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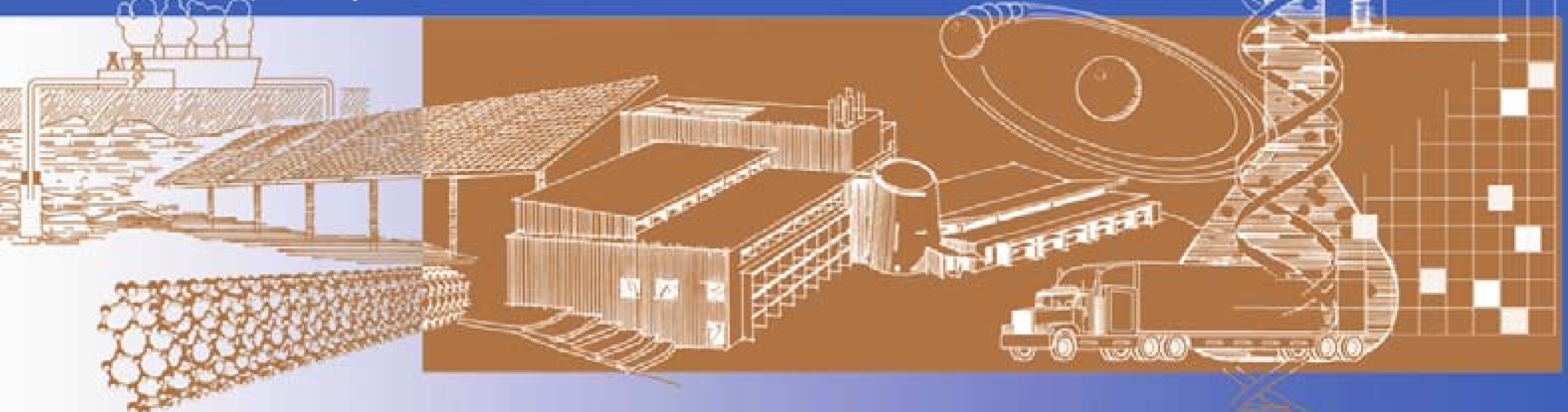

BROADBAND MODEL PERFORMANCE FOR AN UPDATED NATIONAL SOLAR RADIATION DATABASE IN THE UNITED STATES OF AMERICA

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ABSTRACT

The authors participate in a project to update the existing 1961 to 1990 U.S. National Solar Radiation Data Base for 1990 to 2000. When measured hourly solar radiation data is not available, it will be modeled from meteorological data. We evaluated a modified version of Maxwell's METSTAT, Perez's GOES satellite based model, and an empirical model developed by Belcher and DeGaetano at the Northeast Climate Research Center. Two years of high quality solar radiation data at 31 sites in the U.S. were the basis of the evaluation. Model and measured data frequency distributions, probability distribution functions, and correlations were compared, as well as mean bias and root-mean-square (RMS) errors. Average hourly mean bias errors and RMS errors over all sites for all models were less than 10 Wm^{-2} and 100 Wm^{-2} for total hemispherical radiation and less than 32 Wm^{-2} and 220 Wm^{-2} for direct beam radiation, respectively.

1.0 INTRODUCTION

1.1 Updating the 1961-1990 NSRDB

A project to update the existing United States National Solar Radiation Database (NSRDB) is being conducted by the National Renewable Energy Laboratory (NREL), a United States Department of Energy (DOE) national laboratory devoted to the development and deployment of renewable energy systems. The existing NSRDB database contains hourly solar and meteorological data for 239 sites in the U.S. for the thirty years from 1961 to 1990. Over 90% of the data in the NSRDB was modeled using the Meteorological and Statistical (METSTAT) solar radiation model of Maxwell.

The present update project is aimed at (1) evaluating solar radiation models to provide surrogate solar data where measured data not available, (2) developing tools to provide more frequent updates to the database, (3) adding the period of 1990 to 2000 to the existing database, and (4) developing new database products based on experience with the update effort.

