PROCEEDINGS OF

THE 1998
AMERICAN SOLAR ENERGY SOCIETY
ANNUAL CONFERENCE

Albuquerque, NM
June 14 - 17, 1998

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American Solar Energy Society
2400 Central Avenue, Suite G-1
Boulder, Colorado 80301

Printed on recycled paper

A CLIMATOLOGICAL SOLAR RADIATION MODEL

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ABSTRACT

In 1995 the National Renewable Energy Laboratory (NREL) initiated the Data Grid Task under the U.S. Department of Energy Resource Assessment Program. The primary objective of the Data Grid Task is to estimate climatological averages of daily-total solar radiation at each point (cell) on a high-resolution (e.g., 40-km) uniform grid, using climatological parameters as input to a solar radiation model. This paper describes the model, sources of input data, model products, and the initial evaluations of the model performance.

The initial evaluations included comparisons of model output with 30-year averages derived from the U.S. National Solar Radiation Data Base and measured data for India, Saudi Arabia, Egypt, and Sudan. These comparisons indicate that the model is capable of estimating monthly averages of daily-total solar radiation with an uncertainty of ±5%, when accurate input data are available. The results also indicate that available input data will yield results with an uncertainty of about ±10% for most locations around the world.

1. BACKGROUND

A key mission of the NREL Resource Assessment function is to create new techniques for estimating solar resources at any location. During the evaluation of the U.S. National Solar Radiation Data Base (NSRDB), the quality of the output (hourly time series) data products was routinely assessed by the creation and comparison of annual and 30 year climatological monthly mean values for meteorological and solar radiation variables. One of these comparisons, between 30-year monthly and annual averages of daily-total direct normal solar radiation and opaque cloud cover, revealed a strong, consistent negative correlation (1).

The discovery of this relationship suggested the possibility that a model could be created to use climatological (monthly mean) inputs to generate climatological solar radiation outputs. The value of such a model would lie in its ability to use uniformly gridded climatological data to produce a uniform solar radiation data grid. A *solar radiation data grid* contains information on solar radiation resources at each grid point. This information can be used for site selection and system performance estimates. The grid is especially valuable in areas where the nearest time series location is either too distant or unrepresentative due to local climate variations. This line of reasoning led to the 1995 initiation of the Data Grid Task under the U.S. Department of Energy (DOE) Resource Assessment Program.

The feasibility of developing a climatological solar radiation (CSR) model to produce a solar radiation data grid rested on the availability of climatological input data for the model, including cloud cover, aerosol optical depth, precipitable water vapor, ozone, surface albedo, and atmospheric pressure. Hence, a search for such data was the first effort undertaken under the Data Grid Task. Fortunately, large-scale climatological data sets are becoming more available due to well-funded climate analysis and modeling programs in several U. S. and international agencies.

2. CLIMATOLOGICAL INPUT DATA

Crucial cloud cover data were found at the National Climatic Data Center (NCDC) in the Real-Time Nephanalysis (RTNEPH) database. The RTNEPH database originates at the Air Force Global Weather Center (AFGWC) at Offutt Air Force Base, Nebraska. On August 1, 1983, AFGWC started global cloud analyses that produce cloud information every three hours at a nominal 40-km resolution. The AFGWC cloud analyses use all available data including surface observations, polar orbiting satellite data, and upper air data to produce cloud cover for polar stereographic projections of the northern and southern hemispheres. Of particular value to the Data Grid Task is a histogram database formed from RTNEPH data for the period from 1985 to 1991.

The RTNEPH histogram database gives the number of occurrences of low, middle, high, and total cloud amounts in increments of 5% from 0% to 100% for each month and each 3-hour observation time. Each histogram combines all cloud observations, for that month and time, in the entire seven year period. The histograms of total cloud cover for hours between sunrise and sunset were used to determine monthly average total cloud cover during daytime hours. The histograms for low, middle, and high cloud layers were used to estimate monthly average opaque cloud cover.

