National Renewable Energy Laboratory
Innovation for Our Energy Future

Uncertainty for Satellite and Station Solar Data in the Updated NSRDB

Solar Resource Assessment Workshop

Denver, CO

Daryl R. Myers

Oct 29 2008

NREL/PR-550-44456

"Perez", "Gridded", or Satellite Model*

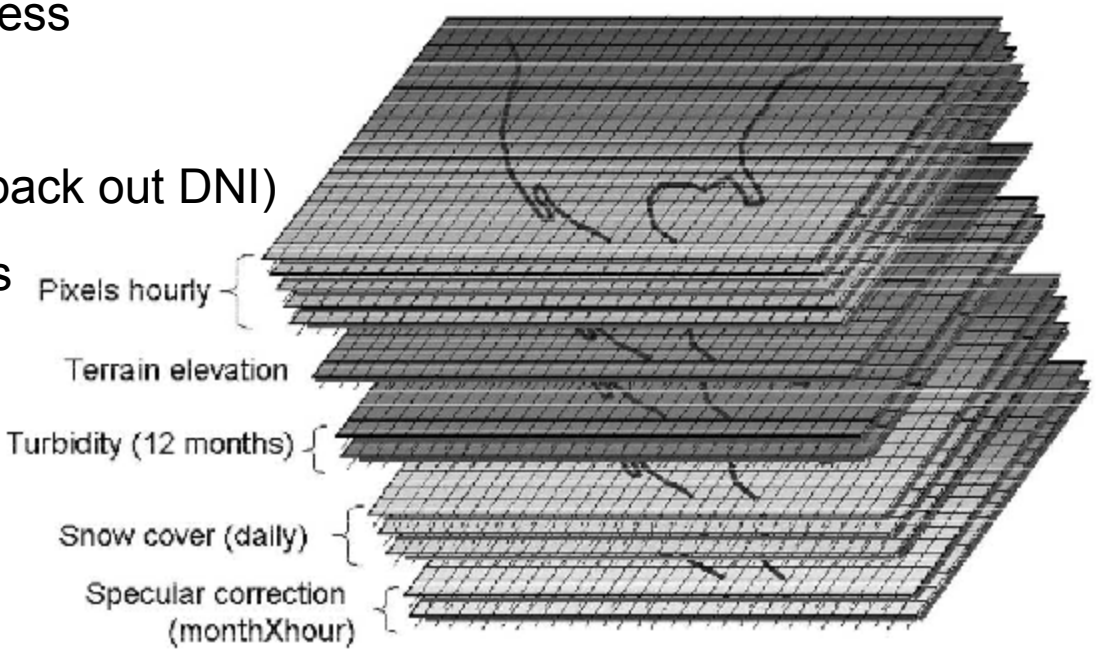
Satellite Image pixel brightness

Elevation

Broadband Aerosol OD (to back out DNI)

Albedo/reflection corrections

Uncertainty in each layer contributes another source of uncertainty



*Perez, R., P.Ineichen, K. Moore, M. Kmiecik, C. Chain, R. George, F. Vignola, "A New Operational Satellite to Irradiance Model." *Solar Energy*, 2002. 73(5): p. 307-317.

Perez, R., K. Moore, S.Wilcox, R. George, M. Anderberg,F. Vignola, P. Ineichen. "Status of High Resolution Solar Irradiance Mapping from Satellite Data". in Proceedings Solar 2004. Portland OR: American Solar Energy Society, Boulder CO.

Perez, R., P. Ineichen, M. Kmiecik, K. Moore, D. Renne, R. George, "Producing Satellite Derived Irradiances in Complex Arid Terrain". *Solar Energy*, 2004. 77: p. 367-371.

"Station" Model *Modified* METSTAT*

METorological STATistical Model

Date	*Translucent and Opaque Cloud Cover*
Time	Ozone
Elevation	*Water Vapor*
Latitude	*Broadband Aerosol Optical Depth*
Longitude	Albedo, Snow Cover,

Cloud Cover

ASOS Automated Cielometer, vertical sounding, < 12000 ft (4000 m)

Integrated Summarized Hourly (ISH) data

Water Vapor

Historical Satellite Observations (NVAP)

Relative Humidity (Garrison Model, same as NSRDB)

Dew Point (ASHRAE model)

Broadband AOD replaced by SPECTRAL AOD @ 550 nm

From NASA MODIS satellite data annual averages

*Maxwell, E. L., "METSTAT The Solar Radiation Model Used in the Production of the National Solar Radiation Data Base (NSRDB)." *Solar Energy*, 1998. **62**(4): p. 263-279.

"Station" Model *Modified* METSTAT*

Uncertainty in each element contributes another source of uncertainty to modeled data

Models: Northeast Regional Climate Center "ASHRAE" *

"Bulk transmittance" model for Global $I = I_o \cos(z) T_R T_g T_w T_A T_c$

$T_R T_g$ closed form expression for Rayl[illegible] as scattering (Kondratev, 1969; Atwater & Brown, 1974)

Tw for water transmittance f[illegible] point (McDo[illegible]954; Smith, 1966)

T_A = Aerosol tra[illegible] X^m (Hough[illegible])

m = air mass [illegible] pirically = f([illegible](R[illegible])*Z typically X ~ 0.80 to 1.04, mean ~[illegible]

Clouds from ASOS [illegible] mental Satellite data:

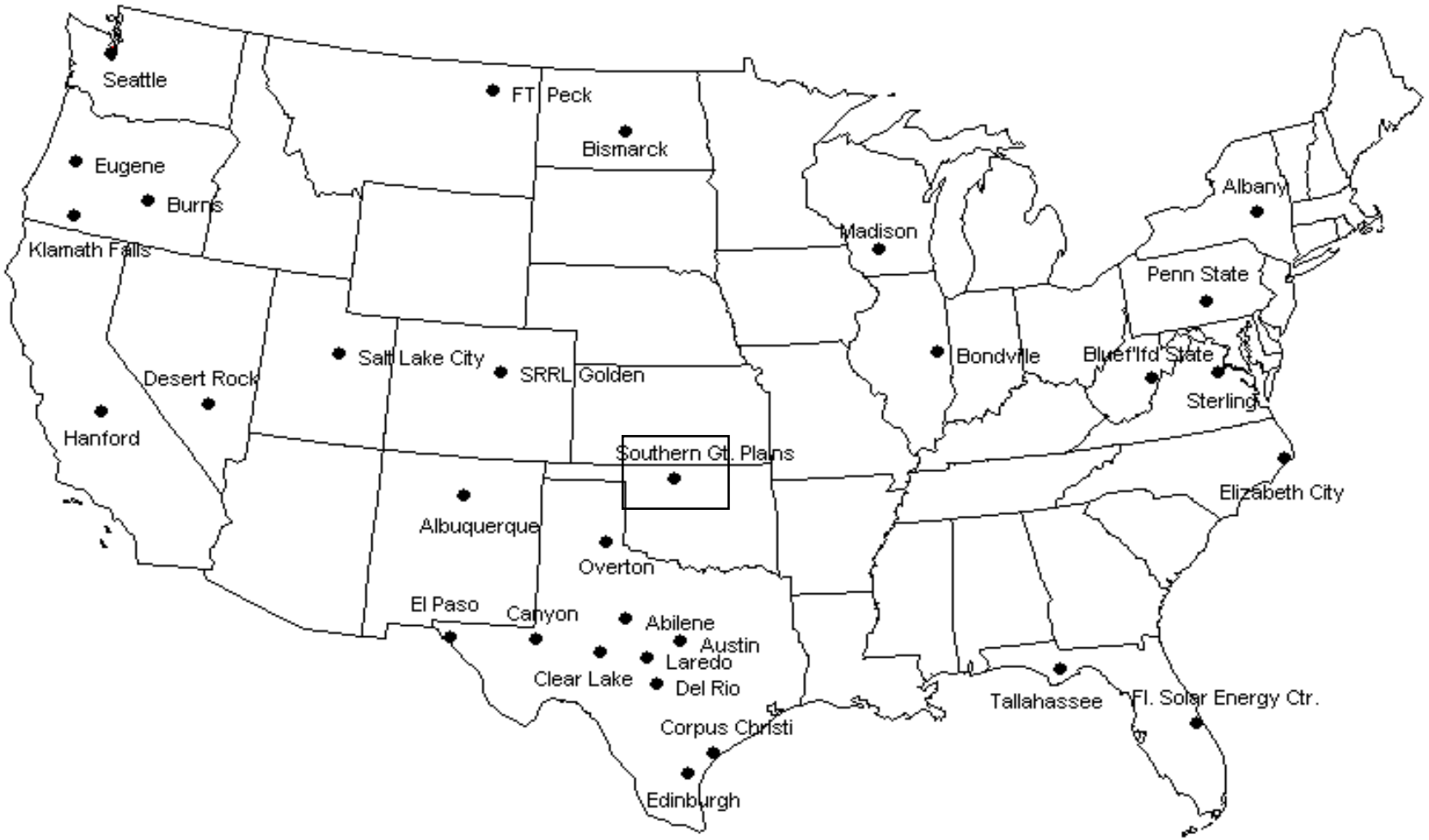
Transmitt[illegible] Co[illegible]ition (Few, Scattered, Broken, Overcast), layers (6, in 2000 [illegible]ements), and layers (up to 4)

