US NREL covers the Western Hemisphere from 60° North to 20°

South from 1998 through 2017, and South Asia from 2000 through 2014, (2) the Copernicus Atmosphere Monitoring System (CAMS) supported by the EU covers the Eastern Hemisphere and half of Latin America from 65° West to 65° East and 65° North to 65° South starting from 2004 to date, (3) STRÅNG developed in Sweden covers Scandinavia starting from 1999 to date, and (4) the Amaterass Solar Radiation Consortium in Japan covers the Eastern Hemisphere from 85° East to 165° West and 60° North to 60° South starting from 2008 to date (see Figure 2).

Figure 2: Coverage of public satellite-derived solar radiation databases.

NREL's National Solar Radiation Data Base (NSRDB)

The National Renewable Energy Laboratory (NREL) is a US Department of Energy laboratory with a large solar program. Starting in the 1990s, NREL has produced several iterations of the National Solar Radiation Data Base (NSRDB) that contains 30 years of solar radiation and related meteorological data, which were then used to produce the TMY files that are the *defacto* standard "typical year" weather files used in the US. Version 1 of the NSRDB (NREL 1992) contains 1961-1990 data for 239 US locations, as do the corollary TMY2 weather files (Marion and Urban 1995). Version 2 (Wilcox 2012) contains 1991-2010 data for 1,454 US locations, while the corollary TMY3 weather files contain 1,020 locations (Wilcox and Marion 2012).

Version 1 was based on standard weather station data (the same as what's in the ISD) and was released online as a set of historical weather files. The hourly solar

radiation was modeled using a cloud-based METSTAT model (Marion and Urban 1995).

Version 2 still used weather station data, but the solar radiation was modeled for a subset of 239 major stations (the same as in Version 1), while for the remaining 1,215 stations they were derived from satellite imagery using the SUNY model (Perez et al. 2002).

The current NSRDB is a major change from previous versions both in providing only satellite-derived solar radiation, as well as releasing the data through an interactive Web-based GIS application called the NSRDB Viewer (NREL 2019a, Habte et al. 2017). The current version (v2.0.0) was developed using the Physical Solar Model (PSM) using satellite imagery from 1998 through 2017 "...for approximately 2 million 0.038-degree latitude by 0.038-degree longitude surface pixels (nominally 4 km²). The area covered is bordered by longitudes 25° W on the east and 175° W on the west,

and by latitudes -20° S on the south and 65° N on the north” (NREL 2019b).

The NSRDB Viewer displays an interactive base map of the world, with the areas covered by the NSRDB indicated by isopleth maps of solar radiation (see Figure 3). The user can drag a pointer to a location, and select the years, data attributes, and download options such as using UTC or local time, half hour or hour intervals, etc. Once the data are ready, the user receives an e-mail with a download link.

Figure 3: NSRDB Data Viewer Selection Screen.

For users wishing to download large amounts of data, there are utilities using python and wget scripts, but these require considerably more set-up effort and are also limited in the number of calls per day.

While the NSRDB Viewer also provides meteorological data, these are not from observations but from MERRA reanalysis (Roth 2019) and should be regarded with caution. The Viewer can also provide “typical year” data extracted from the time-series, but these should also be regarded with caution for the same reason. Lastly, it should be noted that the solar irradiances are instantaneous values and not aggregated totals as needed for building energy simulations. There is more discussion about this topic later in this paper.

An interesting inclusion in the NSRDB is that of satellite-derived solar irradiance for South Asia (see Figure 2). This data set was created in 2008 as part of the India-U.S. Energy Dialogue supported by the US State Department and represented NREL’s first attempt to migrate from modeled to satellite-derived solar radiation. This data set was done in collaboration with the State University of New York at Albany using the SUNY Semi-Empirical Model (Perez et al. 2002) and is limited to 2000-2014 at a grid size of 0.1×0.1 degrees with 1-hour time resolution for the area between 5° to 38° N latitude and 67° to 98° E longitude.