1.2 Candidate models

Three models were selected as candidates for modeling the solar radiation when measured data is not available. These are the Satellite model of Richard Perez et al. [1-3] , a modified version of the METSTAT model [4] , and an empirical model developed at the U.S. Northeast Climate Research Center (NCRC) by Belcher and DeGaetano [5, 6] . A new clear sky model of Gueymard [7] is being considered as a candidate to replace the clear sky model of R. Bird, used in METSTAT. Model details are reported in the respective references, and summarized in [8]. Here we describe the techniques for evaluating the performance of these models with a view to selecting the best approach for producing a complete time series of solar radiation data.

2.0 REFERENCE SITES

Thirty-one stations with high quality measured solar radiation data for the period 1999 to 2000 were selected as reference sites for evaluating model performance. Table 1 lists the sites and abbreviations for the sites. Figure 1 shows the geographic distribution of the selected sites

TABLE 1. REFERENCE STATION LIST

State	Station	Abbreviation
FL	Florida Solar Energy Center	FSE
FL	Tallahassee	TAL
TX	Clear Lake	CLE
TX	Overton (SBR)	OVE
TX	Edinburg	EDI
TX	Corpus Christi (SBR)	COR
TX	Laredo (SBR)	LAR
TX	Austin	AUS
TX	Del Rio (SBR)	DEL
TX	Abilene (SBR)	ABI
TX	El Paso	ELP
OK	Southern Great Plains	SOU
TX	Canyon	CAN
NM	Albuquerque	ALB
NV	Desert Rock	DES
CA	Hanford	HAN
VA	Sterling	STE
WV	Bluefield State College	BLU
CO	SRRL, Golden	SRR
PA	Pennsylvania State College	PEN
NY	Albany	ANY
IL	Bondville	BON
UT	Salt Lake City	SAL
OR	Klamath Falls	KLA
WI	Madison	MAD
OR	Burns	BUR
OR	Eugene	EUG
ND	Bismarck	BIS
MT	Ft. Peck	FTP
WA	Seattle	SEA
NC	Elizabeth City	ELI

(SBR=Silicon-Based Radiometers)

There are a total of 396 station months of data, or 245,909 daylight station hours available for comparison with the measured data in the test sites.

The objective of the NSRDB and the update project is to produce a database of solar radiation with the same statistical properties as measured data. Thus, our focus is on comparing appropriate statistics for the measured and modeled data. Even with great discrepancies in hour-by-hour modeled data with respect to measured data (if it were available), if the model data set provided the correct

Fig. 1. Geographic distribution of reference solar radiation monitoring.

statistics (mean, variance) for monthly solar radiation data, then hourly simulations utilizing this data over periods of a month to a year to many years would result in correct simulation results. This approach does not preclude comparisons with measured data on an hourly basis.

Measured data were quality assessed and flagged using NREL SERI_QC and Data Quality Management System (DQMS) software. 96% of the global data was flagged as being within +/-10% of expected limits. 78% of the direct beam data met these criteria. Twenty-six sites used typical thermopile radiometers. Five Texas sites used less accurate silicon-based radiometers (SBR). The three models performed about the same at most sites, regardless of the sensor. Table 2 shows that ABI has one of the lower RMS errors and a MBE near zero for all three models and is comparable with CAN, a thermopile site.

3.0 BIAS AND RANDOM ERRORS

3.1 Hourly MBE and RMS errors

We computed the usual Mean Bias Error (MBE) and Root-Mean-Square (RMS) errors between the measured and modeled data. Figures 2 and 3 plot the results for the total hemispherical and direct normal irradiances, respectively. Tables 2 and 3 list hourly MBE and RMS results for each site in units of Wm^{-2} . Note that MBE is measured values minus modeled values; negative values imply the model overestimates the irradiance. From the tables we see that the SUNYA satellite model has the lowest average MBE and RMS errors, except that the METSTAT model has a lower direct beam MBE. The NRCC model consistently has the largest MBE and RMS errors.

All three models perform relatively consistently, with average MBE in total global and direct of about than 10 Wm^{-2} and 30 Wm^{-2}, respectively, and RMS errors in total and direct of about 100 Wm^{-2} and 215 Wm^{-2}, respectively.