Evaluated-BUT Not used for NSRDB

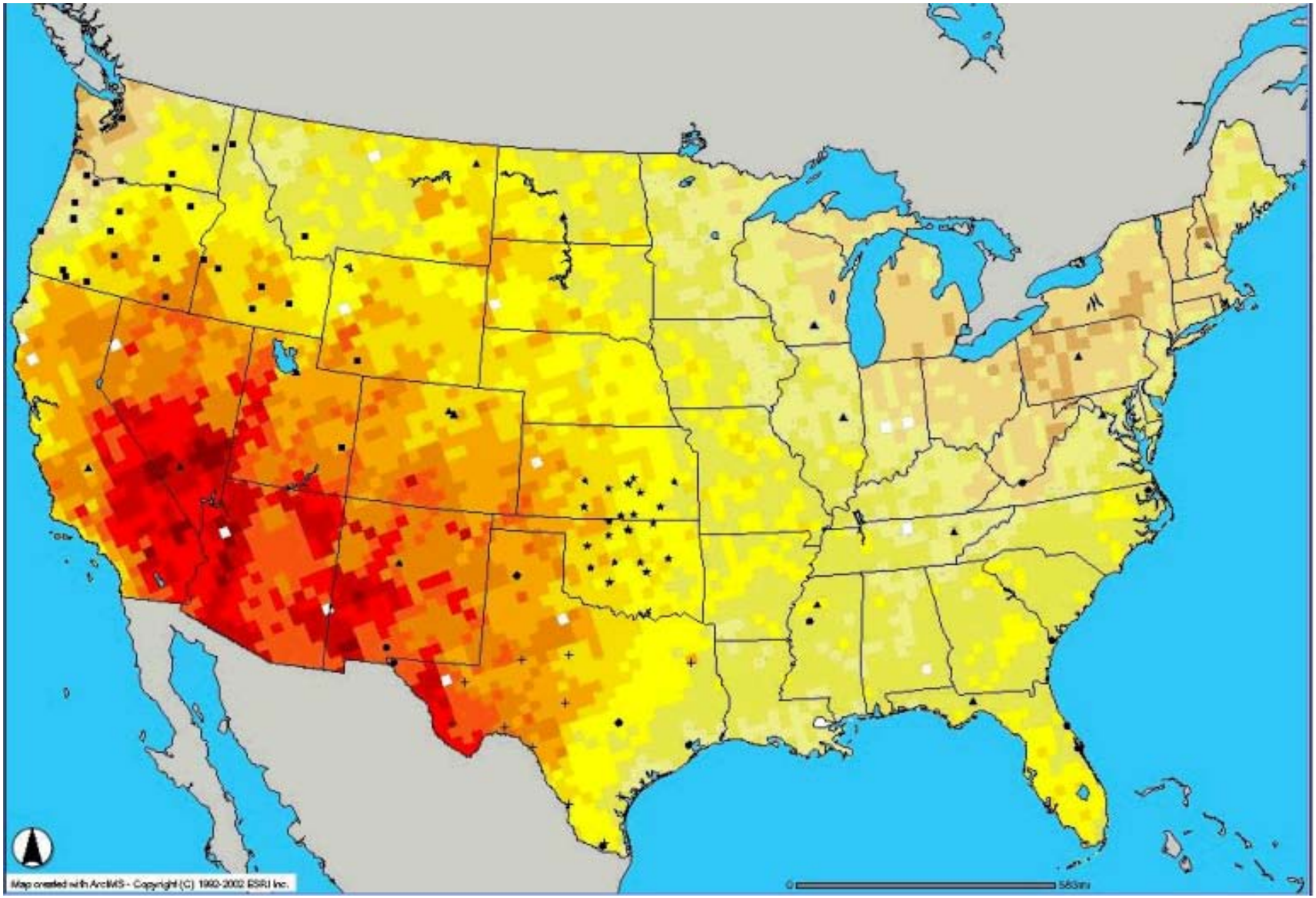
*Belcher, B. N., A.T. DeGaetano. Integration of ASOS Weather Data into Model Derived Solar Radiation. in Proceedings 84th Annual Meeting American Meteorological Society. 2004. Seattle WA: American Meteorological Society.

Belcher, B. N., A.T. DeGaetano, Integration of ASOS Weather Data into Building Energy Calculations with Emphasis on Model Derived Solar Radiation. ASHRAE 1226 RP Northeast Regional Climate Center 2004

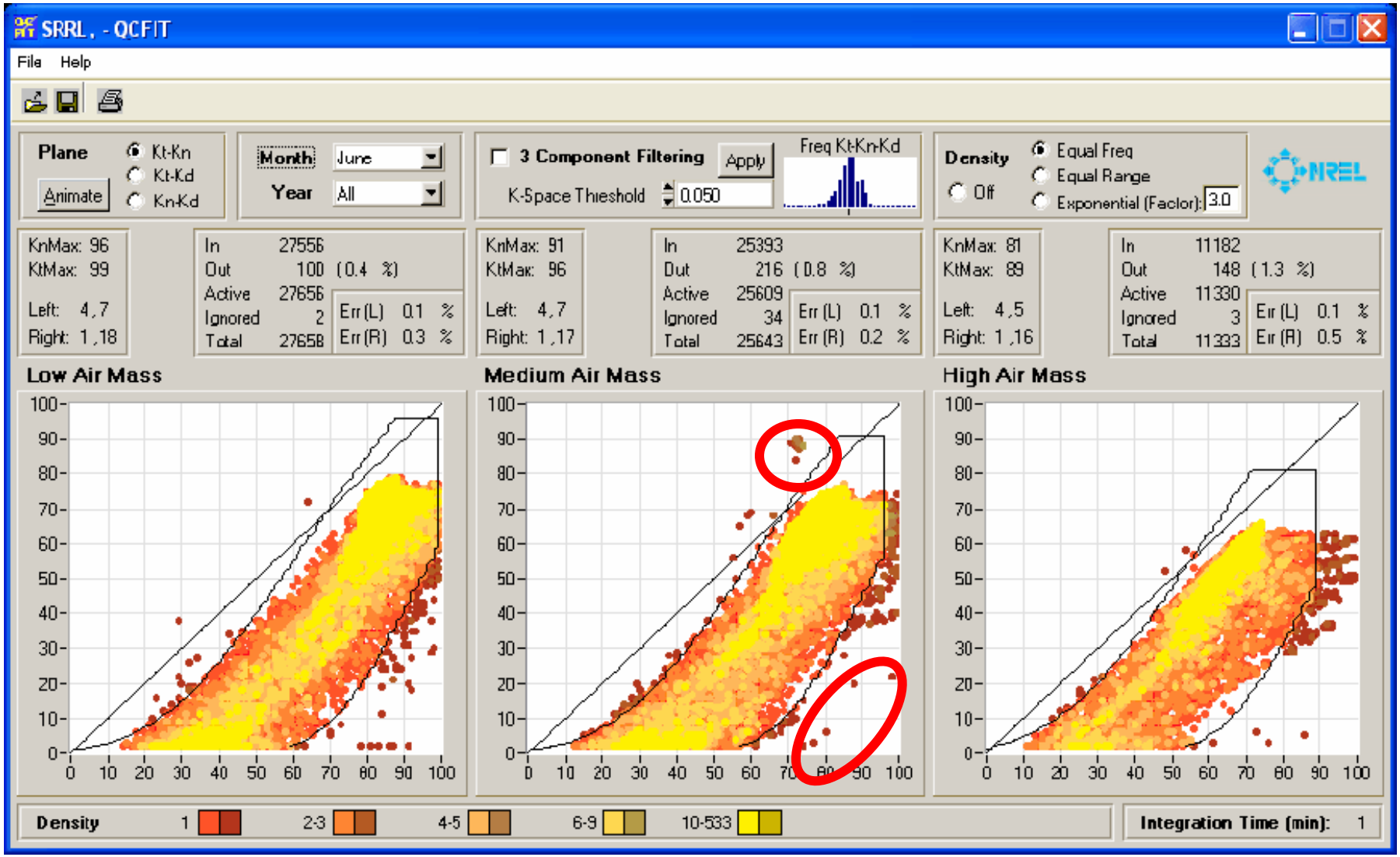
Available Ground Measurements: Schematic locations Solar Radiation Stations



Available Ground Measurements: Schematic locations Solar Radiation Stations



SERI-QC Quality Assessment
Measured Solar Validation Sites



Model Evaluations:

Correlation Coefficient
(Model with Measured -33 stations-)

Mean Bias Error (Watts and %)

Root Mean Square Error (Watts and %)

Frequency Distribution (Meas and Model)

Correlation Plot (Model Vs Measured)

Uncertainty Estimates (U95)

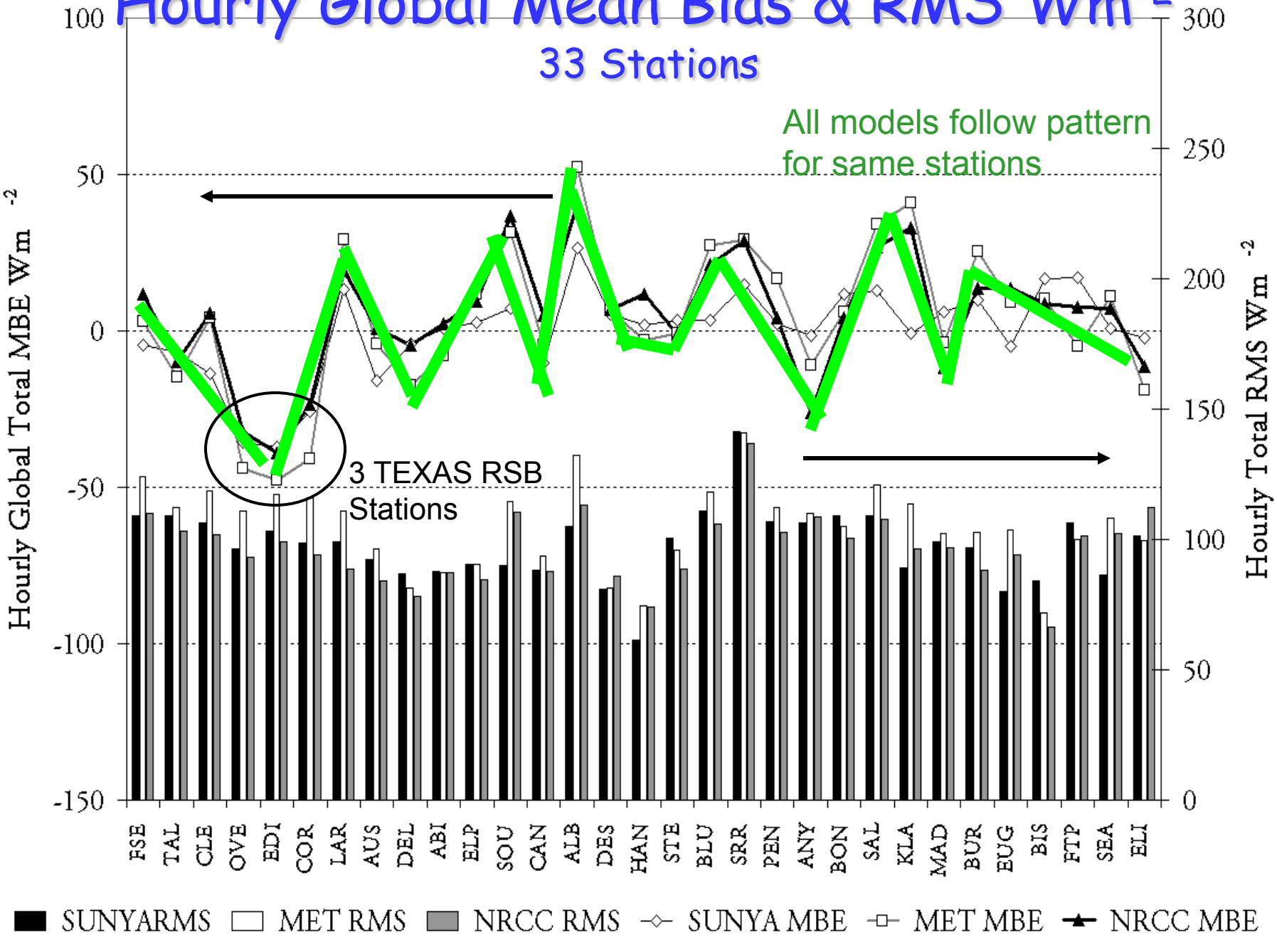
"Sanity" Check U95 Other Models

Correlation Coefficient All Hourly Data with Measured Data

GLOBAL		Direct Normal	
Perez Sat	**0.937**	**Perez SAT**	**0.779**
Met Stats ON	0.923	Met Stats ON	0.786
Met Stats OFF	0.939	Met Stats OFF	0.806
NRC	0.939	NRC	0.777