Atmospheric pressure is estimated from elevation data, which are available worldwide at 5-minute (9- km) resolution (2). Worldwide *surface albedo* data are available from several sources, including the Canadian Center for Remote Sensing (CCRS), which was used here (3). The CCRS data have a resolution of 280 km. *Ozone* data are available on a CD-ROM produced by the National Oceanic and Atmospheric Administration (NOAA) (4). These data are from the Total Ozone Mapping Spectrometer (TOMS) and cover the period from 1979 to 1988 for a 1° latitude by 1.25° longitude grid.

Precipitable water vapor data are available from several sources including radiosonde data from individual weather stations. However, because of its high quality, NREL recommends the use of the NASA Water Vapor Project Data Set (NVAP). NVAP provides water vapor data on a 1° (100-km or less) grid for the entire world (5). It was created from a combination of radiosonde and satellite data for the period from 1988 to 1992.

Aerosol optical depth data are estimated from direct normal solar radiation data and other sources. This is the model input parameter for which data are most difficult to find. Therefore, the acquisition of worldwide data for aerosol optical depth will be a significant part of future work on this task.

3. THE CSR MODEL

The CSR model is a simplified version of the METSTAT model that was used to produce the NSRDB for the United States (6). Using the METSTAT algorithms, the CSR model calculates solar radiation energy for each 5-minute period from sunrise to sunset and then summarizes the 5-minute values to obtain a daily-total value. The 5-minute calculations are performed only for one day of each month—the day for which the daily-total extraterrestrial radiation (ETR) equals the monthly average daily-total ETR. Initially, the dates given in Table 4.2.1 of Iqbal's *An Introduction to Solar Radiation* (7) were used. However, it was determined that adjustments of those dates yielded better agreements for NSRDB and CSR monthly averages. A recalculation of the days when ETR equals monthly average ETR agreed well with the dates of best agreement between CSR and NSRDB monthly averages. The dates used for the monthly calculations are given in Table 1.

TABLE 1: MONTHLY CALCULATION DATES

Month	Date	Day Number
January	18	18
February	15	46
March	17	76
April	16	106
May	16	136
June	13	164
July	16	197
August	16	228
September	15	258
October	16	289
November	14	318
December	10	344

3.1 Preparation of Input Data

As noted earlier, the various model input data come with resolutions varying from 9 km (elevation-pressure) to 280 km (albedo). Because cloud cover plays a dominant role in determining solar radiation at the Earth's surface, the 40-km polar projection grid of the RTNEPH database was selected for both the input and output grids of the CSR model. Therefore, all of the non-cloud cover data inputs are resampled such that input values for all variables are available for each RTNEPH 40-km cell. The resampling process uses standard geostatistical procedures provided by geographical information system (GIS) software.

3.2 CSR Algorithms

The 6-page limitation for conference papers precludes the listing of all CSR algorithms or the computer code. Therefore, only key equations are given, along with brief descriptions of the functions performed by the others. For each month, CSR calculations proceed through the following steps:

Step 1 - Solar Geometry
Starting at midnight, the date and the latitude and longitude of a cell are used to calculate the solar elevation. These calculations are repeated every 5 minutes until the sun rises, at which time the algorithms to calculate solar radiation are implemented and used until the sun sets. Logic statements handle the high latitude situations when the sun never rises or when it never sets.

Step 2 - Direct-Beam and Diffuse Transmittances

Direct-beam transmittance algorithms include the effects of Rayleigh scattering (T_R), ozone absorption (T_O), uniformly mixed gas absorption (T_{UM}), water vapor absorption (T_W), aerosol absorption and scattering (T_A), opaque cloud absorption (T_{OPQ}), and translucent cloud absorption (T_{TRN}). Diffuse sky transmittance algorithms include contributions from Rayleigh scattering (Ks_R), aerosol scattering (Ks_A), opaque cloud scattering (Ks_{OPQ}), translucent cloud scattering (Ks_{TRN}), and multiple ground-to- atmosphere/cloud reflectances (Ks_{GRFL}).