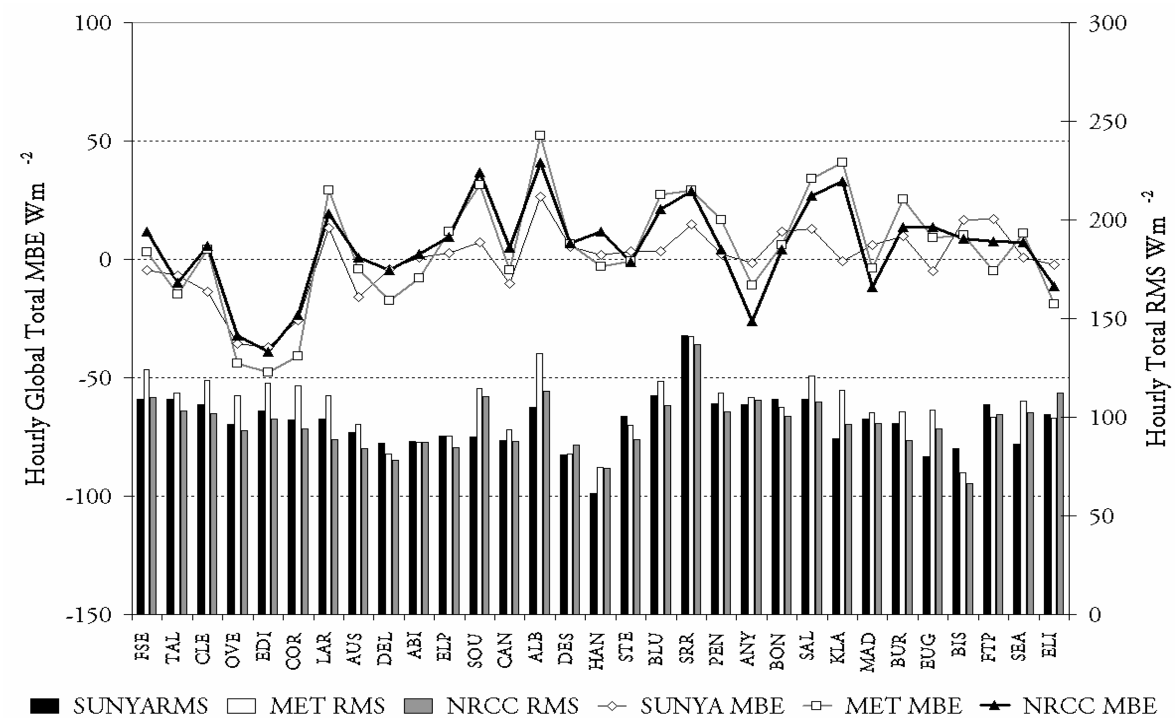

Fig. 2. Mean bias (lines, left scale) and RMS (bars, right scale) error for modeled hourly total hemispherical irradiance by site and by model.

