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Progress on an Updated National Solar Radiation Data Base for the United States

Preprint

Conference Paper
NREL/CP-560-37956
September 2005

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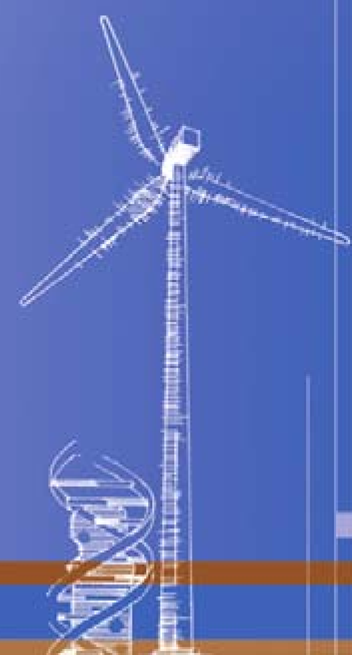
Prepared for ISES 2005 Solar World Congress
Orlando, Florida
August 6-12, 2005



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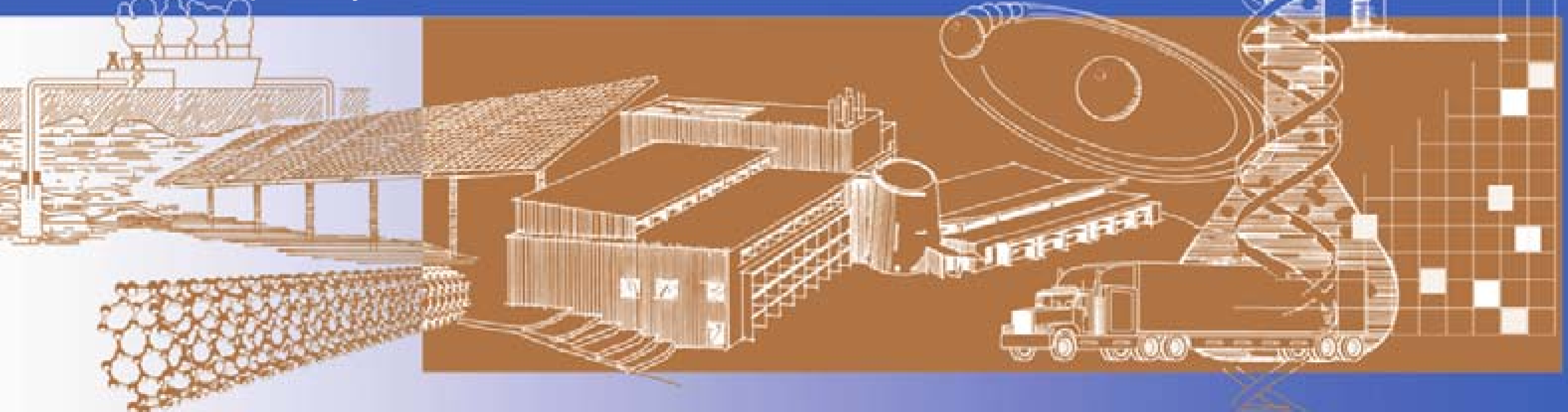

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Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

PROGRESS ON AN UPDATED NATIONAL SOLAR RADIATION DATA BASE FOR THE UNITED STATES

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ABSTRACT

In 1992, The National Renewable Energy Laboratory (NREL) released the 1961-1990 National Solar Radiation Data Base (NSRDB), a 30-year set of hourly solar radiation data. In 2003, NREL undertook an NSRDB update project for the decade of 1991-2000. Recent work on the project includes the production of a two-year test data set, which allowed us to evaluate models, investigate the availability and suitability of model input data, survey the availability of surface meteorological data, expand the scope of a new satellite-based solar radiation model, and propose a plan for a 1991-2000 NSRDB update. This paper describes recent work and evaluation of the test data set. Preliminary recommendations will be reviewed by an expert committee involved since the inception of the update project, and from that review we will develop a full data base update plan.