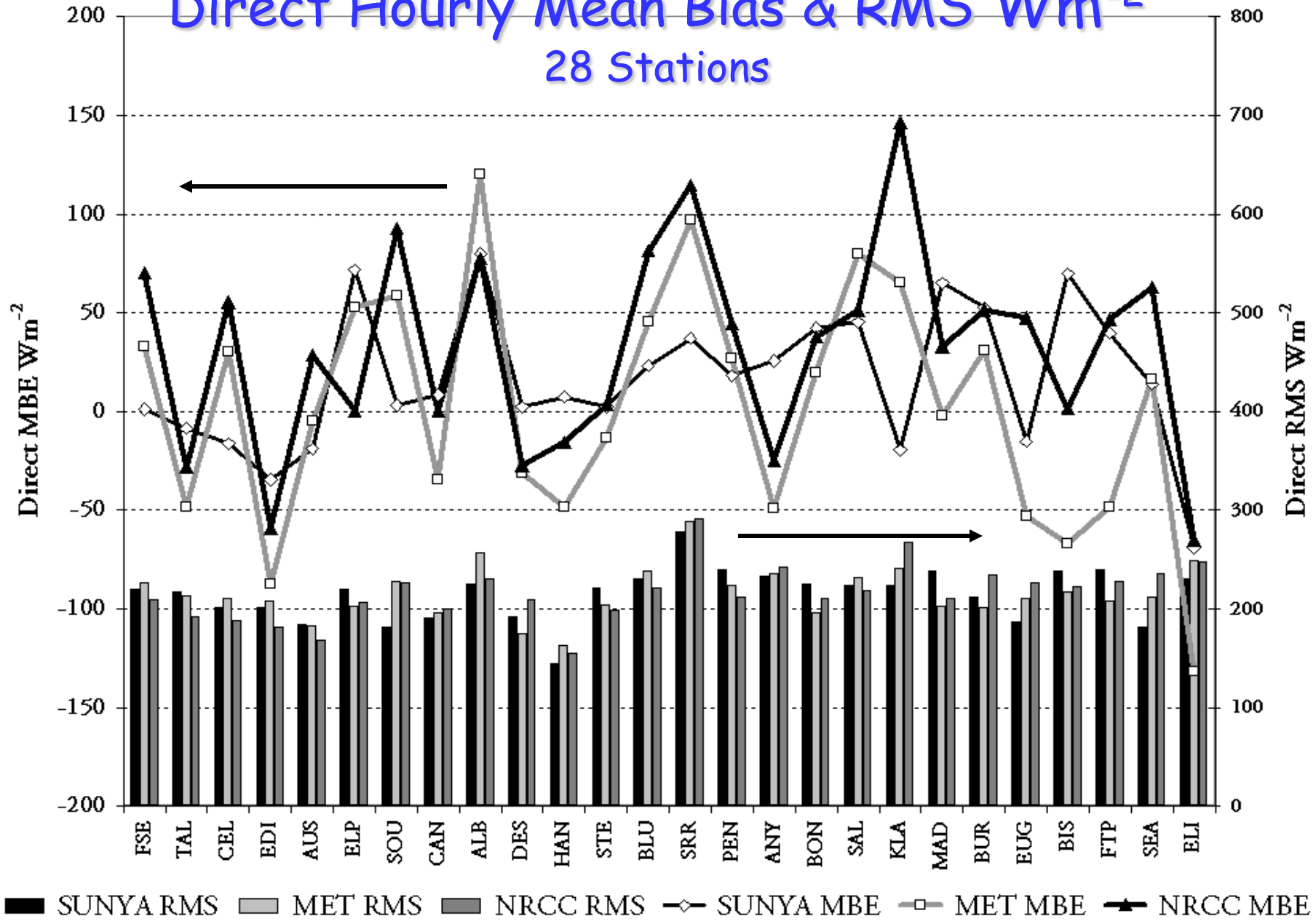
Hourly Global Mean Bias & RMS Wm^{-2}

33 Stations



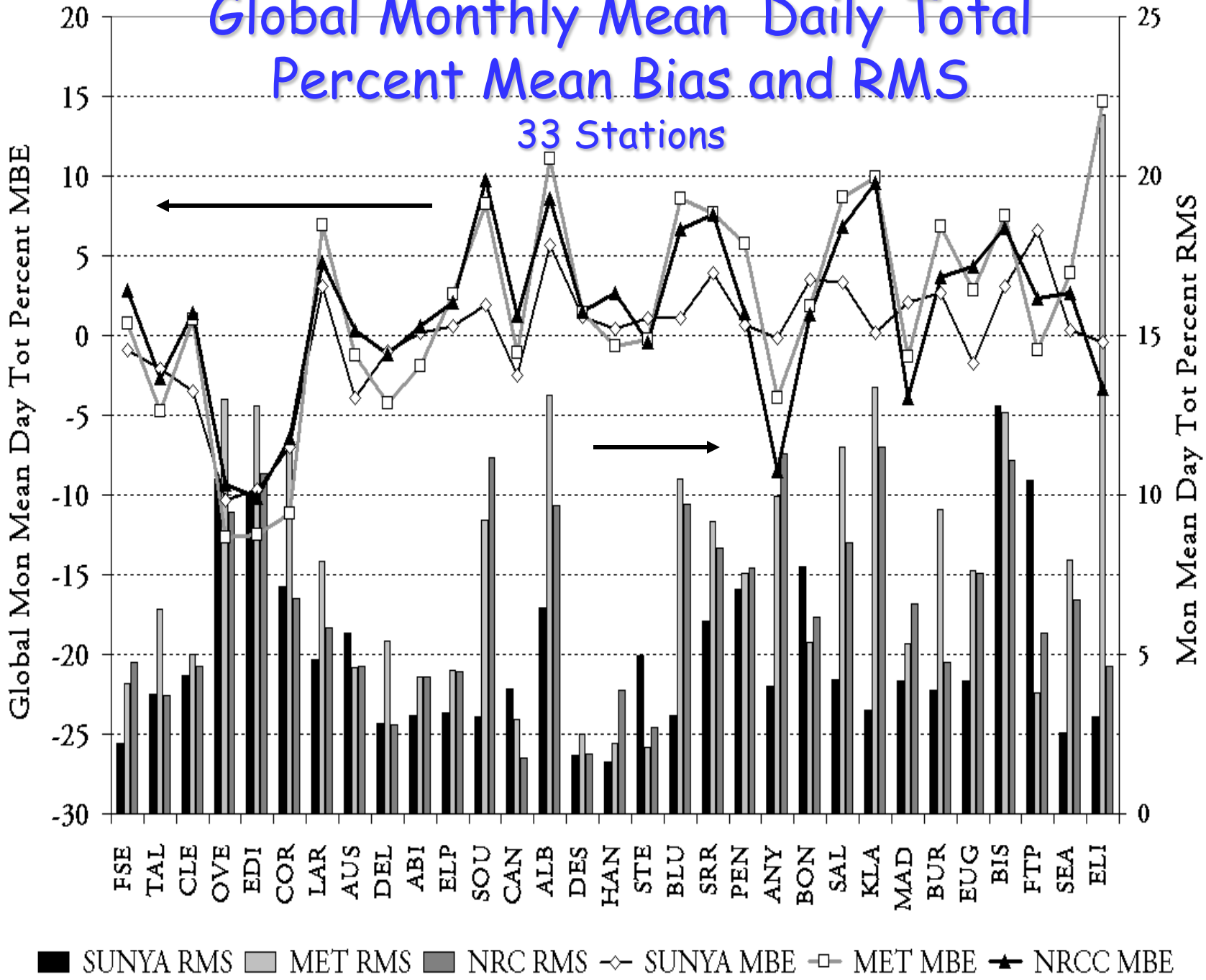
Direct Hourly Mean Bias & RMS Wm^{-2}

28 Stations

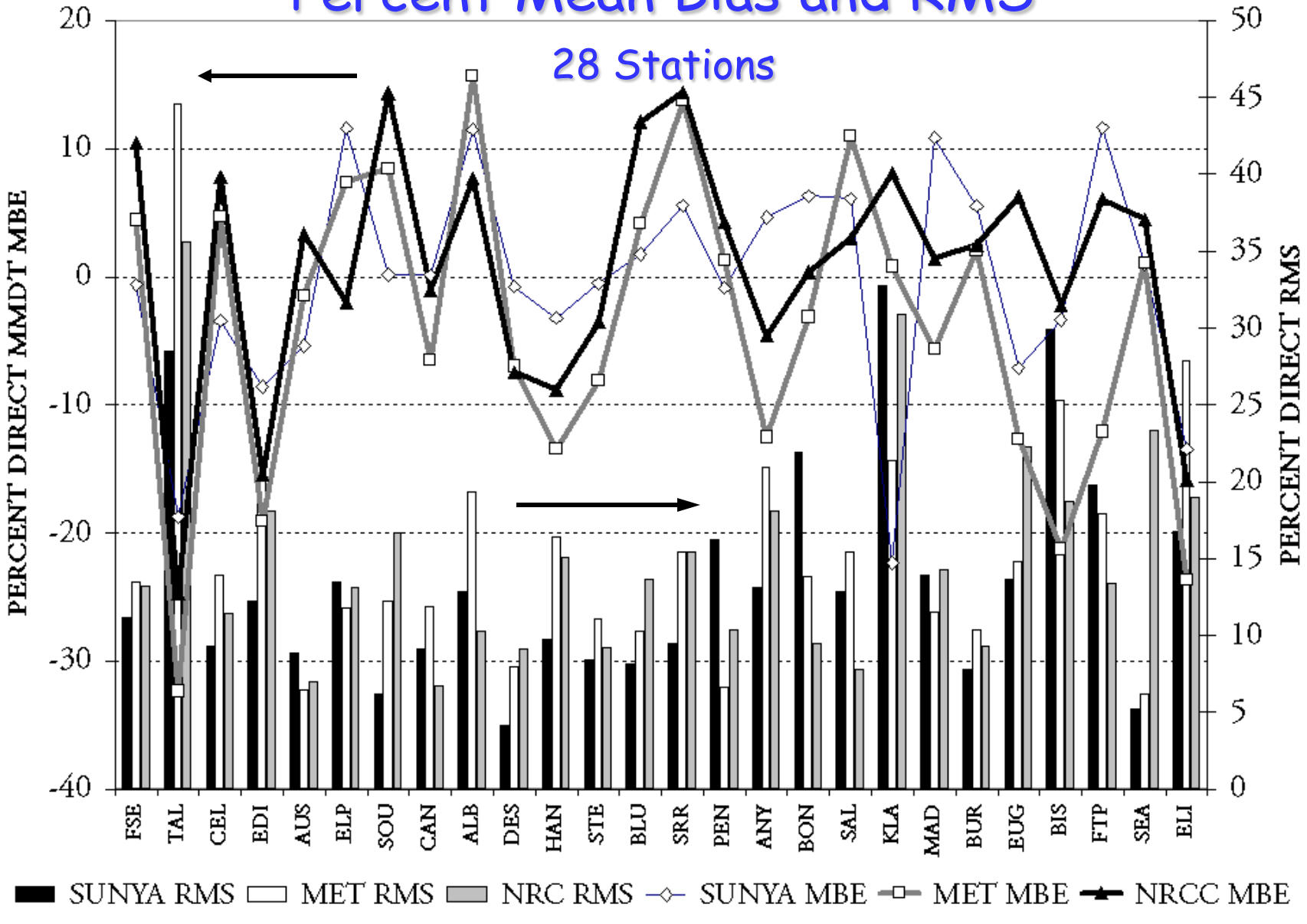


Global Monthly Mean Daily Total Percent Mean Bias and RMS

33 Stations

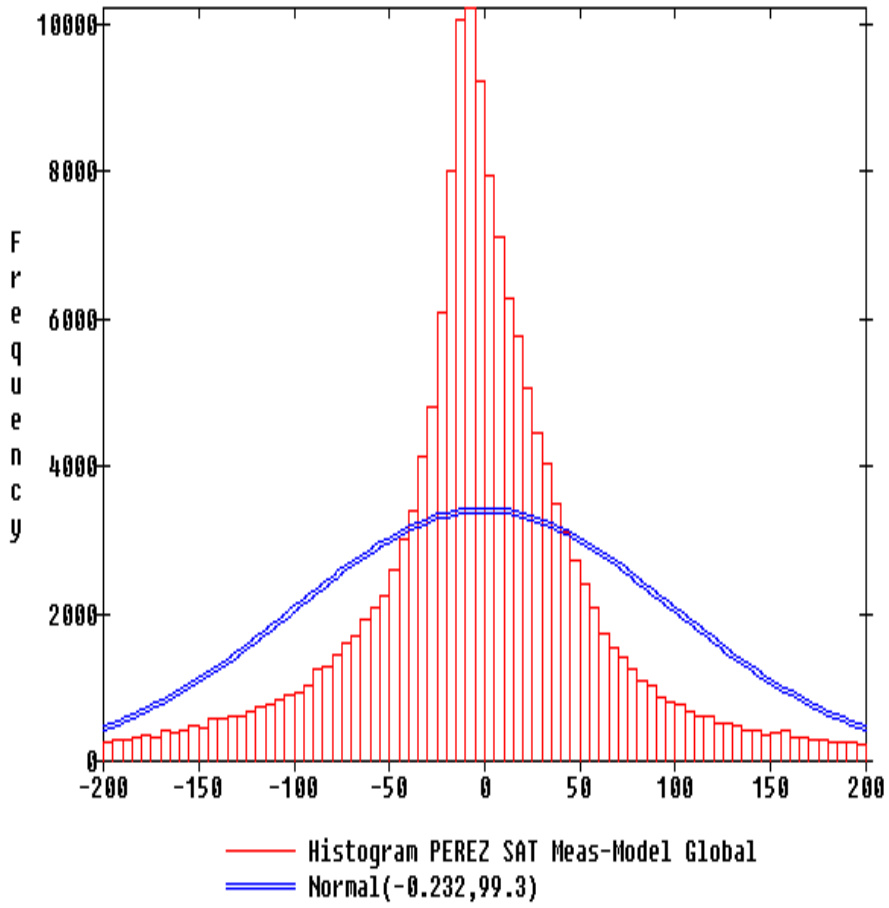


