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Progress on an Updated National Solar Radiation Data Base

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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 April 2003, NREL convened a meeting of experts to investigate issues concerning a proposed update of the NSRDB. The panel determined that an important difficulty posed by the update was the shift from manual to automated cloud observations at National Weather Service stations in the United States. The solar model used in the original NSRDB relied heavily on the methodology and resolution of the manual cloud observations. The meeting participants recommended that NREL produce a plan for creating an update using currently available meteorological observations and satellite imagery. This paper describes current progress toward a plan for an updated NSRDB.

1. INTRODUCTION

In 1992, the National Renewable Energy Laboratory (NREL) released the 1961-1990 National Solar Radiation Data Base (NSRDB), a 30-year data set of measured and modeled solar radiation and accompanying meteorological data, with solar estimates based on the Meteorological/Statistical (METSTAT) solar radiation model developed at NREL (1). In recent years, interest has grown for updating the NSRDB to include the decade of the 1990s or possibly beyond. In April 2003, NREL convened a meeting of experts to investigate the feasibility and desirability of an NSRDB update. Meeting participants concluded that the greatest obstacle to an update was a change in the measurements of cloud cover by the National Weather Service (NWS). During the 1990s, the NWS migrated from a manual (human) system of full-sky cloud observations to the Automated Surface Observing System (ASOS) method, which derives cloud cover from laser ceilometer observations at the zenith. The ASOS cloud observations are not compatible with the necessary inputs for the METSTAT model. This makes it impossible to create an updated NSRDB by simple METSTAT model runs using currently available meteorological data.

Meeting participants agreed that an update was desirable to provide constituents with the most recent climatology and possibly a data set with enhanced spatial resolution. Additionally, recent advances in satellite-based techniques for modeling solar irradiance and cloud algorithms may provide an effective solution to circumvent the change from manual to automated cloud observations.

From the meeting came a multi-stage plan for NREL fiscal year October 2003 to September 2004. This effort will produce a small-scale evaluation database, enabling us to investigate database production issues, assess input data availability and quality, and develop modeling alternatives. This paper discusses plans and preliminary results for tasks identified to produce the test-case database:

- Acquire and quality assess available measurements of solar irradiance data for validation
- Research data filling methods (for missing periods of input meteorological data)
- Modify the METSTAT solar model inputs for ASOS and satellite cloud product

- Evaluate a new American Society of Heating, Cooling, and Refrigeration Engineers (ASHRAE) model (using ASOS and satellite cloud inputs)
- Produce a gridded solar product using State University of New York at Albany (SUNYA) satellite model
- Investigate feasibility of new clear sky algorithms for solar models
- Develop improved atmospheric aerosol and water vapor estimates
- Acquire a comparison satellite-derived irradiance product from the National Aeronautics and Space Administration
- Quantify differences between the original NSRDB methods and update methods.

The year's effort will culminate with a report of recommendations on the feasibility of and preferred methods for producing an updated database. That report will provide the Department of Energy and other interests with the information necessary to allocate resources for a full-scale NSRDB update.

2. PROJECT STATUS

This section describes significant issues or activities that are either underway or planned.

2.1 Cloud Observations

The difficulty of changing from manual to automated cloud observations in the 1990s was exacerbated by significant changes in the operation of several solar radiation networks during the same period of time, removing a consistent reference for studying the effects of changing solar models. Although the changes from manual to automated cloud observations were well supported by cost savings and exploitation of new technology, the effect on solar modelers—particularly in this project—has been to insert a large discontinuity in the cloud observation data record and consistency. (In addition, cloud reporting since the ASOS deployment has been found to be inconsistent from station to station due to the use of augmented human-based observation at several sites.) (2). The cloud observation data applicability from past to present is not clearly delineated. We expect that one result will be difficulty in comparing the methodologies used in the old and new NSRDB data sets.