1. INTRODUCTION

In 1992, the National Renewable Energy Laboratory (NREL) released the 1961-1990 National Solar Radiation Data Base (NSRDB), a 30-year, 239-station data set of measured and modeled solar radiation and accompanying meteorological data (1). In 2003, NREL investigated the feasibility of producing a 1991-2000 update of the NSRDB (2) and devised a proof-of-concept project to investigate solutions to several obstacles, including the switchover by the National Weather Service (NWS) to the Automated Surface Observing System (ASOS) for routine meteorological observations. For this proof-of-concept, we produced a two-year test data set for 33 stations as part of a model evaluation process. During this work, we:

- Acquired solar irradiance data for validation
- Modified the METSTAT solar model inputs for ASOS and satellite cloud product
- Evaluated a new model from the Northeast Regional Climate Center (NRCC) that uses ASOS and satellite cloud inputs
- Produced a gridded solar product using the State University of New York at Albany (SUNYA) satellite model
- Investigated the feasibility of new clear sky algorithms for solar models
- Developed improved atmospheric aerosol and water vapor estimates
- Evaluated differences among the candidate models
- Made preliminary recommendations for how to proceed with a 1991-2000 NSRDB update.

2. PROJECT STATUS

This section describes significant activities on the proof-of-concept project to investigate the feasibility of producing an updated NSRDB.

2.1 Solar Measurements

A significant part of the test case effort was to find, acquire, and quality assess surface solar measurements to form a data set for model evaluation. Thirty-three sites with nearby meteorological stations were identified and data acquired from various solar measurement networks, including SURFRAD, ISIS, University of Oregon, and the NREL HBCU network. Data were downloaded to NREL computers, imported to an interim database, and then evaluated with several quality assessment tools.

Five of the measurement sites used for evaluation produce data collected by rotating shadowband radiometers (RSR), a low-cost, single sensor device that outputs global, direct, and diffuse irradiance using an automated shade-unshade device. While this method produces fairly accurate values of global and direct beam irradiance (roughly within 5% on a daily total) the diffuse values are systematically low by as much as 40% on clear days because of the spectral characteristics of a photodiode-based sensor. However, these shortcomings in RSR measurements can be partially overcome through characterization and post-processing (3). Using RSR data from the University of Oregon Solar Monitoring Laboratory, an analysis of the measurement error produced a method that corrects the sensor's global and diffuse measurements independently. However, additional work is required to validate the method on other sites.

2.2 ASHRAE/NRCC Model

Recently the NRCC, through funding from American Society of Heating, Refrigerating and Air-Conditioning Engineers, produced a solar radiation model aimed primarily at supporting applications for building energy design (4). That model computes global and direct horizontal irradiance from the product of extraterrestrial direct beam, modified by the cosine of the zenith angle, and transmittance functions for typical atmospheric attenuation, Rayleigh scattering, gas and water vapor absorption, aerosol absorption, and cloud absorption. The NRCC ran this model using 1999 and 2000 meteorological input data provided by NREL from the test data set, then sent the output data back to NREL for evaluation.

2.3 SUNYA Satellite Model

One goal of the updated NSRDB is a spatial resolution greater than the ancillary interpolated products that were originally produced from the 239 NSRDB meteorological stations. Toward that end, the project evaluated a model from the Atmospheric Sciences Research Center (ASRC) at SUNYA (5). This SUNYA model derives 10-km pixel solar estimates based on differences between a pixel's clear-sky reflectance as seen by the satellite and the brighter values that occur with increasing cloud reflectance of incoming solar radiation.

During this year's work, the model was modified to accept aerosol optical depth (AOD)-based clear sky limits rather than Linke-based model limits. The AOD-based models currently used are a simplified version of the SOLIS model (6) for clear-sky global horizontal irradiance (GHI) and the Bird model for clear-sky direct normal irradiance (DNI). Evaluation of this model used special model runs for 1999 and 2000 for the 33 sites, in addition to full resolution grids for the 48 lower states, Hawaii and the portion of Alaska below 60º latitude available in our archive. Figure 1 shows a map of annual direct normal averages from this data set.