Direct Monthly Mean Daily Total Percent Mean Bias and RMS

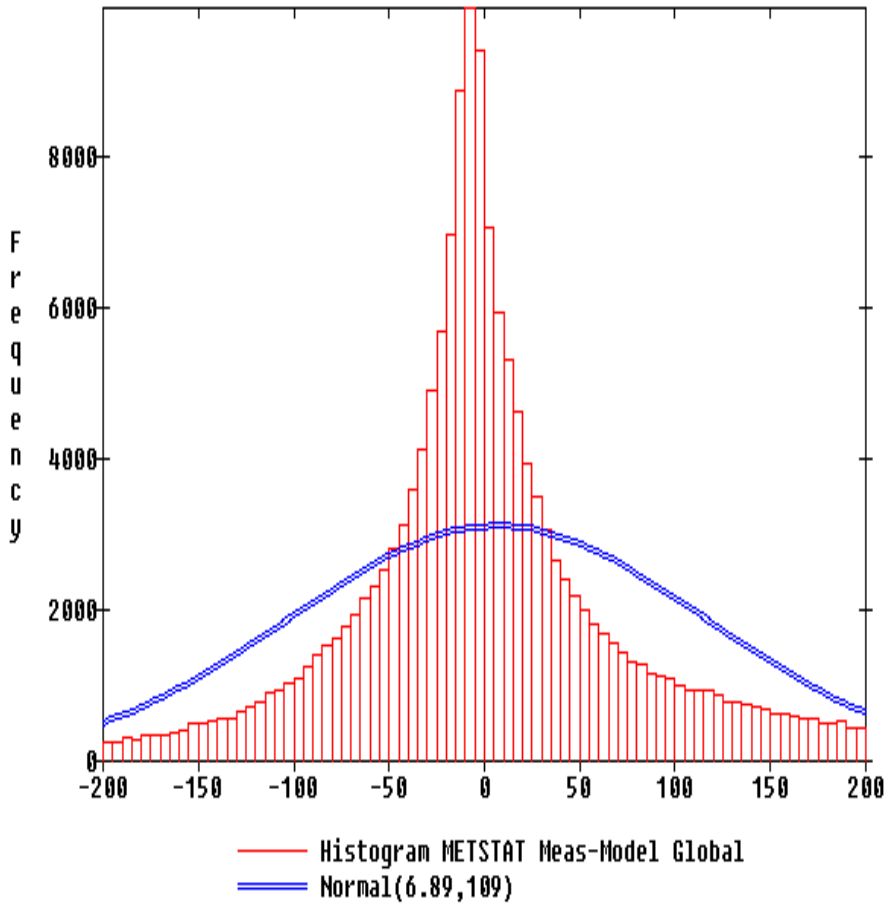


Global Hourly Model Error Distribution Wm^{-2}

SAT Mean ± σ: -0.2 ± 99.3

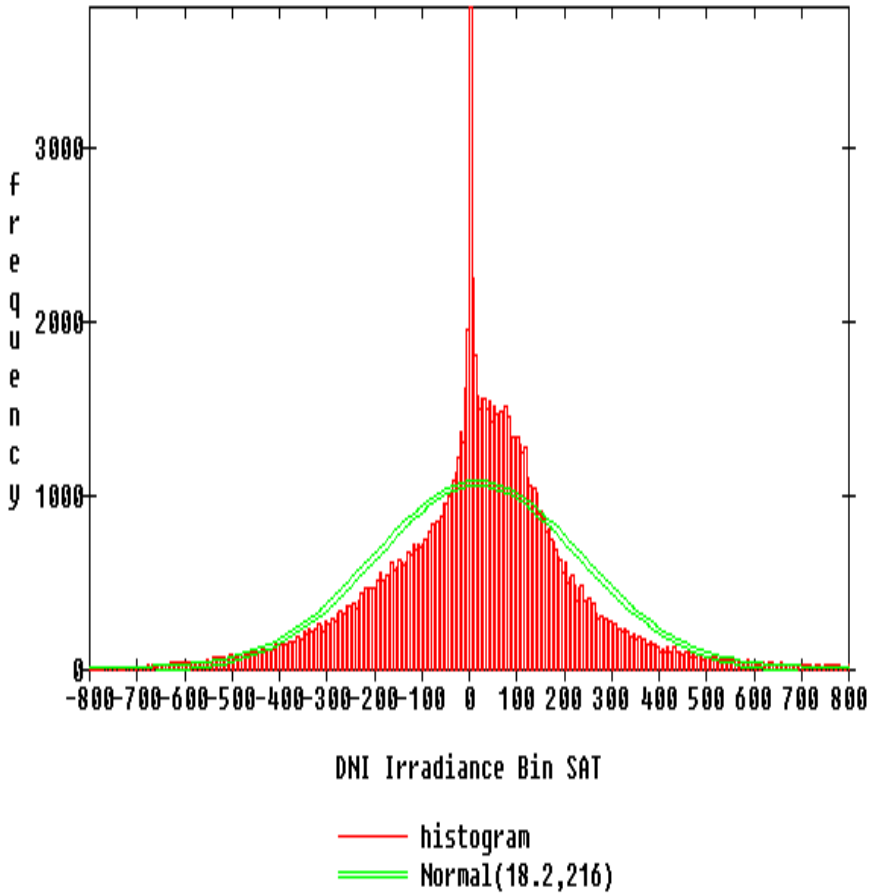


MET: 7.0 ± 109.0

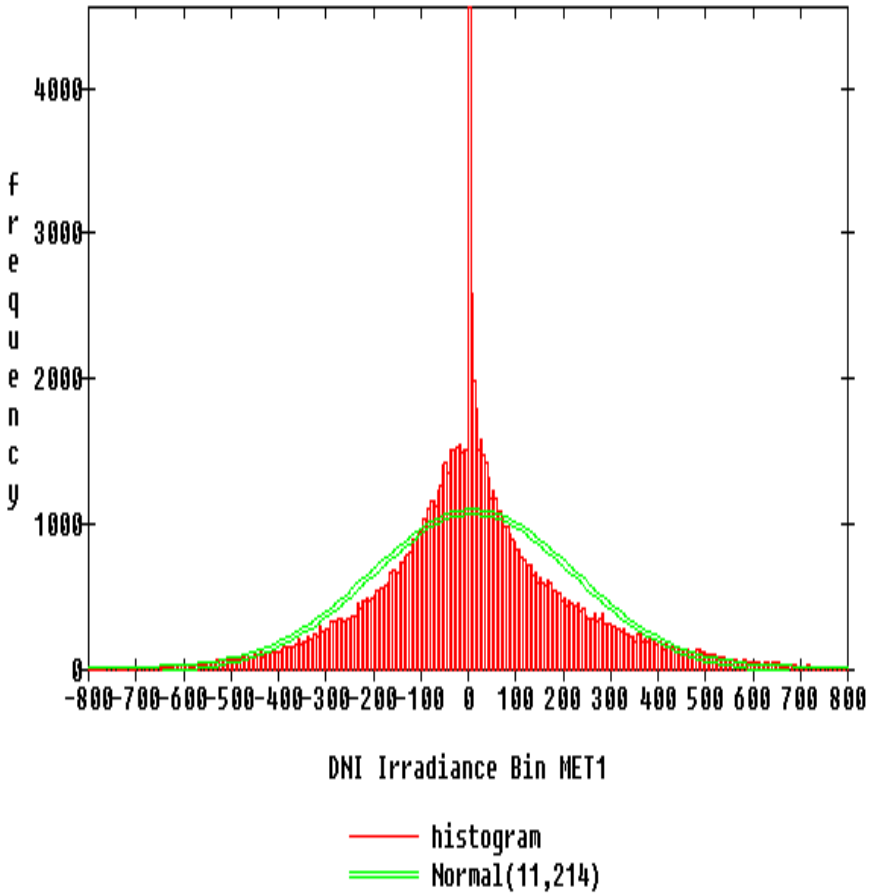


Direct Hourly Model Error Distribution Wm^{-2}