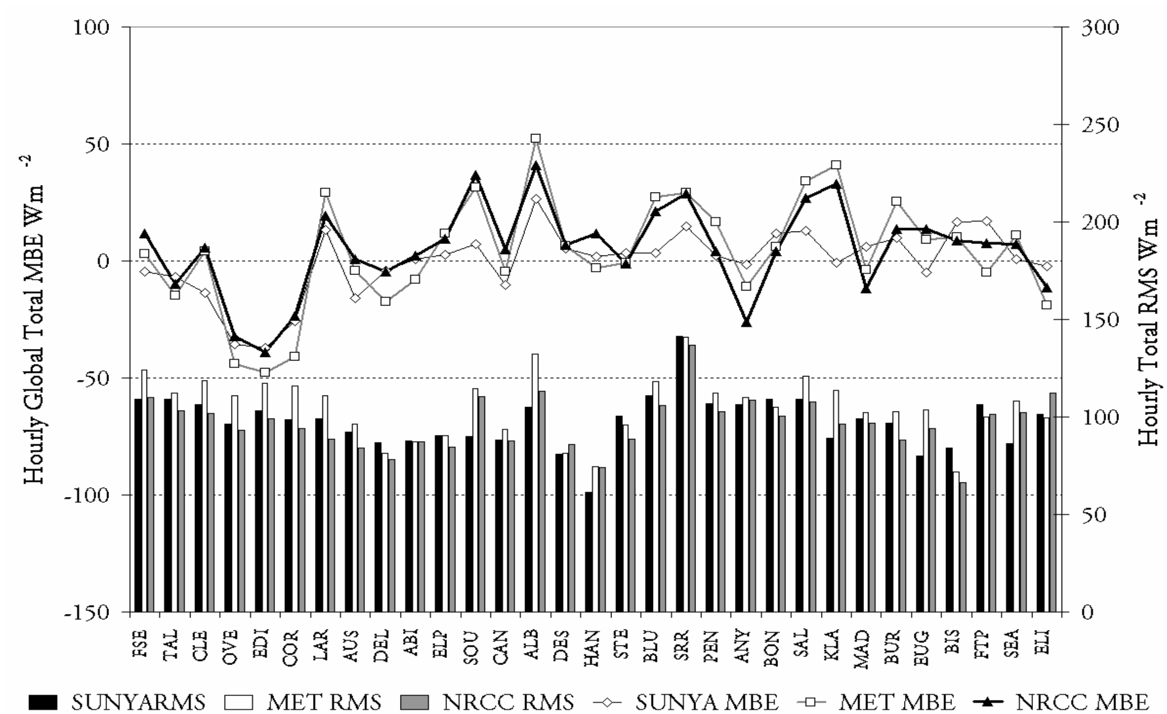

Fig. 3. Mean bias (lines, left scale) and RMS (bars, right scale) error for modeled hourly direct irradiance by site and by model. Note units are Wm^{-2}.

The up and down patterns of error magnitudes in Figures 2 and 3 track each other. This may indicate that all models operate on the input data in a similar fashion, and the quality of the input data is partially driving the errors.

TABLE 2: HOURLY TOTAL MBE & RMS ERROR

Wm^{-2}	SUNYA MBE	SUNYA RMS	MET MBE	MET RMS	NRCC MBE	NRCC RMS
FSE	-4.4	109.3	3.0	123.9	11.9	110.1
TAL	-7.0	108.9	-14.6	112.2	-9.9	103.4
CLE	-13.7	106.4	4.2	118.8	5.5	101.9
OVE	-35.5	96.2	-43.8	110.8	-32.1	93.3
EDI	-37.0	103.1	-47.8	117.1	-39.0	98.9
COR	-25.6	98.5	-41.0	115.9	-23.5	94.2
LAR	13.2	99.0	29.3	111.1	19.3	88.4
AUS	-15.9	92.3	-4.3	96.4	0.7	84.3
DEL	-4.2	86.9	-17.5	81.2	-4.6	78.2
ABI	0.7	87.7	-7.9	87.3	2.3	87.3
ELP	2.5	90.5	11.9	90.4	9.6	84.8
SOU	7.4	90.0	31.3	114.6	36.8	110.6
CAN	-10.1	88.0	-4.4	93.8	5.0	87.7
ALB	26.6	105.1	52.4	132.1	40.8	113.3
DES	5.3	80.8	6.5	81.4	6.7	85.8
HAN	1.8	61.5	-2.9	74.4	11.8	74.1
STE	3.4	100.6	-0.7	96.1	-1.2	88.6
BLU	3.4	111.0	27.3	118.0	21.1	105.9
SRR	14.9	141.5	29.2	141.1	28.9	136.8
PEN	2.1	106.7	16.5	112.1	4.0	102.7
ANY	-1.4	106.6	-11.1	110.1	-26.0	108.5
BON	11.8	109.0	6.1	105.1	4.3	100.4
SAL	13.0	109.0	34.3	120.8	27.0	107.8
KLA	-0.6	89.3	40.8	113.5	33.1	96.5
MAD	6.1	99.2	-3.9	102.3	-11.6	96.7
BUR	9.9	96.8	25.4	102.6	13.5	88.3
EUG	-5.0	80.0	9.2	103.6	13.8	94.3
BIS	16.6	83.9	10.2	71.9	8.6	66.3
FTP	17.2	106.1	-5.1	99.9	7.5	101.5
SEA	0.9	86.1	10.8	108.2	7.2	102.5
ELI	-2.3	101.4	-19.0	99.7	-11.3	112.1
MEAN	-0.2	97.8	4.0	105.4	5.2	96.9

3.2 Monthly Mean Daily Total MBE and RMS Errors.

In Figures 4 and 5 we show the MBE and RMS errors for total global hemispherical and direct irradiance as percent of the Monthly Mean Daily Total (MMDT) for each site. In Tables 4 (global total) and 5 (direct beam) we summarize the differences between model and measured computed MMDT in percent of reading, by model.