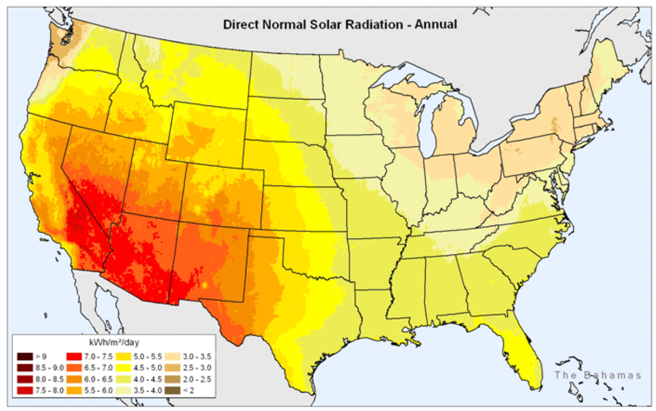

Fig. 1. Annual direct normal irradiance on 10 km grid, derived from the SUNYA satellite model.

The ASRC has satellite imagery archived since mid 1998, leaving a large data gap for most of the 1990s. Access to older satellite imagery is possible, but not access to older snow cover data (a model input parameter), implying less accurate winter model performance in northern states. Another approach that may be considered for prior years would be to relate monthly-averaged post-1998 model runs to time-coincident NASA Solar Meteorology and Solar Energy (SSE) gridded data. The SSE data from prior years could be used to generate high-resolution irradiances (assuming that the micro-structure within the SSE grid cells remains constant).

Two problems exist for satellite modeling of solar radiation for Alaska above 60º latitude. The SUNYA archive does not include imagery above 60º (although GOES effectively extends to about 70º in Alaska), and the angular view of the GOES satellite above 60º may adversely affect the performance of the model. A possible solution could be to increase the northern border to 70º in future archival data and pattern microstructures to the SSE grid as mentioned above.

2.4 Clear Sky Algorithms

All of the solar radiation models evaluated here employ a clear-sky algorithm that attempts to produce an irradiance that can subsequently be modified with cloud cover. The validity of the clear sky component figures prominently because many applications seek to find the greatest solar resource, which typically only occurs under the clearest skies. Because cloud modifiers can be applied to any clear sky value, improvements in the clear sky algorithm would improve the overall model performance.

To evaluate the global clear sky performance of the models, we produced special data sets from each model where the cloud input values were set to zero sky cover. These clear-sky values were compared with the recently developed REST2 model (7) and a data set with identified clear sky measurements. Although the REST2 model showed significant improvements over other clear-sky algorithms during its development using data from Bondville, results for the NSRDB evaluation showed that all models, including REST2, produced up to ±20 Wm^{-2} Root Mean Square errors (RMSE), and depending on the site, about ±10 Wm^{-2} Mean Bias Errors (MBE). These results may be an effect of using long-term averages for some model input data (in particular, aerosols and precipitable water) that do not match actual conditions for the measured data, or the variability may simply be within the measurement uncertainty limits. Additional work will be required to better understand the comparisons.

2.5 METSTAT Model

The changeover to automated stations by the NWS eliminated the human observed total and opaque sky cover amounts used for inputs to the METSTAT model (8), which was used for the 1961-1990 NSRDB. To adapt the model to currently available data sets, we derived equivalent sky cover inputs (total and opaque cloud cover) from a combination of ASOS and ASOS supplemental cloud measurements (the latter derived from GOES satellite data). ASOS detects clouds to 12,000 ft, while the ASOS supplemental cloud measurements provide sky cover estimates for heights above 12,000 ft for a 50 km x 50 km area centered upon the ASOS station.