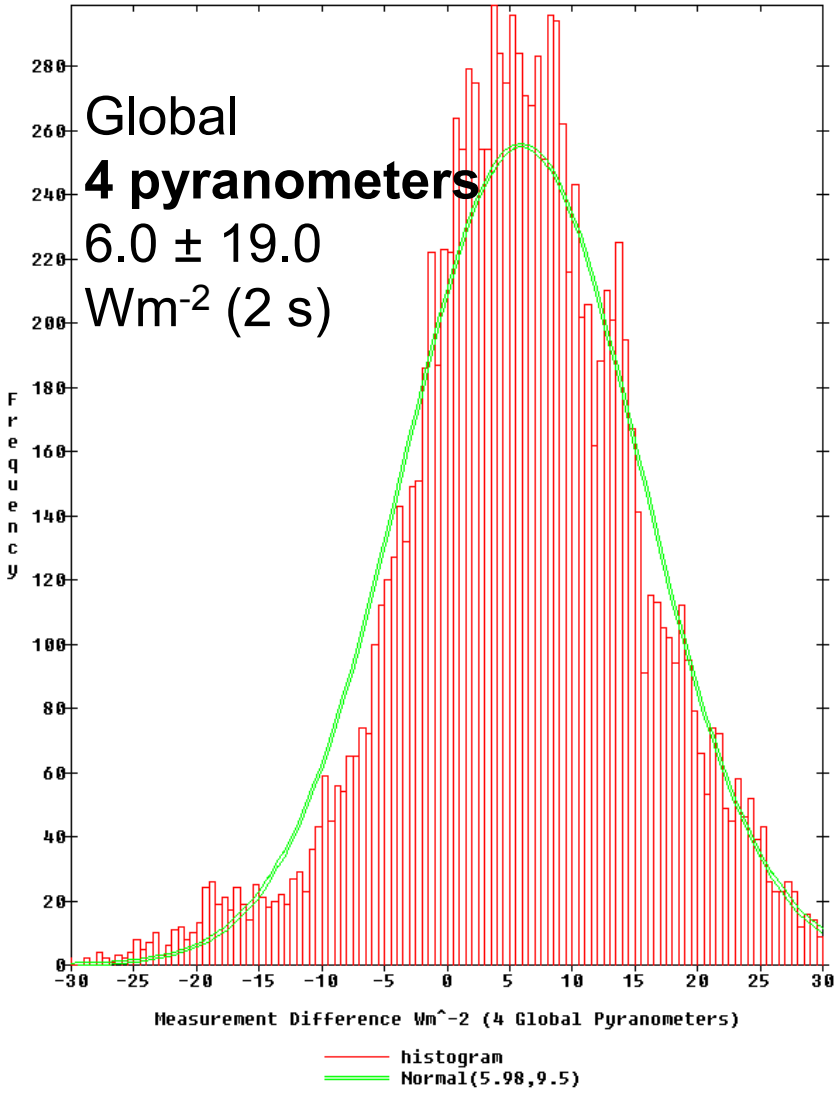
SAT Mean +/- σ: 18.2 ± 216

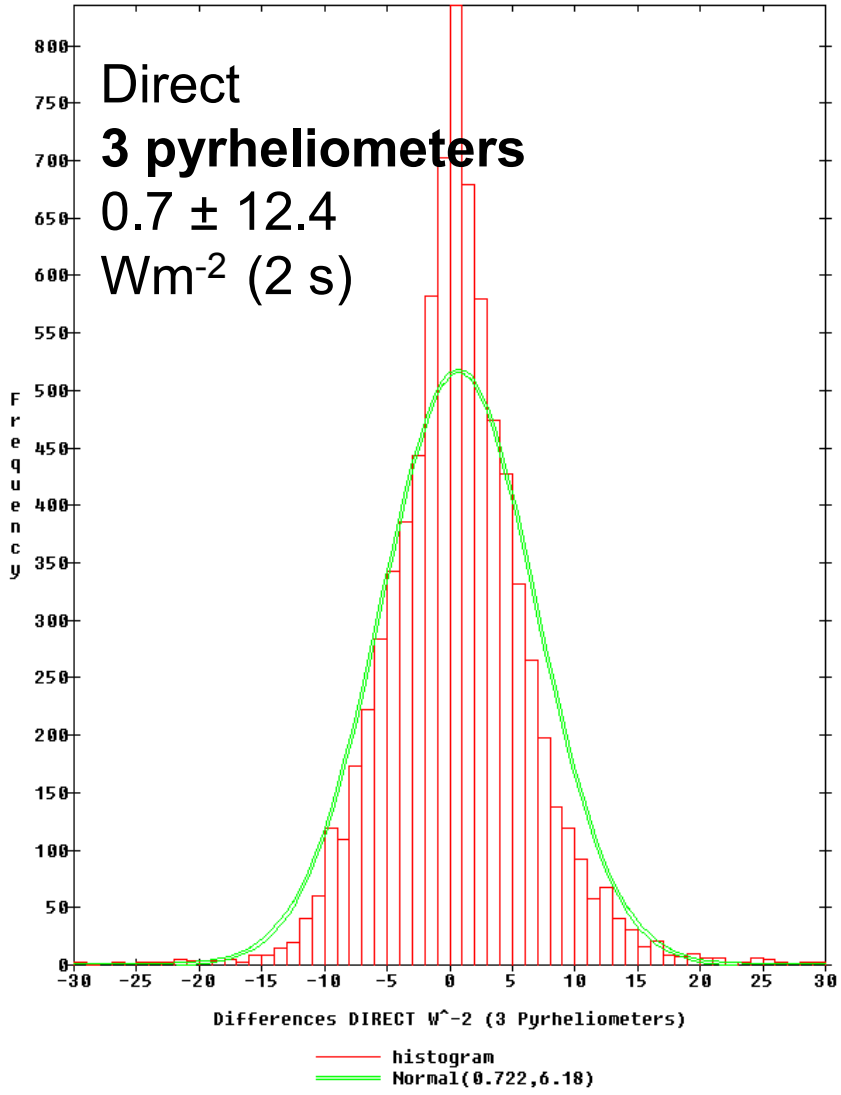


MET: 11.0 ± 214



Global & Direct Hourly *Measurement* Differences (multiple Radiometers @ SRRL)





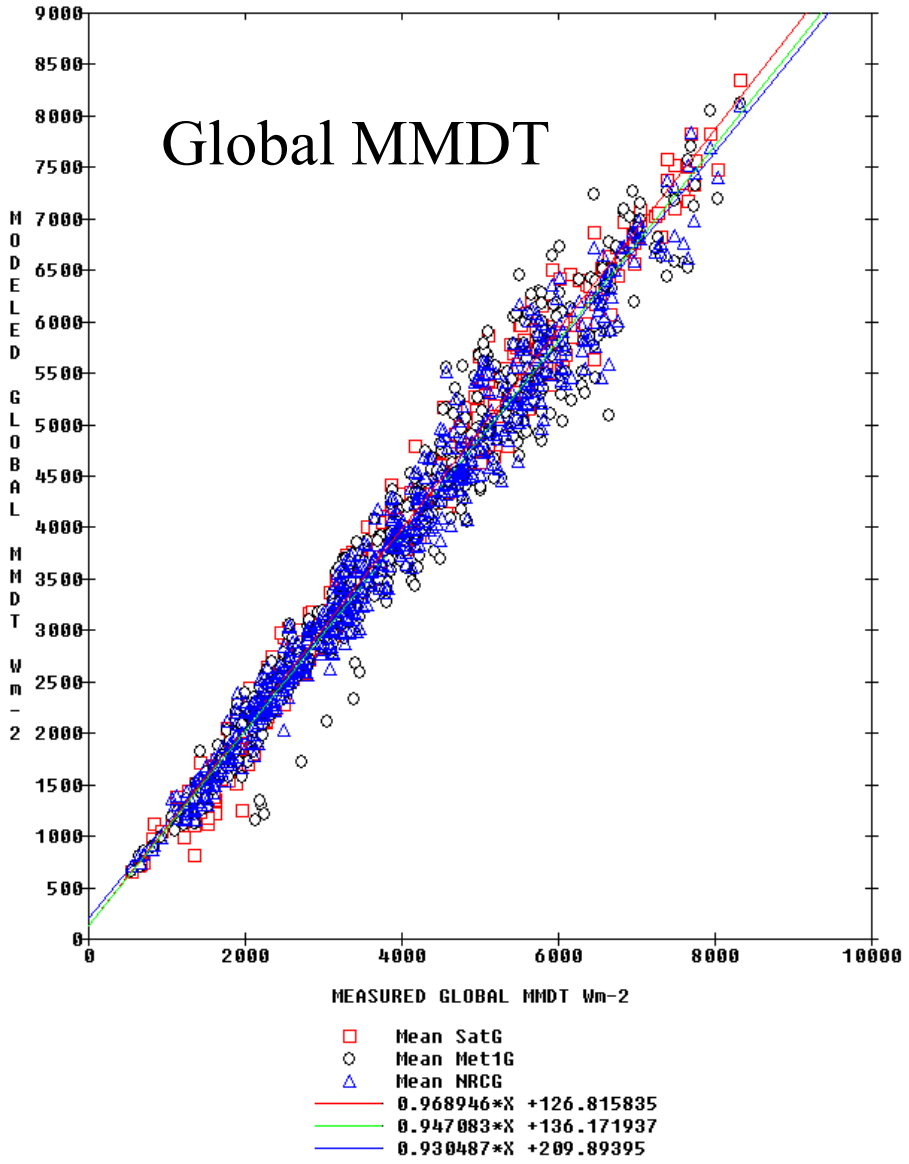
MBE and RMS Percent Statistics
Global Monthly Mean Daily Total 33 sites