Copernicus Atmosphere Monitoring System (CAMS)

“CAMS is one of six services that form Copernicus, the European Union’s Earth observation programme... and implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF) of behalf of the EU...To

acquire all the observations that are needed to produce the CAMS services, ECMWF collaborates with the European Space Agency (ESA) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)” (CAMS 2019a).

The CAMS Radiation Service provides time-series of actual solar irradiance for roughly a third of the earth’s surface from -66° to 66° in both latitude and longitude, which covers all of Europe, Africa, the Middle East, European Russia, and the eastern 2/3 of South America starting from February 2004 to two days before the present (Schroedter-Homscheidt 2018, CAMS 2019b).

Similar to the NSRDB Viewer, the CAMS Radiation Service web site allows users to select a location with a cursor, although it’s probably easier to enter the latitude, longitude, start and end date immediately below the map (see Figure 4).

Figure 4: CAMS Radiation Service Selection Screen.

In contrast to the NSRDB, CAMS provides only solar data, but allows users to select the time step from hourly down to 15 minutes or even 1 minute. All data are provided in Universal Time. Once the data has been processed, the file can be downloaded immediately. For users wishing to download large amounts of data, the CAMS support staff provides sample wget scripts, although there are limitations in the amount of data that can be downloaded. Another difference from the NSRDB is that the solar irradiances are aggregated totals and not instantaneous values.

STRÅNG

STRÅNG has been developed by SMHI, the Swedish Radiation Safety Authority, with support by the Swedish Environmental Protection Agency, to provide satellite-derived solar radiation for Nordic countries, although neighboring countries in northern Europe are also covered (see Figure 5 for coverage). The database began in 1999 with an initial resolution of 22×22 km that was changed to 11×11 km in 2006, and again to 2.5×2.5 km in 2017. The Web interface is very simple and straightforward, consisting of five questions for the radiation parameter, beginning and ending dates, latitude and longitude. Once the request is submitted, STRÅNG will generate the file and return it to the user’s computer.

The turnaround tends to be slow³, nor has any capability been found for downloading multiple data sets offline. The online documentation is also scarce, making it uncertain whether the solar radiation is instantaneous or aggregated.

STRÅNG - a mesoscale model for solar radiation

Figure 5: STRÅNG coverage and selection menu
note: the colored isopleth map covers only Scandinavia, but solar radiation data exist for the domain of the larger map.

Amaterass Solar Radiation Consortium

The Amaterass Solar Radiation Consortium is a nonprofit corporation established in Japan in 2010 to “...provide solar radiation data based on satellite observations and support data distribution efforts and promote their usage.” (Amaterass 2019). Membership in the Consortium is free for Japanese research and academic institutions, but has an annual fee of \$3,000-\$10,000 for commercial entities.

Amaterass currently processes satellite imagery from the Himawari-8 weather satellite launched in 2014, but also has processed data from earlier Himawari satellites going back to the early 2000s. The methodology is described in Takenaka et al. (2011). Consortium members can obtain solar irradiance files for two domains: (A) Japan and Korea at a resolution of 0.01 degree, and (B) entire satellite domain from 60° S to 60° N in latitude and 85° to 155° E in longitude at a resolution of 0.04 degree (see Figure 6).

Compared to the previous three public sources for satellite-derived solar radiation, the Amaterass data are closer to raw data and require considerably more processing before they can be imported into weather files. What the Consortium has done is to convert each satellite image to files containing arrays of 2521 x 3001 numbers for Domain A, or 3000 x 3000 numbers for

Domain B that give the solar irradiance for each point of the array at that time step. Therefore, to get the annual time series for any location would require downloading 8,760 files (if done for the lowest temporal resolution of one hour), each of which has a size of 32MB compressed and 60MB uncompressed, for a total of nearly 300GB even when compressed.

Domain A: Japan and Korea

Domain B: East Asia, Oceania, and West Pacific

Figure 6: Domains covered by the Amaterass Solar Radiation Consortium.

The author has processed one year (2017) so far, and found that downloading the files took more than two weeks, while drilling down through the 8,760 files in chronological order took half a week to develop the software and then another two days of solid computer time.