TABLE 3: HOURLY DIRECT MBE & RMS ERROR

Wm^{-2}	SUNYA MBE	SUNYA RMS	MET MBE	MET RMS	NRCC MBE	NRCC RMS
FSE	1.1	219.5	33.2	227.0	70.1	209.0
TAL	-8.4	216.7	-48.5	213.0	-28.3	191.7
CEL	-16.3	200.7	30.6	210.3	55.5	187.7
EDI	-34.5	201.5	-87.5	208.0	-59.3	180.9
AUS	-18.8	184.3	-4.9	183.5	28.5	167.9
ELP	71.9	219.9	52.6	202.6	0.4	206.4
SOU	3.2	181.9	59.0	227.4	92.8	226.6
CAN	8.4	191.5	-34.3	196.3	0.2	200.3
ALB	80.1	225.3	120.1	256.6	77.6	230.7
DES	2.2	192.3	-31.1	174.6	-27.1	208.8
HAN	7.5	143.8	-48.3	162.9	-15.6	154.4
STE	2.2	221.9	-13.5	204.5	3.5	198.9
BLU	23.3	229.8	45.8	237.8	81.4	220.6
SRR	37.1	278.0	97.2	288.5	114.8	290.9
PEN	18.1	239.9	27.0	224.1	44.5	211.8
ANY	25.8	233.2	-48.9	235.5	-24.8	241.9
BON	42.4	225.5	19.8	196.7	37.9	211.0
SAL	45.4	224.0	79.8	231.8	51.5	218.9
KLA	-19.5	223.6	65.2	241.0	146.5	268.2
MAD	65.1	239.0	-2.3	203.0	33.0	210.9
BUR	52.7	211.3	31.2	201.1	51.6	234.8
EUG	-15.1	187.3	-53.1	211.1	47.5	226.3
BIS	69.7	238.7	-67.1	217.1	1.5	223.2
FTP	39.7	239.8	-48.0	207.5	46.8	227.3
SEA	14.0	182.0	16.2	212.2	63.0	235.3
ELI	-69.0	230.8	-131.5	248.5	-65.2	247.1
MEAN	16.5	214.7	2.3	216.3	31.9	216.6

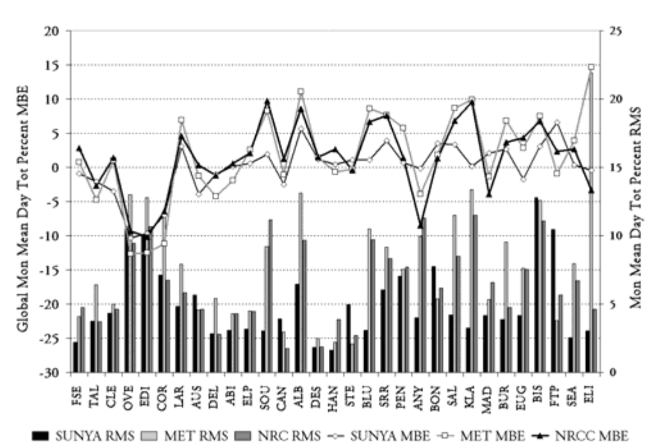

Fig. 4. Mean bias (lines, left scale) and RMS (bars, right scale) <u>percent</u> error for modeled monthly mean daily total for global irradiance by site and by model.

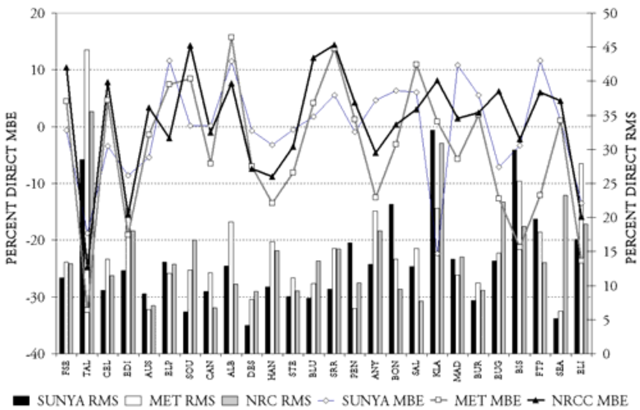

Fig. 5. Mean bias (lines, left scale) and RMS (bars, right scale) percent error for modeled monthly mean daily total for direct beam irradiance by site and by model.