2.2 Solar Measurements

Solar model validation relies on high quality solar radiation measurements to evaluate model performance. A significant part of the effort this year was to find, acquire, and quality assess surface solar measurements to form an evaluation data set. Approximately 35 measurement sites were considered for the project. Most data were available from data distribution web sites developed by network operators. Data were downloaded to NREL computers, imported to a database, and then evaluated with several quality assessment tools including SERI QC (3).

A data analyst used a rough scoring technique to evaluate data quality for each station-month where 0 = Missing or Unacceptable, 1 = Conditionally Acceptable, and 2 = Acceptable. A monthly mean score across all stations was calculated, and figure 1 below shows the moving 12-month average of these monthly means for the period of record (1995-2003). A peak in data quality/availability is evident between 1999 and 2001, which will provide input for choosing the test-case year.

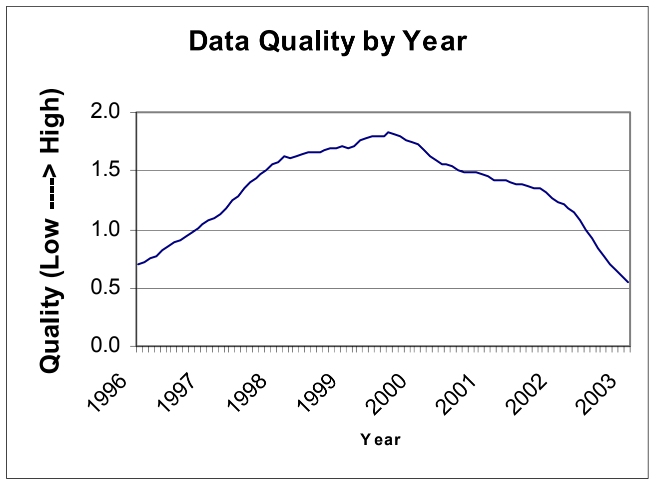

Fig 1: Solar radiation data quality by year (12 month moving average).

2.3 Other Comparison Data

NREL and the National Aeronautics and Space Administration (NASA) have a Memorandum of Understanding, which provides an opportunity to collaborate on the NSRDB project. NASA has offered to provide satellite-derived validation solar radiation data sets for the United States, derived from

- The Cloud and Earth's Radiant Energy System (CERES) satellite using an iterative radiative transfer algorithm, and
- The International Satellite Cloud Climatology Project (ISCCP) using the Pinker/Laszlo method

Data availability and processing considerations will probably dictate that we use the ISCCP data for our project this year. These data sets will be used as another point of reference for comparison to modeled values.

2.4 Choosing the Test Year

This year's effort centers on creating a test-year data set that exercises existing or newly modified models. The test-year will provide insight into model performance, data availability, and production procedures. Using this information, NREL expects to develop a plan for a full-scale NSRDB update and evaluate the availability of required resources to determine if the project is feasible.

The test year model evaluations will further illuminate the issue of comparability between data produced using the new methods and input data versus values in the 1961-1990 NSRDB. Such comparability may be important for applications sensitive to trends in solar radiation due to climate change, but because of a lack of suitable data spanning both periods, a direct and comprehensive comparison of the methods will not possible. Thus, we must rely on inferences drawn by independent evaluations of old and new models based on comparisons of the best validation data available for each time period. From these comparisons, we may be able to deduce some measure of comparability between the methods.

Our original intent was to determine a test year that provided a cross section of sites and modeling methods that would allow us to compare the 1961-1990 NSRDB techniques with newer methods under consideration. Ideally, this would have been a year from the mid-1990s for which manual cloud observations were available for some sites and automated observations available for other sites. Such a mix would allow a comparison of old methods with new methods, including a high-resolution satellite model developed at the SUNYA. However, historical Geostationary Operational Environmental Satellite (GOES) data necessary for the satellite model were not easily available for this project. Thus, our options for a test year were limited by the period of record of GOES data archived at SUNYA (which began in mid-year 1998), solar surface observations, and the availability of other validation data from NASA. The selection of the test year was subject to these constraints:

- GOES data available from 1999 forward
- ISCCP data available from 2001 back
- Optimal solar measurement data from 1999 – 2001

These limitations narrowed the choice to 1999-2001. Given that a significant drought affecting the western United States intensified in 2001, we decided to choose 1999. We also decided to include the year 2000 to include some interannual variability in our analysis.

