Benchmark of satellite and NWP derived solar resource

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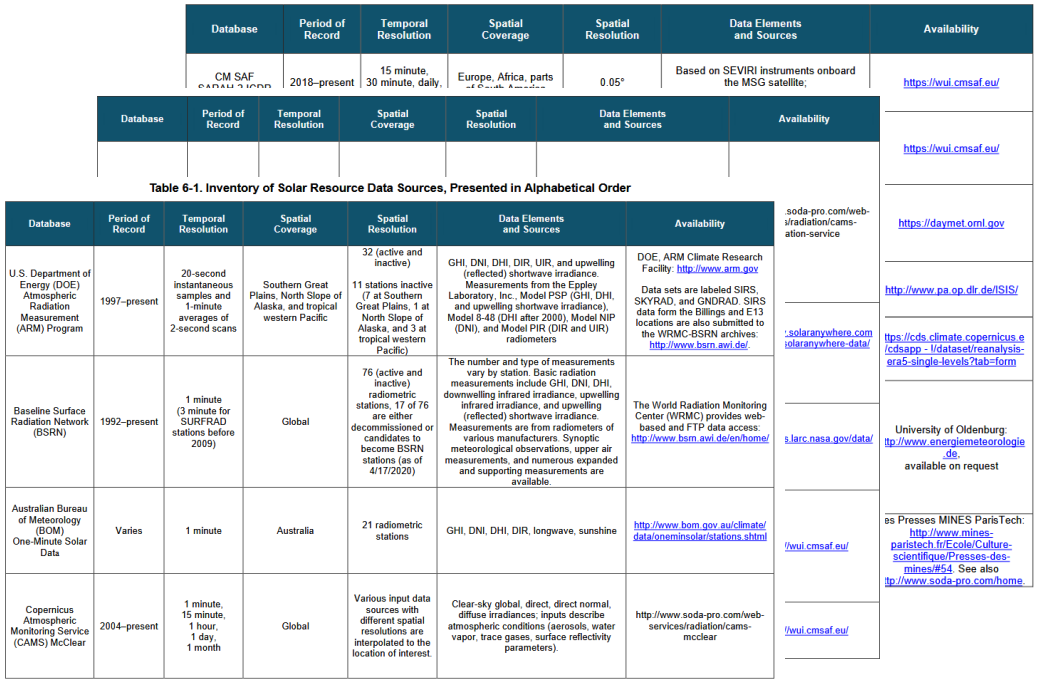
Outline

1. Motivation
2. Data collection
3. Benchmark
4. Results
5. Conclusion

Motivation

Available longterm solar radiation data



Database	Period of Record	Temporal Resolution	Spatial Coverage	Spatial Resolution	Data Elements and Sources	Availability
CM SAF SARAH-2/CORE	2018–present	15 minute, 30 minute, daily,	Europe, Africa, parts of South America	0.05°	Based on SEVIRI instruments onboard the MSG satellite;	https://wui.cmsaf.eu/

Database	Period of Record	Temporal Resolution	Spatial Coverage	Spatial Resolution	Data Elements and Sources	Availability
						https://wui.cmsaf.eu/

Table 6-1. Inventory of Solar Resource Data Sources, Presented in Alphabetical Order