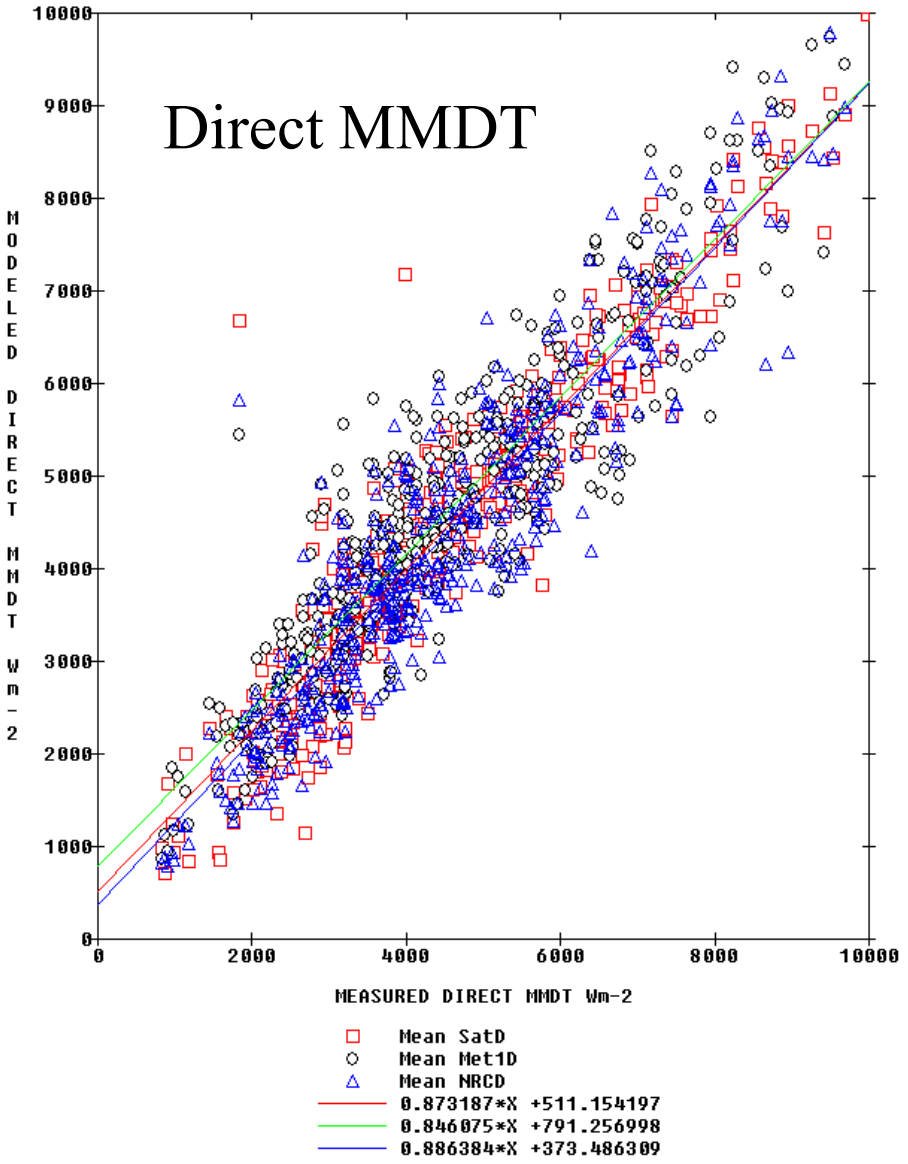
Global Total MMDT%	*SUNYA MBE*	*MET MBE*	*NRCC MBE*	*AVERAGE*
Mean	-0.06	1.73	1.38	1.0
Standard Deviation	3.85	6.70	5.26	5.3
Minimum	-10.30	-12.70	-10.20	
Maximum	6.61	14.68	9.78	
	RMS	RMS	RMS	
Mean	5.0	8.0	6.6	6.5
Standard Deviation	2.8	4.4	2.9	3.4
Minimum	1.6	2.1	1.7	
Maximum	12.8	21.9	11.5	

MBE and RMS Percent Statistics
Direct Monthly Mean Daily Total 28 sites

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	

Model vs Measured Monthly Mean Daily Total Correlation All Sites Wm^{-2}



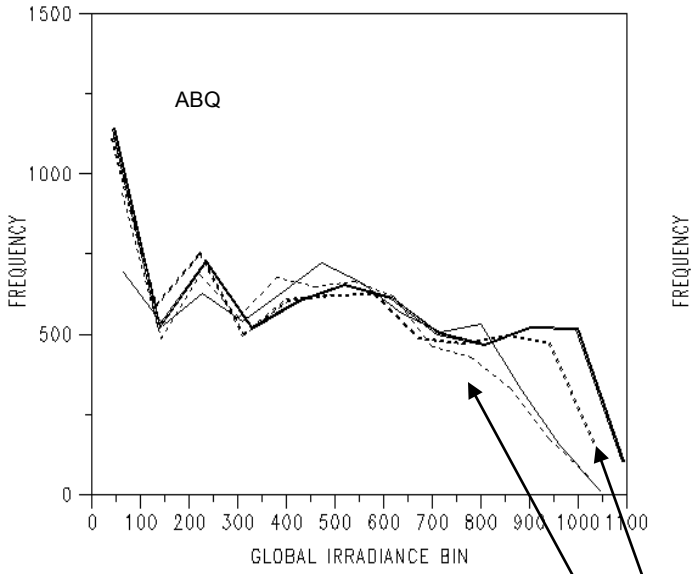


Model vs Measured Monthly Mean Daily Total Correlation All Sites Wm^{-2}

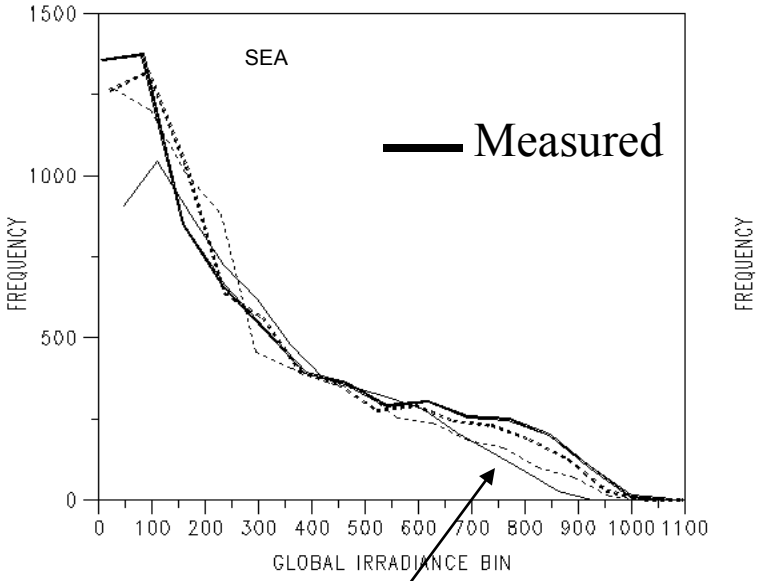
	SLOPE	INTERCEPT	R^2
Global MMDT Fit	0.969	127	0.98
PEREZ SAT	0.947	136	0.96
METSTAT	0.931	210	0.97
NRC			
Direct MMDT Fit	0.873	511	0.88
PEREZ SAT	0.846	791	0.83
METSTAT	0.886	374	0.85
NRCC			