The author also learned during this trial period that the observation time for each pixel is different and can vary as much as a half hour from the time shown in the file name! Lastly, questions rose about the data that have

³ The website states, “As a rule of thumb it will take approximately 30 seconds to retrieve one month of hourly data.”

still not been resolved and will be discussed later in this paper.

Satellite-derived solar from the Himawari-8 for Australia can also be obtained from the Australian Bureau of Meteorology at a low cost (BOM 2019). In 2017, the author purchased such data for Australia 1998-2016, although following enquires about updates in 2017 and 2018 have gone unanswered. Similar to the data from Amaterass Consortium, the solar data from BOM was received on a movable hard drive containing over 130,000 files, each one containing gridded data for all of Australia for one hour.

Accuracy of Satellite-Derived Solar Radiation

Because of the amount of work being done on satellite-derived solar radiation around the world, it should not be surprising there have been numerous papers on their accuracy compared to ground measurements (Marchand et al. 2018, Lave and Weekley 2016, Vignola et al. 2007, Perez et al. 1997). The cited papers report small biases in hourly data from 1-7%, and RMSE of around 12%.

The author in Mar. 2019 compared the NSRDB to solar radiation from a research solar station on the California coast (see Figure 7).

Figure 7: Comparison of measured hourly solar to NSRDB for 2017 Arcata.

The random scatter is because the measured solar is at a single site while the satellite-derived solar is for a 3-km grid cell. However, the correlation for the other hours is strikingly close with no evident bias.

Perhaps the most relevant comparison would be how well the satellite-derived daily solar matches measurements as compared to older modeled methods. Huang 2011 compared measured daily modeled to modeled solar and satellite-derived solar for a location in California (see Figure 8). The improvement is quite apparent, with the satellite-derived solar showing no bias and a R^2 of 0.989.

Importing Satellite-derived Solar Radiation into Weather Files

Ignoring for now the data transposition and time synchronization problems in data sets like Amaterass, importing satellite-derived solar radiation into a standard weather file can be as simple as a line-by-line insertion or substitution of original modelled radiation, provided that the nomenclature and time convention are consistent

Figure 8: Comparison of measured daily total solar to modeled and satellite-derived solar for 2009 Sacramento.

between the two sets of data. Unfortunately, often they are not, making it important to check and if necessary make further adjustments to the solar data.

The main source of problem has not to do with the solar data themselves, but with synchronizing the time with that in the weather files. Of the four sources of satellite-derived radiation mentioned in this paper, only the NSRDB gives users the option to download the data in local time, the other three all use Universal Time (UTC). Converting UTC to local time is easy for locations with integer time zones, but for locations with fractional time zones, e.g., India (UTC+5.5), Iran (UTC+3.5), Nepal (UTC+5.75), etc., downloading subhourly data (if available) or else interpolation would be necessary.

The difficulty of time synchronization is further complicated because there are two ways by which solar radiation is reported, either as a rate or as the total over the time step. In North America, solar radiation on a weather file (and expected as such in building energy simulation programs) is the aggregated total over the previous time step, e.g., Hour 12 would show the total amount of solar from 11:00 to 12:00. In most other countries, it is the instantaneous rate at the time step, e.g., Hour 12 would show the rate of solar radiation at 12:00. Since the vast majority are hourly weather files, the units would be the same, i.e., 1 watt-hour = 1 W/hr, so the only difference between the two would be in time of 30 minutes.

This difference in reporting also occurs in the satellite-derived data, which is dependent more on the capabilities of the weather satellite than the origin of the data. For example, the NSRDB reports the rate, even though it originated in the US, while CAMS reports the totals, even though it originated in Europe! Although Amaterass data can be aggregated to totals, that would require downloading six times as many files (every 10 minutes rather than every hour) and not deemed to be feasible. STRANG only provides hourly data, and it's still unclear whether they are totals or rates.