Database	Period of Record	Temporal Resolution	Spatial Coverage	Spatial Resolution	Data Elements and Sources	Availability	
U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program	1997–present	20-second instantaneous samples and 1-minute averages of 2-second scans	Southern Great Plains, North Slope of Alaska, and tropical western Pacific	32 (active and inactive) 11 stations inactive (7 at Southern Great Plains, 1 at North Slope of Alaska, and 3 at tropical western Pacific)	GHI, DNI, DHI, DIR, UIR, and upwelling (reflected) shortwave irradiance. Measurements from the Eppley Laboratory, Inc., Model PSP (GHI, DHI, and upwelling shortwave irradiance), Model 8-48 (DHI after 2000), Model NIP (DNI), and Model PIR (DIR and UIR) radiometers	DOE, ARM Climate Research Facility: http://www.arm.gov Data sets are labeled SIRS, SKYRAD, and GNDRAD. SIRS data form the Billings and E13 locations are also submitted to the WRMC-BSRN archives: http://www.bsrn.awi.de/.	soda-pro.com/web-services/radiation/cams-radiation-service	https://daymet.ornl.gov
Baseline Surface Radiation Network (BSRN)	1992–present	1 minute (3 minute for SURFRAD stations before 2009)	Global	76 (active and inactive) radiometric stations, 17 of 76 are either decommissioned or candidates to become BSRN stations (as of 4/17/2020)	The number and type of measurements vary by station. Basic radiation measurements include GHI, DNI, DHI, downwelling infrared irradiance, upwelling infrared irradiance, and upwelling (reflected) shortwave irradiance. Measurements are from radiometers of various manufacturers. Synoptic meteorological observations, upper air measurements, and numerous expanded and supporting measurements are available.	The World Radiation Monitoring Center (WRMC) provides web-based and FTP data access: http://www.bsrn.awi.de/en/home/	solaranywhere.com/solaranywhere-data/	http://www.pa.op.dlr.de/ISIS/
Australian Bureau of Meteorology (BOM) One-Minute Solar Data	Varies	1 minute	Australia	21 radiometric stations	GHI, DNI, DHI, DIR, longwave, sunshine	http://www.bom.gov.au/climate/data/oneminsolar/stations.shtml	s.larc.nasa.gov/data/	https://cds.climate.copernicus.eu/cdsapp - !/dataset/reanalysis-era5-single-levels?tab=form
Copernicus Atmospheric Monitoring Service (CAMS) McClear	2004–present	1 minute, 15 minute, 1 hour, 1 day, 1 month	Global	Various input data sources with different spatial resolutions are interpolated to the location of interest.	Clear-sky global, direct, direct normal, diffuse irradiances; inputs describe atmospheric conditions (aerosols, water vapor, trace gases, surface reflectivity parameters).	http://www.soda-pro.com/web-services/radiation/cams-mcclear	/wui.cmsaf.eu/	University of Oldenburg: ttp://www.energiemeteorologie.de, available on request
							/wui.cmsaf.eu/	es Presses MINES ParisTech: http://www.mines-paristech.fr/Ecole/Culture-scientifique/Presses-des-mines/#54. See also tp://www.soda-pro.com/home.

Which data set is best for my project?

Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications, 3rd Ed. Chapter 6-6 –16

https://iea-pvps.org/key-topics/best-practices-handbook-for-the-collection-and-use-of-solar-resource-data-for-solar-energy-applications-third-edition/