Step 3 - Combining Transmittances

The algorithms to combine direct-beam and diffuse transmittances are,

$$Kn = T_R\ T_O\ T_{UM}\ T_W\ T_A\ T_{OPQ}\ T_{TRN}$$

$$Ks = (Ks_R + Ks_A)\ f_m$$

$$Kd = (Ks + Ks_{OPQ} + Ks_{TRN}) + Ks_{GRFL}$$

$$Kt = Kn + Kd$$

where Kt, Kn, and Kd are transmittances for global horizontal, direct normal, and diffuse horizontal solar radiation, respectively, and f_m is an empirical air mass function. Corrections are made for sunrise and sunset periods shorter than 5 minutes in length.

Step 4 - Calculating Solar Radiation Intensity

Solar radiation intensity for each 5-minute period is calculated by multiplying transmittances by ETR and ETRN (extraterrestrial solar radiation on a surface normal to the sun),

$$In = ETRN\ Kn$$

$$Id = ETR\ Kd$$

$$It = ETR\ Kt$$

where ETRN, ETR, In, Id, and It are in Watts/m^2.

Step 5 - Calculating Daily-Total Energy

For the final step, the daily-total solar radiation energy in Watt-hours/m^2 is calculated by summing 5-minute values and dividing by 12 (there are 12, 5-minute periods per hour).

$$In_{TOT} = \Sigma\ In/12$$

$$Id_{TOT} = \Sigma\ Id/12$$

$$It_{TOT} = \Sigma\ It/12$$

3.3 CSR Output Products

The data grid can be used to prepare maps of solar radiation resources, which can be used to assemble a solar radiation atlas. The CSR product of greatest value, however, is the digital solar radiation data grid. With the digital data, geostatistical methods can be used to estimate solar radiation resources at any location within the boundaries of the grid. Furthermore, using GIS techniques, the solar radiation data can be combined with demographic, land use, economic, environmental, and other data to select the best locations for solar systems (8).

4. DATA GRID PRODUCTION

During 1997, monthly average values of direct normal, diffuse horizontal, and global horizontal daily-total solar radiation energy were calculated for each point on a 40-km grid covering the 48 contiguous states, Mexico, the

Caribbean, and the lower portion of Canada. Similar solar radiation grids were prepared for India and surrounding countries and a Middle East region centered on Saudi Arabia. The maps for Saudi Arabia were used to produce a solar radiation atlas for that country. These grids and maps were calculated using the CSR model and the climatological input parameters described above. The available sources for aerosol optical depth data were different for each of these three regions.

For the North American region, the aerosol optical depths used in the production of the NSRDB (9) were used in the United States. Extrapolations of these data were used for southern Canada and northern Mexico. For the Caribbean and southern Mexico, a worldwide NCDC data set known as "TD-9614 Aerosol Analyses" was used. These data were derived from NOAA/AVHRR (Advanced Very High Resolution Radiometer) satellite data for ocean areas only. Their use in the Caribbean and along Mexico's coasts was justified by the general agreement found between TD-9614 data and NSRDB data at coastal sites. For interior regions in southern Mexico, elevation, population and other factors were used to estimate optical depths. Somewhat higher values were assigned around Mexico City and other large cities, based on the senior author's personal observations of air pollution in Mexico.

For India and the surrounding region, aerosol optical depth data were obtained from two sources, a 1973 publication in *Solar Energy* (10) and the TD-9614 data. The values in the Solar Energy article were based on approximately 10 years (1961-1971) of spectral direct normal data and sun photometer data. The upward trend from 1961 to 1971 (values doubled) was used to extrapolate the 1960s data to the 1980s. Similar to their use in Mexico, the TD-9614 data sets provided estimates for coastal regions.

For Saudi Arabia, aerosol optical depths were calculated from direct normal solar radiation data collected by a 12-station solar radiation network established under a joint Saudi Arabia-United States project (11). Because of the high quality of the Saudi network data, a high level of confidence can be placed in the calculated aerosol optical depths. However, because of the short time the network has been in operation (since 1995), the confidence in these optical depths as climatological averages is low.