Measured and Modeled Hourly GLOBAL Frequency Distributions

Albuquerque Global



Seattle Global



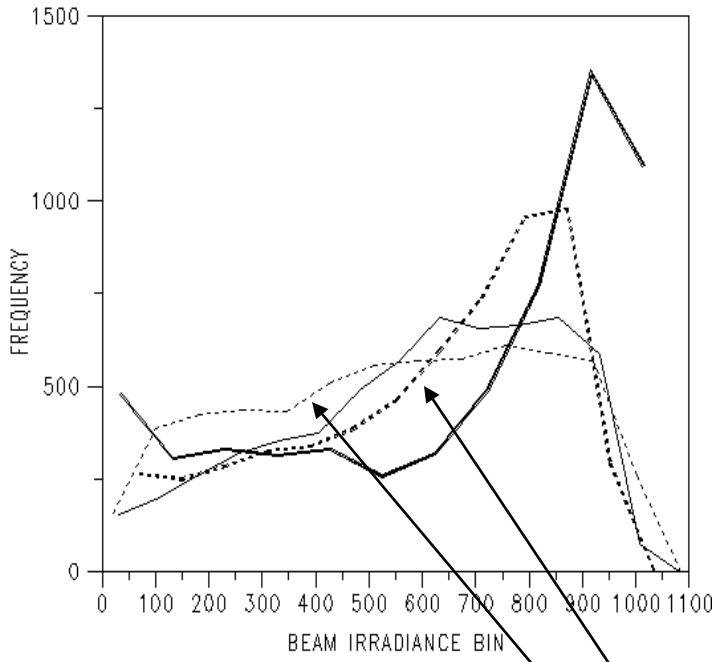
PEREZ/SUNY

METSTAT

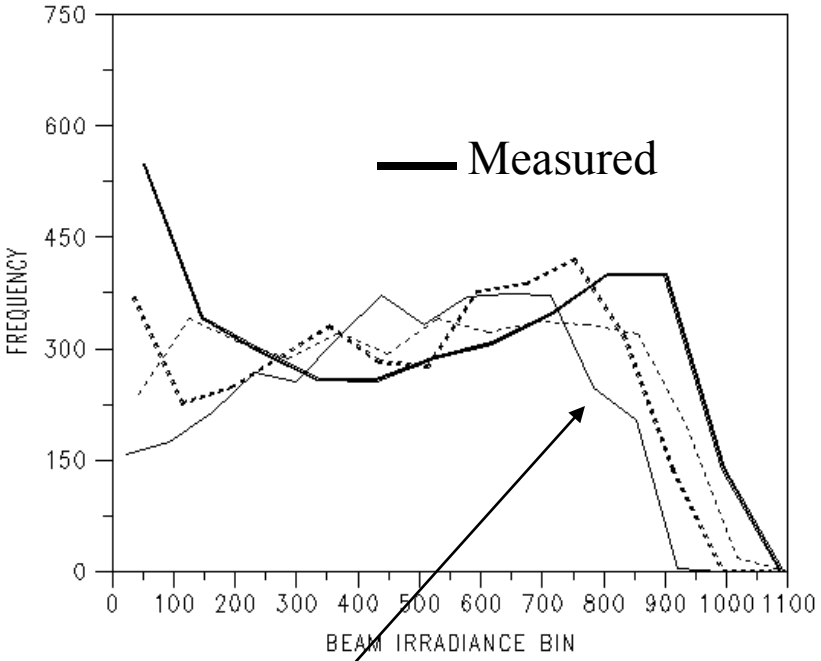
NRCC/ASHRAE

Measured and Modeled Hourly DIRECT Frequency Distributions

Albuquerque Beam



Seattle Beam



PEREZ/SUNY

METSTAT

NRCC/ASHRAE

Uncertainty

MEASUREMENTS

U_{meas} (±%)

Global	Direct	Diffuse
6	5	6

MODELS

U_{mod} (±%)

Model	Glo/Dif RMS (U_{mod})	Glo/Dif MBE (U_{bias})	Dir RMS (U_{mod})	Dir MBE (U_{bias})
METSTAT	8	2	15	4
SUNY	5	0	14	1

$$U_{opt} = (U_{meas}^2 + U_{mod}^2 + U_{bias}^2)^{1/2} (\pm\%)$$

U_{opt} (±%)

Model	Glo/Dif	Dir
METSTAT	10	16
SUNY	8	15

U_{add} Satellite (±%)

Condition	Additional Uncertainty
Time shifting	2
Ground snow cover	5
High latitude	10

U_{add} METSTAT (±%)

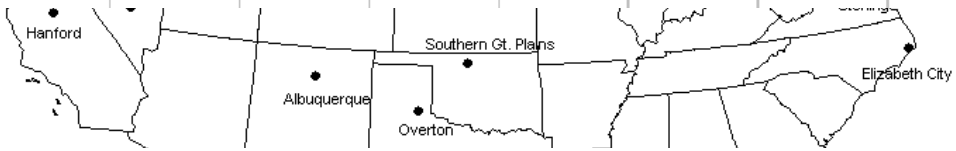
Condition	Additional Uncertainty
Short- and med-termfilling	4
Long-term filling	14
Cloud probability derivation	4
Cloud probability nearby site	4
ASOS-only	22

$$U_{95} = (U_{opt}^2 + U_{add1}^2 + U_{add2}^2 \ldots)^{1/2} (\pm\%)$$

Uncertainty Calculations

NSRDB		Uopt		Rtype (%)	FLAG	Rflg (%)	% MISS	Rsta(%)	Rflg (%)	Rsta(%)	Ucc=UccB+UccR	9%	note A	Umod	10%	note F	9%
UNCERTAINTY	Glob	**3%**	3 com	3%	1	***3%***	0	0%	***2%***	0%	Usup=UsupB+UsupR	1%	note B	MBE	5.00%		1%
ELEMENTS	Dir	***2%***	2 com	3%	2	5%	2	0%	4%	2%	Udist=UdistB+UdistR	4%	note C				4%
	Dif	5%	1 com	**6%**	3	5%	5	0%	6%	4%	Usub=UsubB+UsubR	4%	note D				4%
	3comp	6%	Need to select which		4	5%	10	0%	8%	6%	Uint=UintB+UintR	9%	note E				9%
Protection Password: NSRDB			Component to		5	5%	15	0%	10%	8%							
			Insert		6	5%	20	0%	18%	10%							
					7	**5%**	25	0%	25%	20%							
					8	5%	50	0%	35%								
					9	5%			50%		Global		Direct			Diffuse	

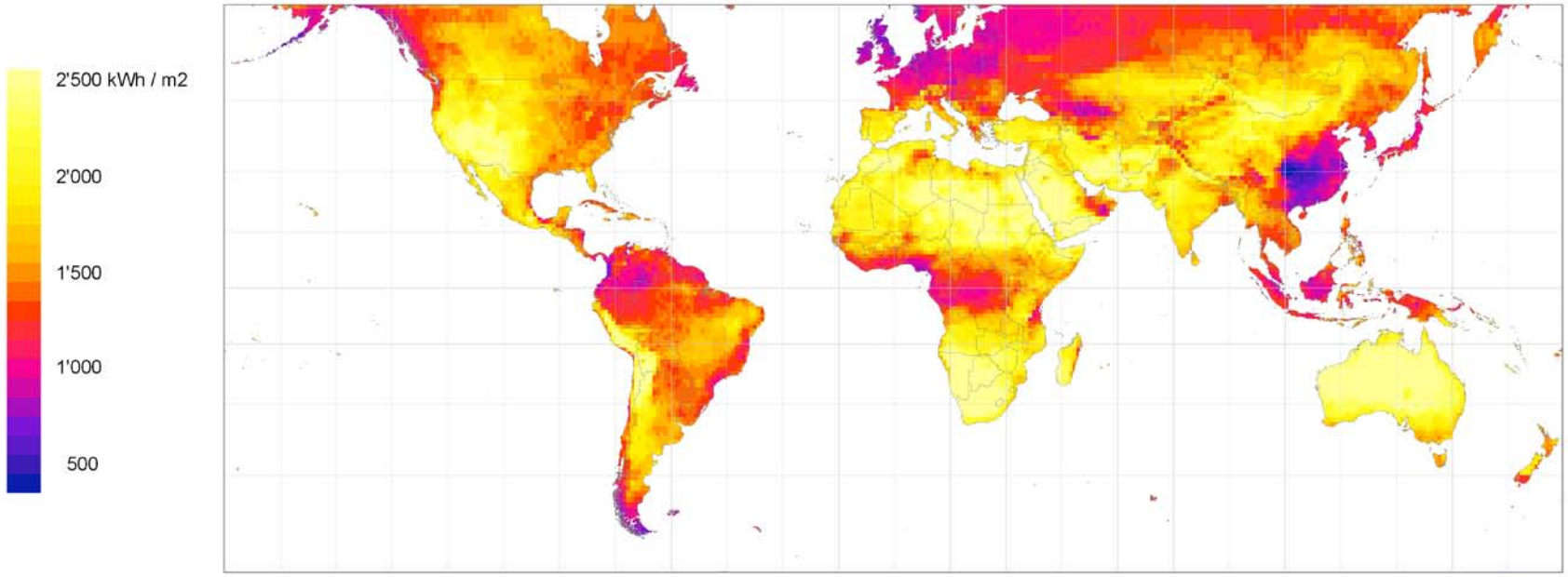
			Since filtered in validation select value for filter			Low	Typical	Max
Measured		U^2=	Uopt^2+Rtype^2+Rflg^2+Rsta^2		limit	5%	7%	8%
Measured + Correction								
PRE 76 + Syncal								
Derived by Calculation			Ua^2+Ub^2			7%	9%	12%
MOD OBS CLD AOD MANUAL			U^2+Ucc^2+Umod^2+MBE^2			13%	16%	17%
MOD OBS CLD ASOS + SUP CLOUD			U^2+Ucc^2+Umod^2+MBE^2+ Usup^2			15%	16%	17%
MOD OBS CLD ASOS+ DISTRIBUTION			U^2+Ucc^2+Umod^2+MBE^2+Udist^2			16%	16%	17%
MOD OBS CLD NEARBY DISTRIBUTION			U^2+Ucc^2+Umod^2+MBE^2+Udist^2+Usub^2			16%	17%	18%
MOD INTPL LCLD MANUAL			U^2+Ucc^2+Umod^2+MBE^2+Uint^2			18%	18%	19%
MOD INTPL CLD ASOS + SUP CLD			U^2+Ucc^2+Umod^2+MBE^2+Uint^2+Usup^2			18%	18%	19%
MOD INTPL CLD ASOS + Dist			U^2+Ucc^2+Umod^2+MBE^2+Uint^2+Usup^2+Udist^2			18%	19%	19%
MOD INTPL CLD Nearby Dist			U^2+Ucc^2+Umod^2+MBE^2+Uint^2+Usup^2+Udist^2+Usub^2			19%	19%	20%



Sanity Check: Other Methods; Other Satellites Meteonorm Direct

Source: Meteonorm 6.0 (www.meteonorm.com); uncertainty 15%
Period: 1981 - 2000; grid cell size: 1°