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Data collection

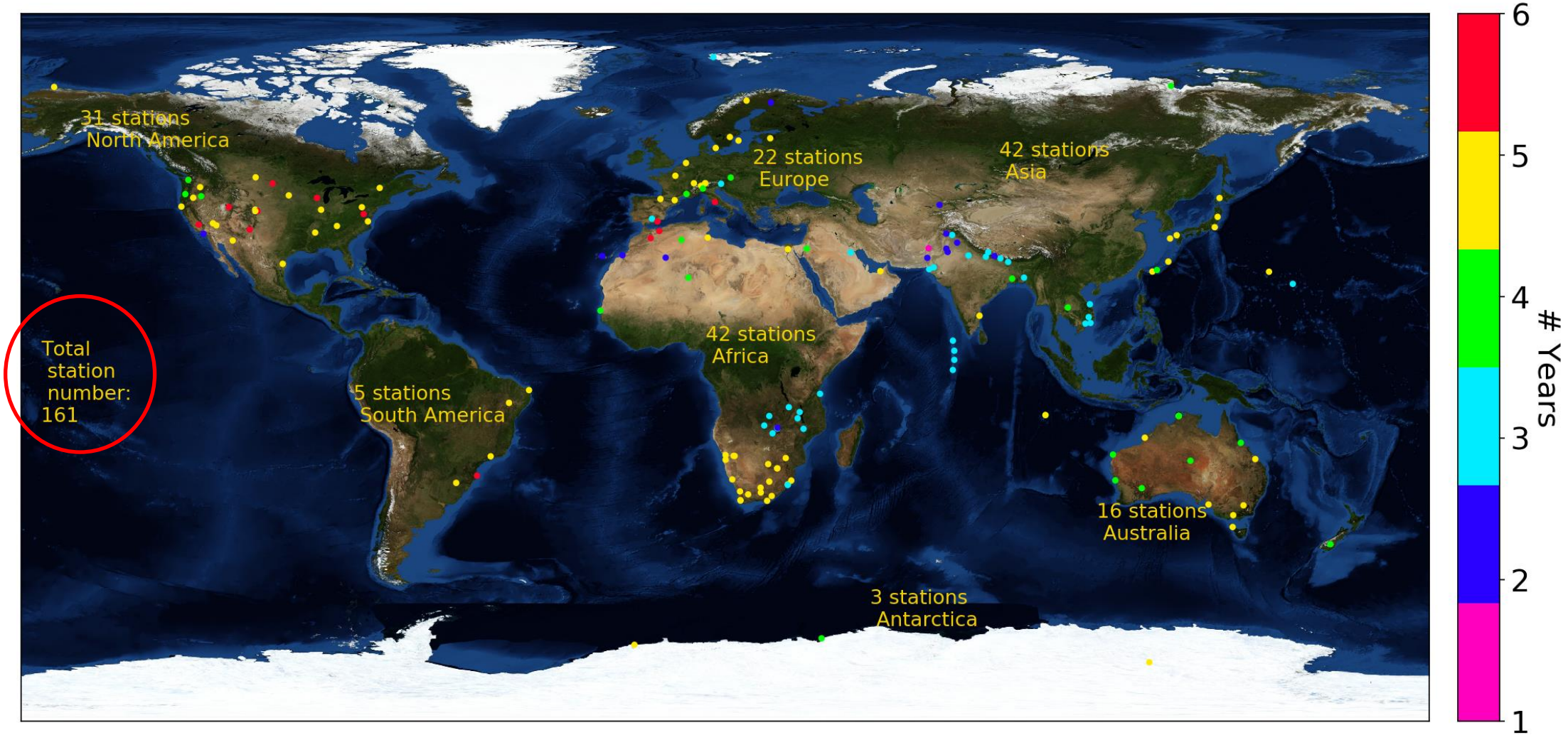
Data from ground stations as reference data from 2015 to 2020

- **Global Horizontal Irradiation - GHI, Direct Normal Irradiation – DNI , Diffuse Horizontal Irradiation - DIF**
- **Minimum of 2 years within 2015 to 2020 (1 minute data resolution)**