2.5 New Clear Sky Algorithms

With many solar models, the starting point for estimating solar radiation from meteorological and satellite data is a clear sky model that is later modified to include the effect of clouds. The clear sky model can produce estimates of any combination of the three solar components (direct normal, global horizontal, and diffuse horizontal). In the case of the 1961-1990 NSRDB, the METSTAT model used a modified version of the clear sky component direct model of Bird (4).

The influence of aerosols on scattering and absorption of the direct beam presents a critical issue for modeling clear skies. The properties of aerosols, such as size distribution, composition, and optical properties define aerosol optical depth and aerosol optical transmittance. Measurements of any of these properties, including optical depth (AOD) or transmittance, are difficult, sometimes unreliable, and relatively rare. As a result, estimates of AOD from broadband measurements are attempted, as in the 1961-1990 NSRDB (1). Empirical parameterizations of AOD such as that used in the new ASHRAE model (see below) are essentially deriving aerosol transmittances from measured broadband data, as well. Many direct beam models are evaluated by Gueymard (5), especially with regard to their performance vis-à-vis varying AOD.

One of the authors has developed an improved clear sky model, REST2 (6), based on using parameterizations of the parameters alpha and beta in the Angstrom turbidity equation, $\tau = \beta \lambda^{-\alpha}$. Besides alpha and beta, the model requires date, time, and location, as well as estimates of water vapor (from surface dew point or relative humidity), pressure, temperature, ozone and nitrogen dioxide concentration. The model, as well as algorithms to empirically derive or otherwise establish input values for alpha and beta, will be included in the test year evaluation of results along with the METSTAT Bird algorithm and the ASHRAE clear sky component. Table 1 summarizes required model inputs. Pressure, water vapor, ozone are readily available. Broadband AOD requires direct normal data or parameterization, and nitrogen dioxide, α, and β require specialized sources or parameterizations.

TABLE 1. INPUT REQUIREMENTS FOR CLEAR SKY MODELS

Model	P	W †	O	N	τb	β	α
Bird	●	●	●		●		
REST2	●	●	●	●		●	●
METSTAT	●	●	●		●		
ASHRAE	●	●	●		●		

P= Atm pressure; W = Water vapor †(From Temp & RH)
O=Ozone;N=Nitrogen Dioxide; τb=broadband AOD
β=Ångstrom's beta, α= Ångstrom's alpha

2.6 METSTAT Model

As previously discussed, the recent switch to automatic weather stations eliminated the human observed total and opaque sky cover amounts used for inputs to the METSTAT model. The approach we are evaluating for this year's work is to derive equivalent sky cover inputs (total and opaque cloud cover) for use with METSTAT from a combination of ASOS and ASOS supplemental cloud measurements. ASOS detects clouds to 12,000 feet, while the ASOS supplemental cloud measurements provide information about clouds for height above 12,000 feet for a 50 km x 50 km area centered upon the ASOS station. The ASOS supplemental cloud measurements are derived from GOES satellite data.

Output from METSTAT using the cloud cover derived from ASOS and the supplemental product cloud inputs will be part of the evaluation data set.

2.7 ASHRAE/NRCC Model

Recently the American Society of Heating and Refrigeration Engineers (ASHRAE) and the Northeast Regional Climate Center have made a concerted effort to produce a solar radiation model for applications in the architectural community (7). Their approach was to modify a model developed for estimating global horizontal radiation for the northeast region of the US. (8). That model computes global 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.