The certainty of the aerosol optical depths assigned to the regions surrounding Saudi Arabia are even lower because there were no direct normal solar radiation data with which to calculate them. The optical depths assigned to these areas are estimates based on climate similarities and the TD-9614 data.

5. EVALUATION OF RESULTS

The performance of the CSR model was initially evaluated by comparing model calculations with monthly mean daily-totals extracted from the NSRDB for the 213 sites in the contiguous United States. The data for the cells containing each of the 213 sites were used for these comparisons. The first comparison (see Table 2) used monthly average cloud cover values from the NSRDB. The opaque cloud amounts are the averages of directly observed hourly opaque cloud observations. These results represent a comparison of the CSR and METSTAT models.

TABLE 2: CSR MINUS NSRDB DIFFERENCES
(Wh/m2/day)
(using NSRDB cloud cover data)

	Mean Bias			RMS		
Mo	GLO	DIR	DIF	GLO	DIR	DIF
1	21	-35	9	87	95	78
2	34	-10	8	118	84	105
3	30	50	-51	119	82	114
4	82	62	-26	140	98	100
5	86	33	-6	161	92	99
6	18	-17	-32	134	103	111
7	-18	-51	-40	131	133	109
8	-12	-4	-67	110	111	111
9	88	51	-2	127	103	73
10	30	30	-16	70	92	53
11	26	2	-2	63	86	42
12	24	-49	19	60	96	53

TABLE 3: CSR MINUS NSRDB DIFFERENCES
(Wh/m^2/day)
(using RTNEPH cloud cover data)

	Mean Bias			RMS		
Mo	GLO	DIR	DIF	GLO	DIR	DIF
1	29	-9	5	111	277	85
2	-11	-148	32	147	354	121
3	76	163	-71	197	373	131
4	129	159	-42	246	400	117
5	24	-108	27	197	325	114
6	50	37	-38	201	296	118
7	-42	-113	-25	200	328	111
8	-56	-98	-51	185	331	121
9	51	-47	15	144	279	88
10	21	7	-14	98	262	69
11	-12	-135	13	85	309	63
12	44	57	6	90	264	58

The second comparison (see Table 3) used monthly average cloud cover values derived from the RTNEPH histogram database. The opaque cloud amounts used in these model runs were parameterized from layered cloud amounts in the RTNEPH database. These results represent a comparison of the models and the RTNEPH cloud cover values. In general, these monthly mean bias differences are less than 3% of typical monthly mean daily-totals and the root mean square (rms) differences are less than half of typical interannual variations (standard deviations of monthly means). Overall these results indicate the CSR model is capable of estimating monthly mean daily-total solar radiation with an uncertainty of ±5%.

5.1 Evaluation of the India Data Grids

Measured solar radiation data for the India region were obtained from the archives of the World Radiation Data Center at St. Petersburg, Russia. Global horizontal data only were available for 14 sites in India, 6 sites in Pakistan, and 1 site in Sri Lanka. No data were found for any other country in the region. The location of each site was matched with a data grid cell, and comparisons were made between measured and modeled monthly mean global horizontal daily-totals.

The results of these comparisons revealed an apparent national bias. The average measured-modeled difference for all months for the 14 sites in India is +186 Wh/m^2/day, whereas the average difference for the six sites in Pakistan is –544 Wh/m^2/day. All the sites in Pakistan indicate a large underestimation, whereas the sites in India show a mixture of over- and underestimation that changes from month to month. A reexamination of the model input data showed no discontinuity at the India-Pakistan border. Long-term data from the WRDC for other countries did not show any consistent mean bias (see section 5.2). Therefore, we considered the Pakistan results to be anomalous, and did not include them in Table 4.

The average monthly differences for all 14 stations in India show a seasonal pattern with differences reaching a high of +500 Wh/m^2/day in August and being essentially zero during December and January. This could be related to the monsoon season that extends from May to September and the METSTAT model's known tendency to over- estimate solar radiation under low, thick clouds (6, 12).