Tier 1
GHI, DNI and DIF measured separately
Solar tracker

Tier 2
GHI and (DNI or DIF) measured

Data collection



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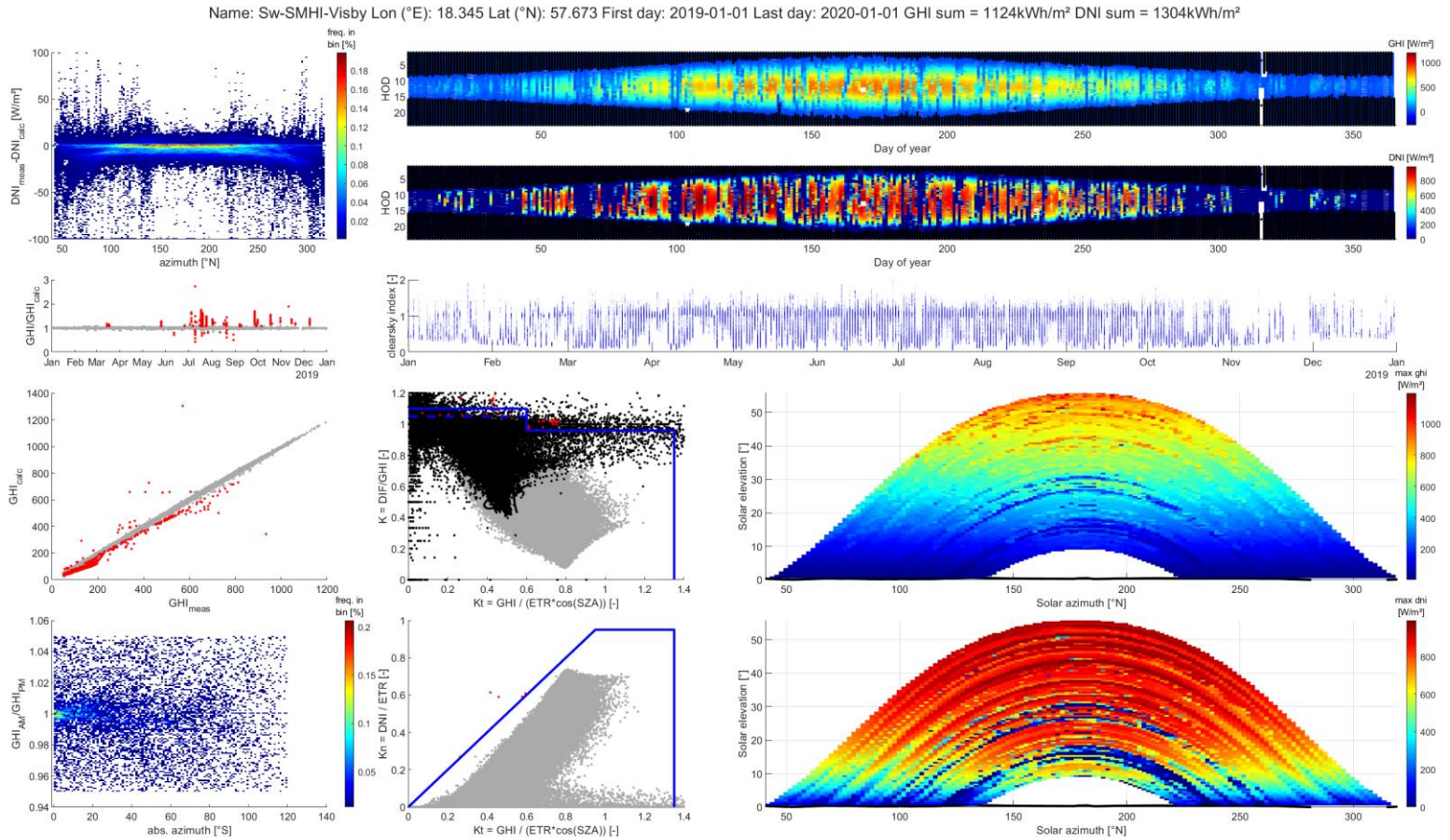
Data collection - Quality control of measurements

- Method developed by experts
- Single QC method for all stations
- Automatic flags and manual review
- Most advanced QC method for 1-min measurements
- Published method doi:10.18086/swc.2021.38.02
  - Publication includes a data catalogue of most reference data (incl. flags)