Combining the low cloud amounts determined from the ASOS data, and the middle and high cloud amounts determined from the ASOS supplemental data, produced an equivalent total cloud estimate. Applying opacity factors based on cloud types inferred from cloud height produced estimates of opaque cloud amounts (low clouds opacity factor = 1.00; middle clouds opacity factor = 0.93; and high clouds opacity factor = 0.44). While availability of ASOS data for the 33 test sites was 95% or greater for 1999 and 2000, the ASOS supplemental cloud data was only available for about 70% of the period, with no data available for Alaska. About 1% of the ASOS supplemental data was unusable due to file format errors.

The original METSTAT included an algorithm to compensate for human perception of cloud amounts nearer the horizon being greater than actual. This feature was eliminated because of the strictly vertical view of the ASOS cloud detector.

2.6 Improved Aerosol, Water Vapor and Ozone estimates

The 1961-1990 NSRDB used only DNI measurements to estimate broadband Aerosol Optical Depth (BAOD). Today there is much less measured DNI data available, but much more aerosol data from other sources, including sun photometers and satellite-based estimates. These sources produce data that are spectral rather than broadband. A combination of surface sun photometry, satellite data from the NASA MISR project, and legacy DNI estimates of BAOD allowed creation of monthly mean estimates of BAOD for all locations in the U. S. Spectral AOD data are converted into BAOD using estimated Alpha parameters from sun photometry. All BAOD is adjusted to local elevation, utilizing an exponential function (9). These monthly values were smoothly fit to daily values using a mean-preserving interpolation method (10).

For water vapor, NREL used the NASA Water Vapor Project (NVAP) dataset for daily estimates of water vapor on a 1º x 1° grid. NVAP integrates sounding data with satellite measurements of atmospheric water vapor. For the years 1983–1999, NVAP provides once daily estimates of water vapor on a 1º x 1º worldwide grid. For years 2000 and beyond, NVAP provides the data on a 0.5º x 0.5º grid twice daily. These data were interpolated in space to the location of each of the 33 NSRDB test stations and interpolated in time to provide hourly data for all stations for the years 1999 and 2000.

For total column ozone, daily satellite observations from the Total Ozone Mapping Scanner (TOMS) are available once per day on a grid with spatial resolution of 1º in latitude and 1.25º in longitude. The missing data are replaced with long-term mean values from that location.

2.7 Data Filling Methods

Serially complete data was a primary goal of the 1961–1990 NSRDB. However, maintaining this restriction for the 1991–2000 update may not be practical given the changes in the NWS network during the switchover to ASOS. The intersection of all qualifying stations for four rather than three decades would result in an even smaller roster of sites.

Despite the noted disadvantages of ASOS observations for this project, one distinct advantage may be an increased pool of sites with more consistent observations. Hence, it may be an advantage to include as many sites as possible with the expectation that more and more sites with a 30-year period of record will emerge in the future. Nonetheless, short gaps of data can be expected at any operating site, and reasonable efforts will be made to fill all missing model input data (2).

2.8 Database and software

A simple flat-file database was developed to serve the needs of our two-year test set. Records held approximately 130 fields that included all input parameters, output fields for all models, and numerous flag and ancillary fields. For speed and programming simplicity, file records were a binary image of the data structure developed for the C programs, allowing rapid I/O without the need for complex data formatting. The full production database will likely be similar to the concept used in the test database. A more conventional final output format will be developed for database distribution.

Most software development for the test data set involved programs to read the many and varied formats of input data to transfer the values to the database. To provide easy access to the binary data, we developed a Windows-based extractor tool, allowing a user to select any of the database fields in any order and output them in a custom-configured comma-separated value ASCII file.