Yearly sum of direct normal irradiance

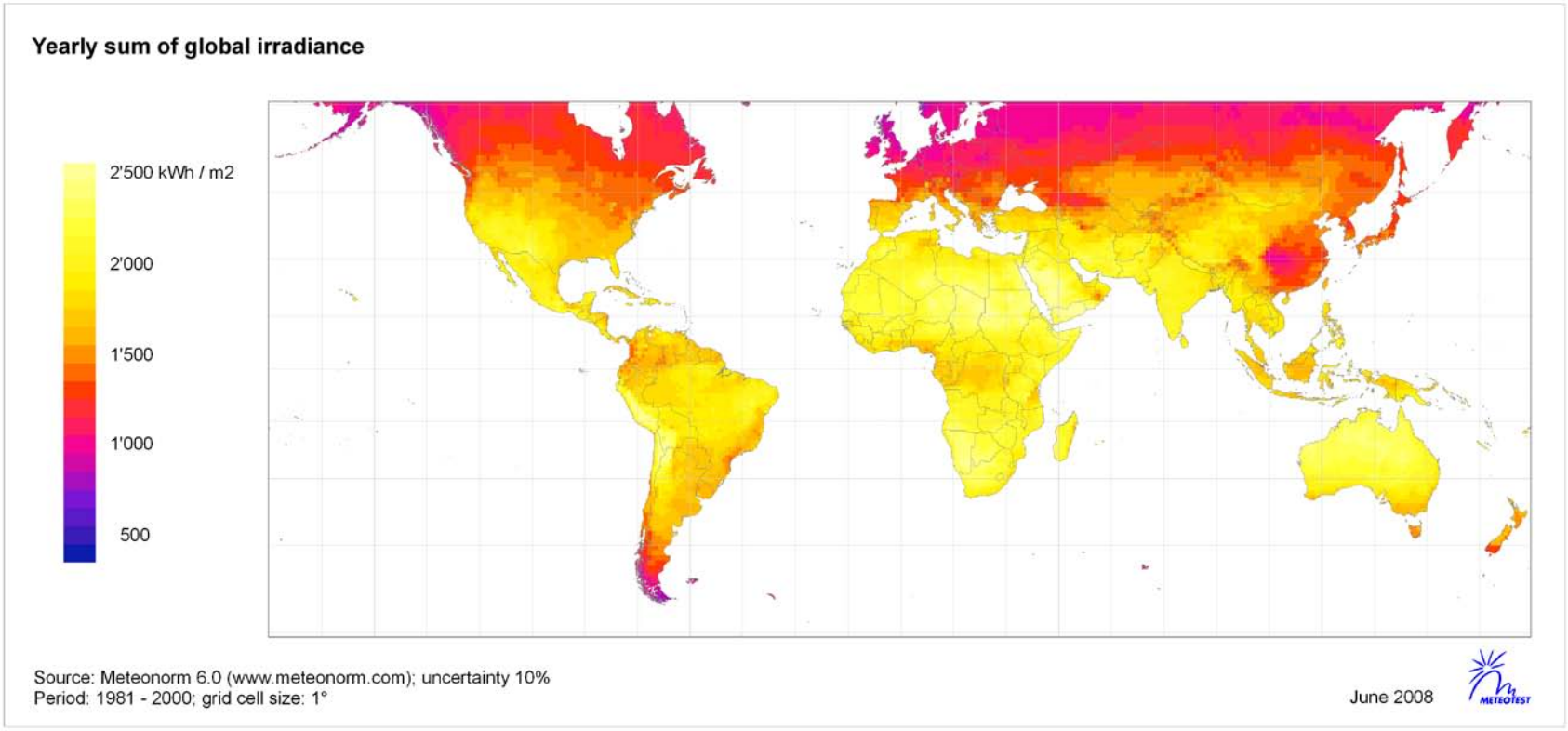


Source: Meteonorm 6.0 (www.meteonorm.com); uncertainty 15%
Period: 1981 - 2000; grid cell size: 1°

June 2008

Meteonorm Global

Source: Meteonorm 6.0 (www.meteonorm.com); uncertainty 10%
Period: 1981 - 2000; grid cell size: 1°



Analysis 6 Solar Databases Europe

Šúri1, et al., "First Steps in the Cross-Comparison of Solar Resource Spatial Products in Europe" *Proceeding of the EUROSUN 2008,*

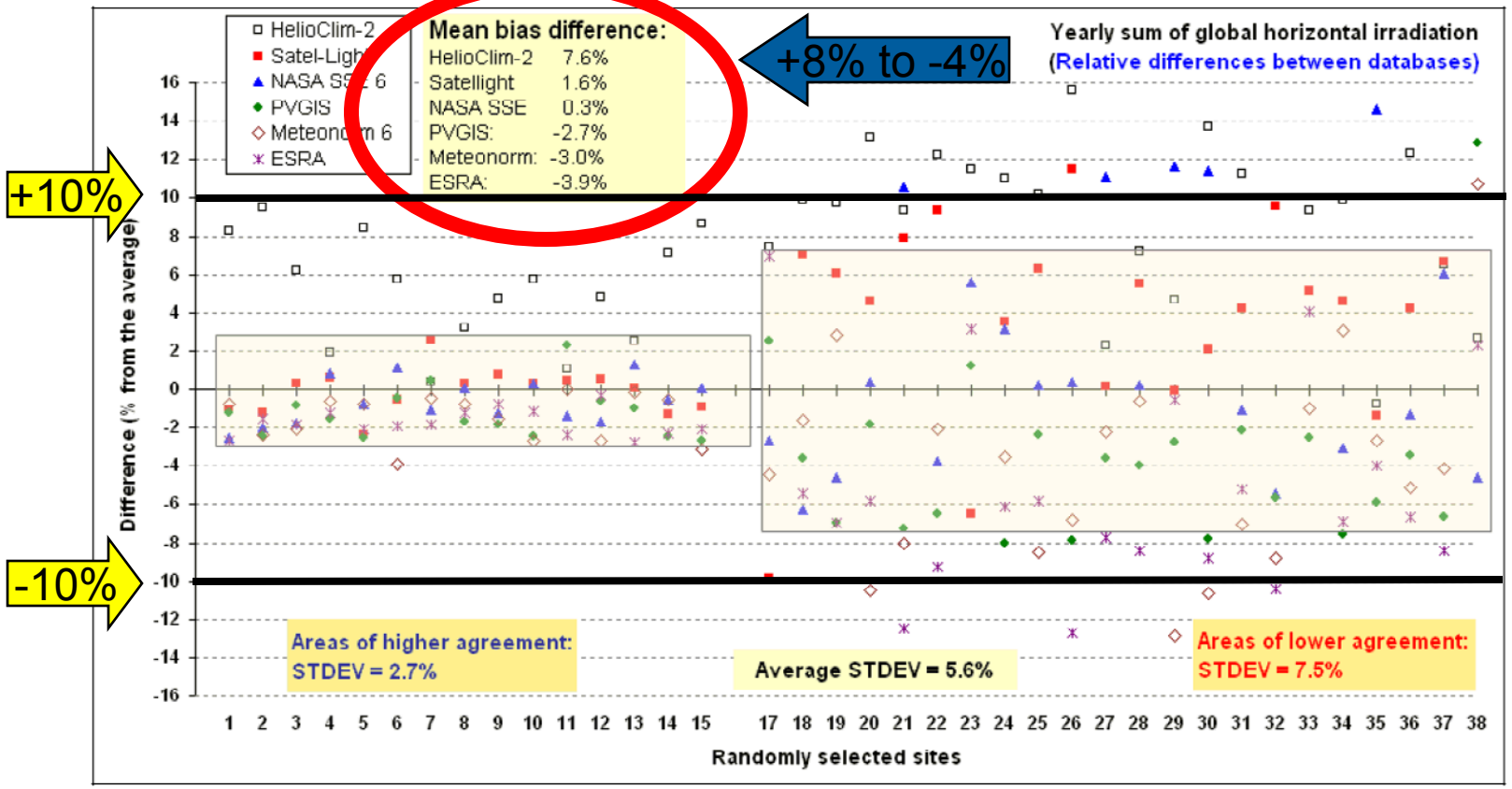
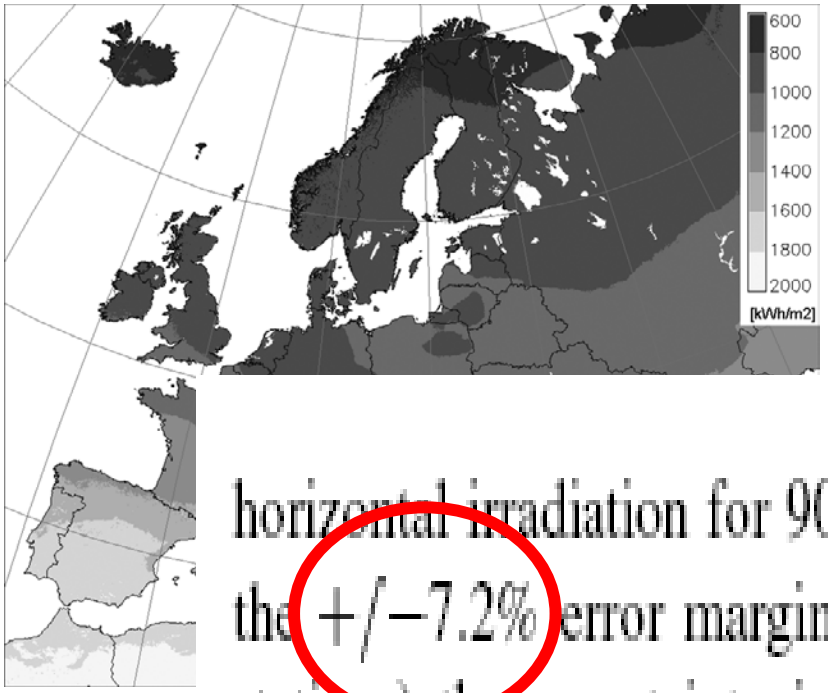


Fig. 3. Yearly sum of global horizontal irradiation – differences of the values from 6 databases relative to the overall average. First 15 points represent areas with higher agreement between databases; the other 22 points are randomly selected in areas where the difference between the databases is higher.

European PVGIS Uncertainty

Súri et al., "Geographic Aspects of Photovoltaics in Europe: Contribution of the PVGIS Website" *IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING*, VOL. 1, NO. 1, MARCH 2008



—the estimate of yearly global horizontal irradiation for 90% of station locations falls within the +/−7.2% error margin, and in 19 locations (3.5% of all stations) the uncertainty is higher than +/−10%.

PV system monitoring vs satellite based solar maps

A. Drews et al., “Quality of performance assessment of PV plants based on irradiation maps”, *Solar Energy* 82 (2008) 1067–1075

Modeled and measured annual yield of the 10 systems under inspection

Location	Modeled yield (kWh/kW)	Measured yield (kWh/kW)	Relative error (%)
Borna	928	998	−7.0
Seifennersdorf	926	930	−0.4
Starbach	942	930	1.3
Hartha	976	957	1.9
Zwickau	906	957	−5.3
Plauen	921	850	8.4
Berzdorf	1040	964	7.9
Freiberg	906	977	−7.3
Mittweida	912	958	−4.7
Dresden	966	989	−2.3

-7%

-5 to +8 %

SUMMARY

- All three models performed remarkably alike
- Measured-Model difference patterns => function of Site, INPUT data
- METSTAT radiation derived from clear sky model modified by cloud cover.
- NREL estimates Satellite (SUNY) Uncertainty comparable European estimates (state of the art)
- Satellite based on a measurement (radiance) ; METSTAT comparable to Satellite; but METSTAT approach in both

Similar Uncertainty Limits:

5% - 10% Global Month Mean Daily Total

10%- 15% Direct Month Mean Daily Total

NOTE: NO HIGHER UNCERTAINTY ON HOURLY DATA: MOST OF UNCERTAINTY ORIGINATES FROM ~ CONSTANT MODEL MBE FOR HOURLY DATA (~ 50 W/ 500 W ~ 10%, on average)