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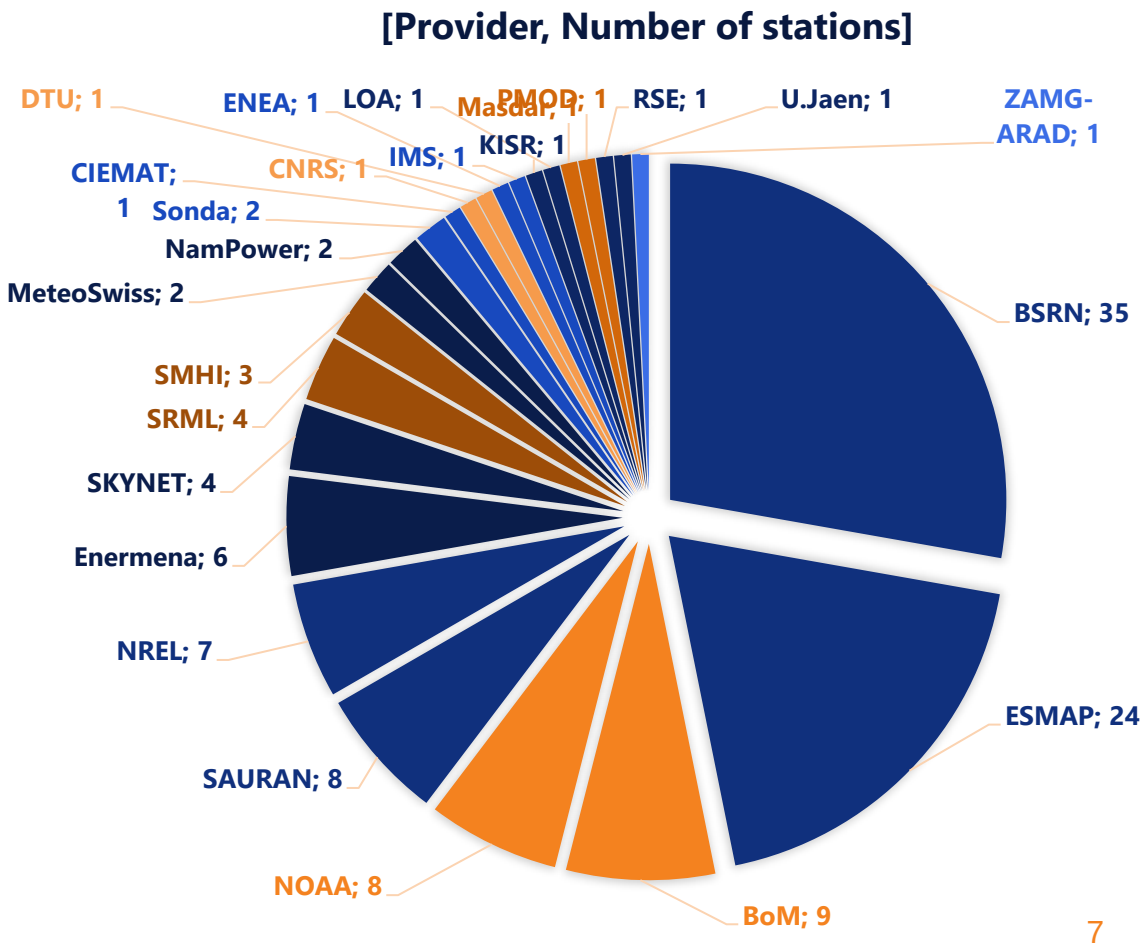
Data collection - Quality control of measurements

- **"Only" 28% of the stations from BSRN** (Baseline Surface Radiation Network)
- **Some are private**

Total station number: 126



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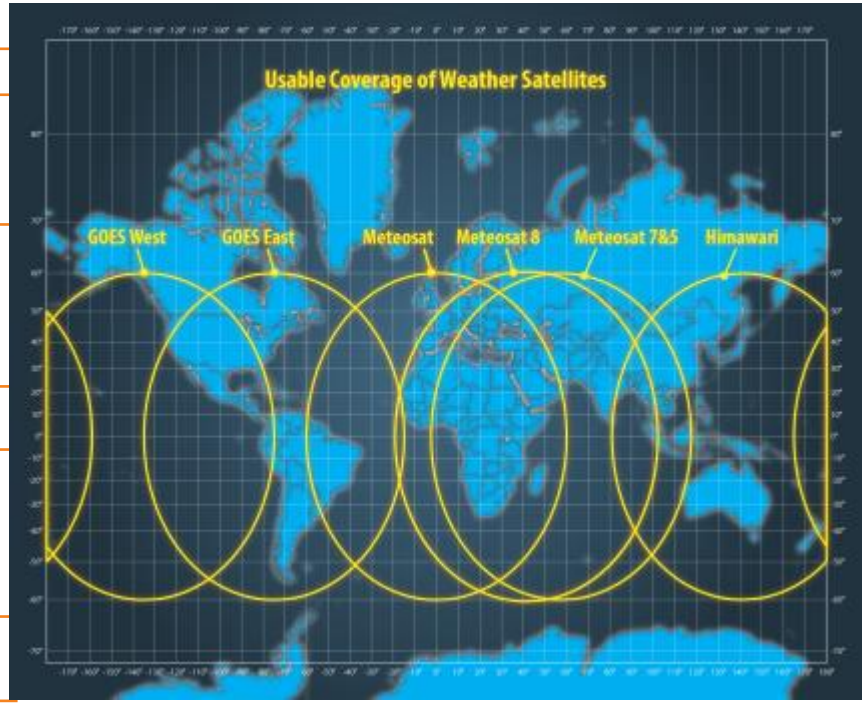
Data collection - benchmark participants