Aerosol transmission (Ta) functions were based on the form $Ta = X^m$, derived by Houghton (9), where X was empirically derived from broadband solar radiation data, and m is air mass. Cloud transmission was based on four cloud fraction categories (clear, scattered, broken, overcast) and six height ranges. The cloud parameter inputs were derived from human observations.

The new, revised model uses new algorithms for cloud transmittances for cloud input data from either human observations, the new ASOS, or ASOS data augmented with additional data from a "carbon dioxide slicing" (CDS) satellite derived product. Fifty-three automated (ASOS) ground measurement stations and 17 "manual" or human based observation stations were used to develop and verify the model.

Essentially, the model consists of closed form transmittance equations for Rayleigh, gas, and water vapor transmission (estimated from dew point), and a look-up table of empirical expressions for aerosol transmission and cloud transmissions to computed global and direct irradiance. Diffuse irradiance is computed from these two estimated components.

The model was evaluated with respect to estimates of daily and hourly radiation results by computing Root-Mean-Square Error and Mean Average Error statistics for each of the stations used in the model development. Daily model output errors were on the order of 10% for human based inputs and 14% for automated inputs. Augmenting the ASOS with CDS data reduces the errors to about 12%. Errors were largest in the winter and smallest in the summer. Errors tended to be smaller for clear conditions, and largest for overcast conditions. The human based results are comparable with the estimates of errors in the METSTAT model (1), which also depended upon human observations. For this reason, the ASHRAE model will be compared with a modified METSTAT model during the test year.

2.8 SUNYA Satellite Model

One goal of the updated NSRDB is a spatial resolution greater than the ancillary interpolated products that were later produced based on the 239 NSRDB meteorological stations. Toward that end, we are considering using a model that estimates solar radiation from satellite imagery. The Atmospheric Sciences Research Center (ASRC) at SUNYA has been developing such a model. It 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.

The SUNYA model has been refined to take into account anomalous ground conditions that occur either geographically (specular reflections from bright sand or water) or with time (snow cover). Perez, et al. (10) have shown that the refined model when compared with 13 ground measurement stations has an average MBE in global irradiance of 3 W/m^2, (less than 1% of the average irradiance) and an average RMSE of 54 W/m^2 (14%). The errors for direct normal estimates are an MBE of 4 W/m^2 (1%) and RMSE of 137 W/m^2 (30%).

2.9 Improved Aerosol and Water Vapor estimates

The 1961-1990 NSRDB used only direct normal irradiance (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. For the southwest U.S., NREL recently created new BAOD estimates based largely on sun photometry. This includes a method of adjusting the BAOD for site elevation for relatively unpolluted sites in the interior Southwest. As shown in figure 2, the BAOD decreases exponentially, such that it is reduced by 50% at an elevation of 2 km above sea level. Satellite based techniques will be used to complete the map of the U. S. in the current phase of the NSRDB project.

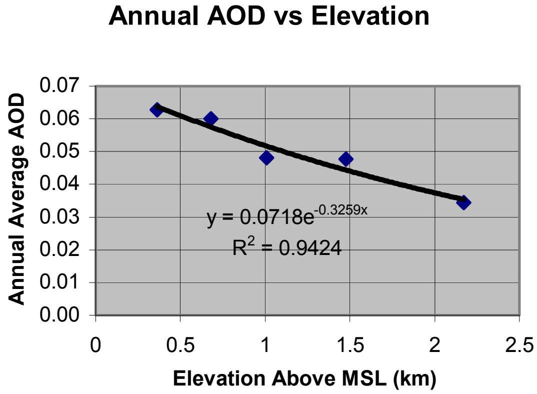

Fig. 2: Measured BAOD plotted against elevation for 5 stations, Maricopa, Rogers Lake, Desert Rock, Sevilleta, and Flagstaff.

For water vapor, NREL uses the NASA Water Vapor Project (NVAP) dataset for daily estimates of water vapor on a 1x1° grid. NVAP integrates sounding data with satellite measurements of atmospheric water vapor. For selected areas near National Weather Service upper air sounding locations, NREL may choose to directly use water vapor estimates from available twice-daily soundings.