3. ANALYSIS OF MODELS AND METHODS

The analysis of the test data sets and evaluation of the results are treated more thoroughly elsewhere (11). The analysis data set included those hours from all sites for which measured and output data for all models were concurrent. This process completely eliminated two sites from the analysis because there were no overlapping data (Barrow, Alaska and Hermiston, Oregon). The analysis compared the measured data to the output for each model using the statistical measures of RMSE, MBE, frequency distributions, probability distributions, correlation, and autocorrelation.

The analysis reveals little significant differences among the three candidate models (NRCC, SUNYA, and METSTAT). The GHI monthly mean daily total (MMDT) MBE for all models ranged from -0.06 to 1.73%, and the RSME ranged from 5 to 8%. The uncertainty of the validation data is estimated to be about 5-10%, which easily encompasses these errors. The DNI MMDT RMSE was somewhat larger, but all models were very close, ranging from 13.7-15.0%. Figure 2, which shows errors for hourly global irradiance, illustrates not only the closeness of the model performance, but also the similarity of excursions for all models in site-to-site variability. These excursions may indicate a common bias in the models or input data, or an error in the ground validation data. Whatever the cause, it is important in this context to note that all models perform similarly. Figure 3 shows measured versus modeled for DNI MMDT.

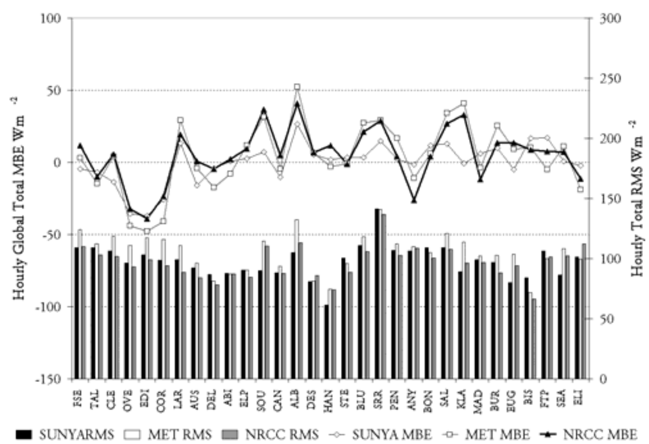

Fig. 2. MBE (lines, left scale) and RMSE (Bars, right scale) for modeled hourly total GHI by site and by model. From (11)

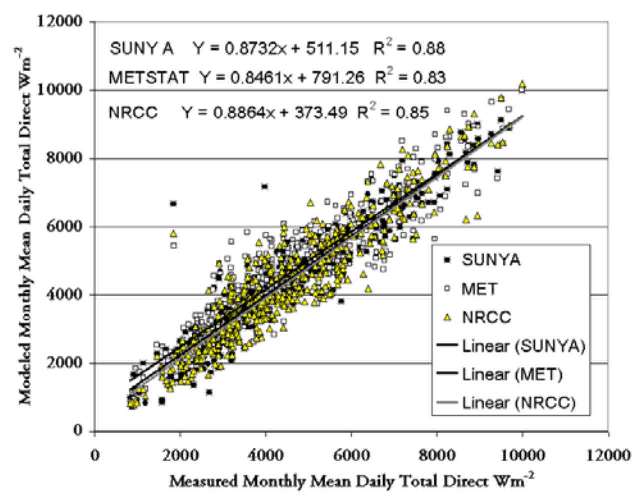

Fig. 3. Modeled versus measured DNI monthly mean daily totals, regression fit, and correlation coefficients by model

4. RECOMMENDATIONS

From a meeting of NSRDB experts in 2003, goals for an updated NSRDB included both a ground-based data set to match as close as possible the original NSRDB and a new high-resolution gridded data set (2). The committee identified four pivotal questions to guide the direction of the update plan: 1) What solar model should replace the METSTAT model, 2) whether to expand the scope of NSRDB to include a gridded solar data set, 3) how to determine which sites to include in the update, and 4) how to characterize the compatibility of the new data set with the original NSRDB. Additionally, we expect to address the question of producing annual updates of the NSRDB as new data become available. Based on answers to those questions, we will make recommendations on how to proceed with a full ten-year update of the NSRDB. These preliminary recommendations are discussed below.