The SUNYA model appears to be the best performer for both direct and global total monthly mean daily totals. The differences in average MBE for global radiation of less than 1% and average RMS of about 5% are about the expected uncertainty in measured data of ±5%. A combined root-sum-square (RSS) of measurement uncertainty (5%), model MBE (1%) and average RMS (7%) result in an expected uncertainty in modeled database MMDT global total solar radiation of ±8.6%, or about the same uncertainty of ±9% claimed for the existing NSRDB global total MMDT. Similarly, for the DNI MMDT, the RSS of measurement (2%), model MBE (4%), and RMS (15%) errors produces an estimated uncertainty in direct MMDT of ±15%. The direct uncertainties are larger due to the "on or off" nature of direct beam irradiance as influenced by clouds, whose influence is only roughly accounted for in the models.

TABLE 4. GLOBAL MMDT MBE & RMS % ERRORS

Global Total MMDT%	*SUNYA MBE*	*MET MBE*	*NRCC MBE*	*AVERAGE*
Mean	-0.06	1.73	1.38	1.0
Standard Deviation	3.85	6.70	5.26	5.3
Minimum	-10.30	-12.70	-10.20	
Maximum	6.61	14.68	9.78	
	RMS	RMS	RMS	
Mean	5.0	8.0	6.6	6.5
Standard Deviation	2.8	4.4	2.9	3.4
Minimum	1.6	2.1	1.7	
Maximum	12.8	21.9	11.5	

4.0 FREQUENCY DISTRIBUTIONS

Figure 6 shows example distribution functions for total global irradiance for Albuquerque, NM and Seattle, WA.

TABLE 5. DIRECT MMDT MBE & RMS % ERRORS

Direct Beam MMDT%	*SUNYA MBE*	*MET MBE*	*NRCC MBE*	*AVERAGE*
Mean	-0.4	-4.0	0.8	-1.2
Standard Deviation	8.7	12.0	9.5	10.1
Minimum	-22.4	-32.4	-24.8	
Maximum	11.7	15.7	14.4	
	RMS	*RMS*	*RMS*	*AVERAGE*
Mean	13.7	15.7	15.0	14.8
Standard Deviation	7.4	8.1	7.0	7.5
Minimum	4.1	6.2	6.8	
Maximum	32.8	44.6	35.6	

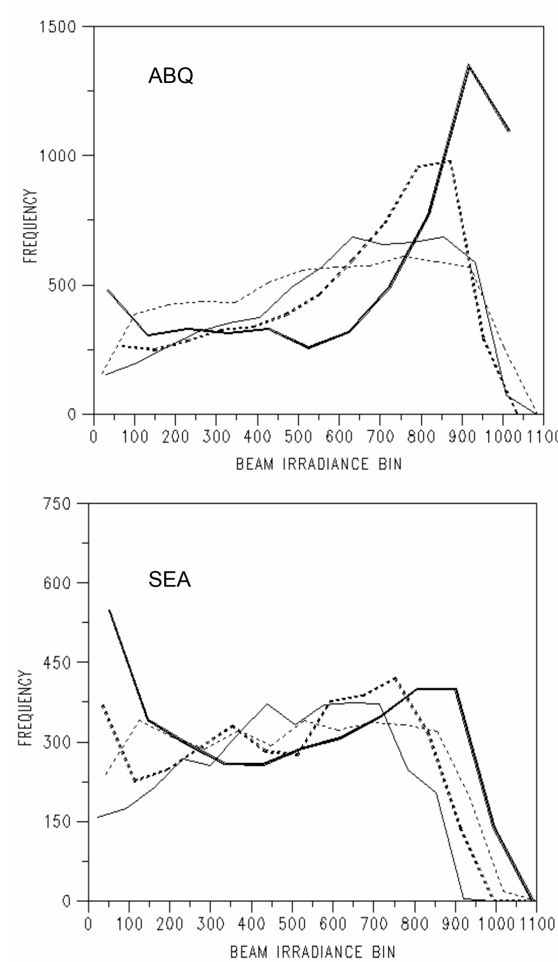

Fig. 6. Example frequency distributions for hourly global irradiance for ALB (top) and SEA (bottom). Thick solid lines are measured data. Thick dashed lines are SUNYA, thin dashed lines are MET, and thin solid line is NRCC model.