Since it's possible to select data at 00:30 for NSRDB and Amaterass, that would be a simple way to have them conform to the North American convention, e.g., use the solar rate at 11:30 for the aggregate total for Hour 12. Since the NSRDB also provides data at 00:00, the author has been calculating the hourly solar as

$$0.25 \cdot \text{SOL}_{-1\text{hr}} + 0.50 \cdot \text{SOL}_{-30\text{min}} + 0.25 \cdot \text{SOL}_{0\text{hr}} \quad (1)$$

Although a 30-minute discrepancy in the solar radiation may seem like a minor difference, it can cause numerous strange effects, especially at sunrise and sunset hours when the energy simulation program may think the sun is below the horizon the entire hour, while the solar data indicate there is solar gain, and vice versa.

For the past year and more, the author has tried with moderate success various methods to detect synchronization problems, e.g., counting the number of hours with non-zero sun angles that indicate the sun is

above the horizon and yet there's no solar radiation, etc. In 2018, the author learned of a graphical method that was found to be very useful. The method plots the ratio between the global and the extraterrestrial horizontal irradiance (K_t/E_t) against the ratio between the diffuse and global horizontal irradiance (K_d/K_t). Figure 9 shows the striking difference in the plots when the solar radiation is synchronized (middle) compare to when they're ahead (left) or behind (right) by a half hour. The thick red line shows the theoretical relationship as

Figure 9: K_d/K_t versus K_t/E_t for Devil's Island WI 2016 with the time stamp for solar irradiance at various shifts.

calculated by the well-known Erbs Model (Erbs, Klein, and Duffy 1982).

Although this plotting routine was implemented as a way to look at time synchronization, a number of issues occurred when it was applied to the Amaterass solar data (see Figure 10). Not only did the points not fall along the Erbs Model line, but there were also two distinctly different distributions. As of January 2019, this issue is still under investigation.

Figure 10: K_d/K_t versus K_t/E_t for Beijing China, based on Amaterass satellite-derived solar data.

Conclusions

Four Web-based satellite-derived solar databases or services have been identified covering more than 90% of the world's land area: (1) the National Solar Radiation Database maintained by US NREL covers the Western Hemisphere from 60° N to 20° S from 1998 through 2016, and South Asia from 1998 through 2014, (2) the Copernicus Atmosphere Monitoring System (CAMS) supported by the EU covers the Eastern Hemisphere and half of Latin America from 65° W to 65° E and 65° N to

65° S starting from 2004 to date, (3) STRÅNG supported by covers Scandinavia starting from 1999 to date, and (4) the Amaterass Consortium in Japan covers the Eastern Hemisphere from 85° E to 165° W and 60° North to 60° South starting from 2008 to date (see attached map).

The solar radiation data from each of these databases or services are all somewhat different, requiring differing techniques to process and synchronize to the weather station reports. The author has developed the necessary software and is now able to merge satellite-derived solar with standard weather files in volume. For three of the databases (NSRDB, CAMS, STRÅNG), the results look normal and make a definite improvement to the weather files. However, for the fourth database (Amaterass), questions remain about the extracted solar that still need to be addressed and hopefully resolved, in which case it would be possible to obtain satellite-derived solar radiation for over 90% of the world, all except Chile and southern Argentina, Central Asia and Western China (Xinjiang) between 65° and 85° E and above 35° N, and the Polar regions of Canada, US (Alaska), and Russia (Siberia) above 60° N.

CAMS, STRÅNG, and Amaterass are operated like Web services, providing satellite-derived solar data in near real time. NSRDB, however, is more like an annual project, so that (if funded) there will be a 10-month delay for the past years solar data to appear on the NSRDB Viewer. In such cases, or with data sets that are no longer supported, i.e., NSRDB's South Asia set that ended in 2014, the old data can still be useful for calibrating existing solar models.

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Nomenclature

Kd	Diffuse Horizontal Solar Irradiance
Kt	Global Horizontal Solar Irradiance
Et	Extraterrestrial Horizontal Solar Irradiance
RMSE	Root Mean Square Error
SOL	Solar parameter, either Global Horizontal or Direct Normal

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