2.10 Data Filling Methods

When designing the 1961-1990 NSRDB, serially complete solar data was a primary goal of the project. Rather than attempting to fill gaps in the measured or modeled solar radiation data, we chose to fill the solar model input parameters, and model the solar irradiance based on the filled input parameters. This approach allowed the statistical algorithms of the model to operate, producing more realistic model output. Other meteorological parameters were also filled at the same time in an effort to produce a more complete output data set.

A criticism of the 1961-1990 NSRDB, was that missing nighttime data were not filled (nighttime input data were not necessary for solar model operation). This approach had the benefit of increasing the population of sites in the NSRDB because many weather service sites routinely closed down at night, an operational constraint that would have eliminated them from a serially complete database. However, applications that required serially complete meteorological data were hampered by this approach.

In the context of the above discussion, significant value would be derived from an updated NSRDB with both serially complete solar and meteorological data. However, stricter requirements for serially complete data will increase the probability of a site's exclusion from the data set (even at full-time sites, there can be gaps of days, weeks, or months). To determine if the design goal of serial completeness is reasonable, we have investigated other data filling methods.

The following methods were used in the 1961-1990 NSRDB:

- Short-term filling – for gaps of 5 hours or less, linear interpolation
- Medium-term filling – for gaps of 6 – 47 hours, substitution of data from the same hours of adjacent days
- Long-term filling – for gaps of 2 days to one year, substitution of data from the same calendar days from another similar year.

Additional techniques were employed to fill missing data when NREL developed the Typical Meteorological Year 2 (TMY2) data sets (for those data gaps that still existed after NSRDB methods were applied):

- Cloud cover was linearly interpolated over a nighttime-only gap
- Dry bulb temperature was linearly interpolated over a nighttime-only gap and modified for expected non-linearities, such as more rapid changes near sunrise or sunset
- Dew point temperature (which was not filled by NSRDB methods) was filed using psychometric relationships with dry bulb and relative humidity values (which were filled) (11)
- Missing nighttime relative humidity was filled using psychometric relationships with dry bulb and dew point temperatures (11)
- Wind speed and direction (up to 47 hours) were filled with linear interpolation and (wind speed) adjusted for expected diurnal non-linearities
- Precipitable water (up to 47 hours) was filled with linear interpolation.

Another technique used for other projects is the Linacre method, which characterizes measurements from a nearby station to form a constant relationship with like measurements from the target site (12). Data at the target site are then filled with data from the nearby station, adjusted according to the relationship.

One possible outcome of the data filling analysis may be a relaxed requirement of serially complete data by allowing the inclusion of stations with a short period of record. We will investigate the pros and cons of a larger data set (more stations) that allows large gaps of data. For example, TMY data sets from stations of differing periods of record may not be comparable because of the smaller pool of years from which to typify the station's climate.

2.11 Planned Analysis of Models and Methods

Our goal is to create a database of (some) measured and (mostly) modeled data that reproduce the principle statistics of measured data for monthly and annual periods. For the test year chosen, we will investigate how well the distributions of modeled and measured data match on various time scales.

The usual hour-by-hour and daily comparison of measured and modeled solar radiation data will be evaluated and reported, but "correct" statistics for the overall data set over the monthly and annual periods will be our target. Besides mean and standard deviation, the range, median, and 2nd moments of the distributions (kurtosis and skewness) will be compared, and the cumulative frequency distributions of modeled and measured data will be examined. Based on our results, recommendations for the modification, inclusion, or exclusion of a particular model will be made.

3. CONCLUSION

We are tasked this year with determining the feasibility of producing an updated NSRDB, by examining tools, input data availability, processing constraints, and uncertainties of the output product. The tools described in this paper are available to do the job, and we hope to show that the uncertainties due to changes in cloud observations or different models can be minimized to produce a product with more recent climate data, improved solar modeling, and increased spatial resolution.

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