4.1 Solar Models

Test data evaluation has shown little or no significant differences among models in their ability to produce solar irradiance estimates. The SUNYA model, however, has a clear advantage with its high-resolution output grid and a simpler, more reliable input data stream. If it is possible to produce a gridded satellite-based data set for all ten years, we recommend using the satellite model and choosing appropriate grid pixels to produce the ground-based data set (station-based, as in the original NSRDB). If the ten-year goal for the SUNYA model is not possible, we recommend using it for as many years as possible concurrently with a ground-based model. This approach allows the start of a longer-term gridded data set.

In the likely event that data input data availability prevents production of a ten-year satellite-based data set, we must devise a hybrid scheme using ground-based models. For years prior to the ASOS switchover, we recommend using the unmodified METSTAT model, which is eminently compatible with the original NSRDB. However, for the ASOS period, with no clear performance advantage between the modified METSTAT and NRCC models, the decision rests with other factors, primarily ease of use and availability of input data. An investigation continues for these issues.

4.2 Missing Data and Site Selection

The original NSRDB contained data for 239 stations that represented all sites for which a 30-year period of meteorological and other model input data could be obtained or interpolated. For the 1991-2000 update, we recommend including all sites that have significant periods for which solar modeling could be accomplished despite missing data. *Significance* in this context has yet to be defined, but could be based on a minimum percent of the ten-year period or intact spans of some minimum number of years. While gaps in the data frustrate efforts for a clean merge with the original NSRDB, missing data may not hamper many end-user applications. We recommend devising a dual classification system or even two distinct data sets to include as many sites as possible. A classic NSRDB data set would include those sites for which an uninterrupted period of record is available. All other sites would populate an ancillary data set for applications not requiring serially complete data.

4.3 Compatibility with the original NSRDB

By using different models and different methods of cloud observations, discontinuities or inconsistencies may exist in data quality over the decade of the 1990s. We recommend characterizing the differences between the old and new NSRDB by 1) comparing model performance against measured data for both the original METSTAT model and the model used for the update, and 2) using the NASA SSE data grid for the 1990s as a reference for identifying differences among the hybrid methods. These characterizations will also help illuminate the limitations of the NSRDB for certain critical applications (such as climate change).

4.4 Future updates

At the current level of funding, the planned release of the updated NSRDB will occur in 2006, which will leave even the most recent data five years old. Part of our production plan includes a method to produce incremental annual updates, which will be immediately applied to years 2001–2005, then annually through 2009. In 2011, a 2001–2010 decade update will be produced, funding permitting.

5. CONCLUSION

We have shown the feasibility of an updated NSRDB that not only extends the period of record for the existing NSRDB, but also exploits new technologies that pave the way for greatly enhanced solar resource assessment applications. We have made recommendations to overcome obstacles in the production of an updated NSRDB and will develop a comprehensive plan to complete the project sometime in 2006.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
September 2005	Conference Paper	

4. TITLE AND SUBTITLE	
Progress on an Updated National Solar Radiation Data Base for the United States: Preprint	**5a. CONTRACT NUMBER** DE-AC36-99-GO10337
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)	
S. Wilcox, M. Anderberg, R. George, W. Marion, D. Myers, D. Renne, W. Beckman, A. DeGaetano, C. Gueymard, R. Perez, M. Plantico, P. Stackhouse, and F. Vignola	**5d. PROJECT NUMBER** NREL/CP-560-37956
	5e. TASK NUMBER PVA57501
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	NREL/CP-560-37956

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	
	10. SPONSOR/MONITOR'S ACRONYM(S) NREL
	11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT

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Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*

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15. SUBJECT TERMS

solar radiation data base; nsrdb

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			
Unclassified	Unclassified	Unclassified	UL		**19b. TELEPHONE NUMBER** (*Include area code*)

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F1147-E(12/2004)