5.2 Evaluation of the Middle East Data Grids

Measured solar radiation data (global, direct, and diffuse) for Saudi Arabia were available from the 12-station network. These data are of high quality but have periods-of-record less than 3 years. Furthermore, none of these measured data are for the same periods-of-record as the input data to the CSR model, except for aerosol optical depth that was derived from the Saudi direct normal data. We should expect these period-of-record differences to result in fairly large mean bias and rms differences between measured and modeled (data grid) data, and we should expect large differences from month to month. The results shown in Table 5 confirm this expectation.

TABLE 4 - CSR MINUS WRDC GLOBAL DIFFERENCES (14 stations in India)

Mo	Mean Bias		RMS	
	Wh/m^2	%	Wh/m^2	%
1	-17	-0.4	328	6.7
2	23	0.5	367	6.9
3	102	1.7	337	5.6
4	146	2.5	257	4.4
5	448	7.9	434	8.4
6	302	6.6	371	8.4
7	383	10.6	511	12.7
8	508	13.5	433	11.8
9	460	10.2	400	9.2
10	65	1.3	308	6.4
11	-64	-1.4	187	4.0
12	-10	-3.4	307	7.3

TABLE 5 - CSR MINUS SAUDI NETWORK DIFFERENCES (11 stations)
(Wh/m^2/day)

	Mean Bias			RMS		
Mo	GLO	DIR	DIF	GLO	DIR	DIF
Jan	335	383	47	180	736	276
Feb	35	112	-21	392	1116	346
Mar	691	1409	-237	411	1022	358
Apr	-41	173	-77	296	718	381
May	352	753	-109	218	624	359
Jun	-47	-128	90	265	706	306
Jul	120	491	-149	312	801	390
Aug	-10	203	-75	130	685	314
Sep	50	370	-221	293	479	329
Oct	7	-432	162	270	572	189
Nov	284	336	58	272	686	187
Dec	386	402	69	253	529	217
Ann.	180	339	-39	274	723	304

Measured global horizontal data for the region surrounding Saudi Arabia were obtained from the WRDC archives. WRDC data were found for 26 stations in the region. However, because the CSR model was developed to produce climatological estimates of solar radiation resources, only stations with a period-of-record of 10 years or more were used for the comparisons given in Table 6. All these stations are in Egypt or Sudan. The mean bias differences are similar to those obtained for comparisons with NSRDB data for the United States (Table 3).

TABLE 6 - CSR MINUS WRDC DIFFERENCES
(10 stations in Egypt & Sudan)

Mo	Mean Bias		RMS	
	Wh/m^2	%	Wh/m^2	%
1	35	0.7	360	7.3
2	-5	-0.1	378	6.6
3	36	0.5	404	6.2
4	58	0.8	429	6.0
5	108	1.5	418	5.9
6	109	1.5	647	9.2
7	-30	-0.4	694	10.1
8	-8	-0.1	642	9.5
9	116	1.8	565	8.9
10	148	2.5	432	7.4
11	90	1.7	404	7.9
12	-6	-0.1	339	7.2

6. SUMMARY & FUTURE PLANS

Under the auspices of DOE, the Data Grid Task has developed a climatological model that may be capable of producing 40-km solar radiation data grids with ±5% uncertainty. Evaluation of the model results is hampered by the lack of long-term climatological solar radiation measurements. We can say that we have found reasonable agreement between CSR modeled monthly mean global horizontal radiation and measured radiation from stations with 10 or more years of data. We also find close agreement between the model results and the NSRDB long term means, as expected.

These data grids can be used for site selection and estimating solar resources at specific sites. Future efforts will seek higher- quality input data for the model, including more accurate input values and new datasets with higher spatial resolution. The model will be modified to calculate daily-total energy collected by various collector systems such as tilted flat-plate collectors. Future data processing strategies will include the input of diurnally varying cloud amounts, from the 3-hourly data in the RTNEPH database and other sources. This will provide more accurate monthly totals, and monthly average diurnal profiles of solar radiation. RTNEPH histogram data from more recent years will be used to update current data grid products, subject to funding constraints.

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