Low and high irradiances are under-predicted at clear and cloudy sites, with reasonable matches to the measured frequency distributions for midrange irradiances. Figure 7 shows that all models slightly over-predict mid-range direct beam irradiances, and under-predict low and high beam irradiances. The NRCC model distributions are generally furthest from the measured distributions.

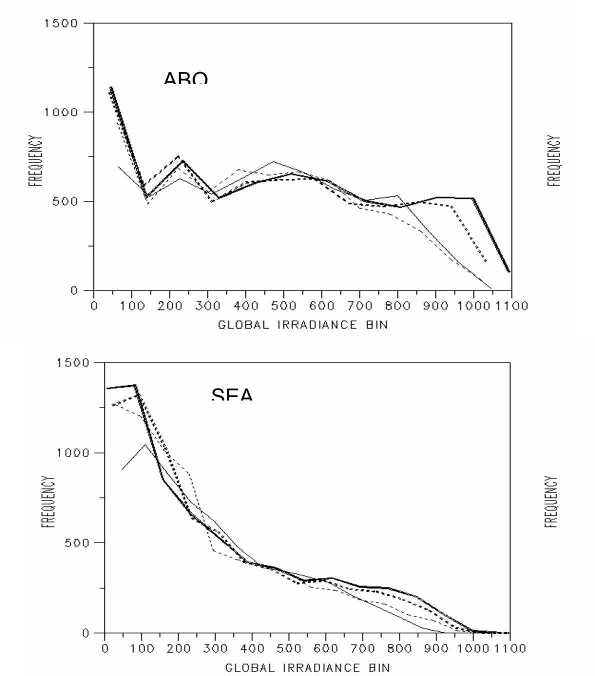

Fig. 7. Frequency distributions of hourly direct beam irradiance, ALB (top) and SEA (bottom). Thick solid lines= measured data, thick dashed = SUNYA, thin dash = MET, thin solid = NRCC model.

5.0 PROBABILITY DISTRIBUTIONS

Figure 7 indicates that probability distribution functions for solar radiation data are not Gaussian; a uniform distribution may be more appropriate. Figure 8 shows model and measured uniform probability distributions at the SEA site. All three models track the probability distribution of the global total irradiance, but less so for the direct beam. High irradiance is over-predicted at cloudy sites and under-predicted at clear sites.

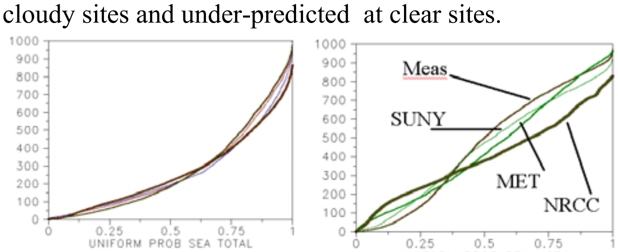

Fig. 8. Uniform probability plots for SEA global total (left panel) and direct beam (right panel)

6.0 MMDT CORRELATION

Regression parameters for modeled versus measured MMDT, and correlation coefficients are shown in Table 7.

TABLE 7. MMDT FIT PARAMETERS

Global Total Fit	SLOPE	INTERCEPT	R^2
SUNYA	0.969	127	0.98
METSTAT	0.947	136	0.96
NRCC	0.931	210	0.97
Direct Beam Fit			
SUNYA	0.873	511	0.88
METSTAT	0.846	791	0.83
NRCC	0.886	374	0.85

Slope and R-square of modeled MMDT parameters are all within three percent of each other.

7. CONCLUSION

The three models examined performed remarkably alike. MBE and RMS errors are similar for global irradiance. Direct beam performance for all three models is worse, but by a similar amount for all three models. METSTAT may be simpler to implement; however, the SUNYA satellite model would be slightly better at the expense of added complexity in generating an updated NSRDB.

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