Provider	Dataset / model	Main data source	Spatial coverage
DWD	SARAH-2.1	MSG satellites	Full disk, Meteosat
CAMS	CAMS v3.2	MSG satellites	Europe / Africa / Middle East / Atlantic Ocean (Meteosat 2nd Gen. field of view, -66°N to 66°N). Clear-sky data available globally.
	CAMS pre-v4		
Meteotest	Meteotest, various sat.	GOES-16, MSG-4, IODC, HIMAWARI-8, Meteotest MOS	Global (-66°N to 66°N)
CSIRO	CSIRO	Himawari-8	Australian continent
NREL (NSRDB)	Physical Solar Model Version 3	GOES	Contiguous United States, part of Alaska, southern Canada, Central America, and part of South America. Longitudes: 25°W to 175°W Latitudes: 21°S to 60°N to the north
Solargis	Solargis v2.x, various sat.	various satellites	Global (60°N to 45/55°S), land area and adjacent sea and oceans. Regions between 60--65°N on request.
BoM	BoM APS3 ACCESS-G3*	Numerical Weather Prediction Models	Global
NASA	CERES**	various satellites	Global (60°N to 55°S), land area
KNMI	MSG-CPP algorithm v1	MSG satellites	Full disk, Meteosat



Location of the current geostationary satellites that provide coverage around the globe. *Image from NREL*

*DNI Data not available **DNI Data calculated from direct horizontal

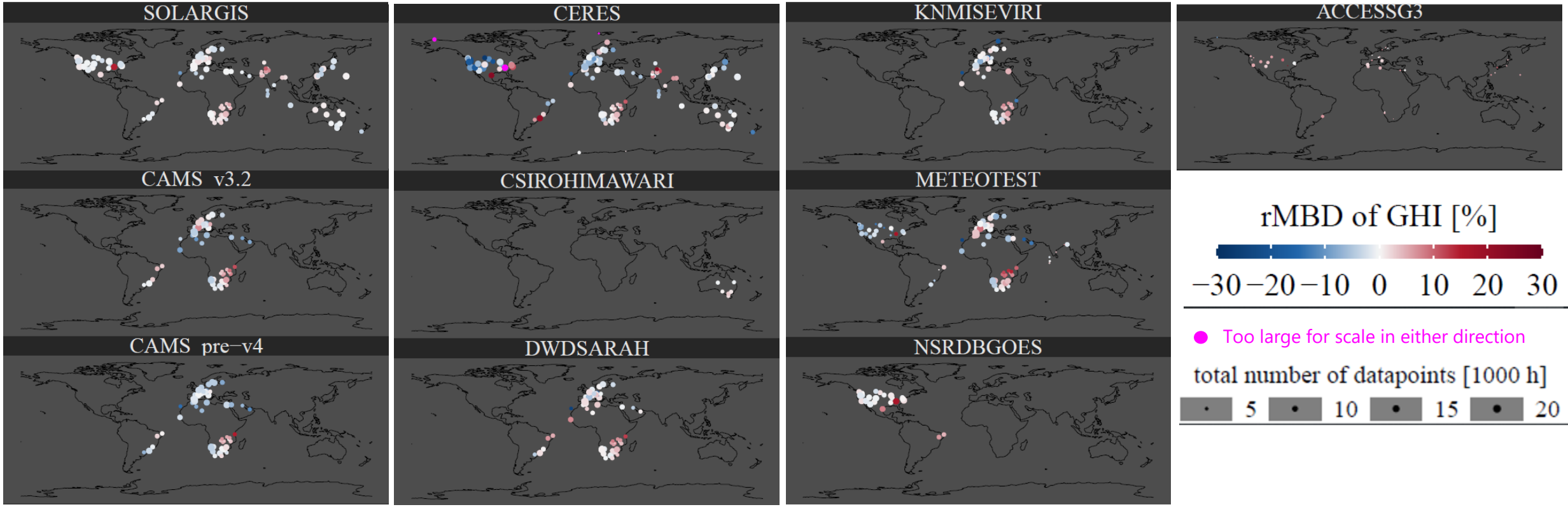
Benchmark

- Evaluation on hourly averaged data

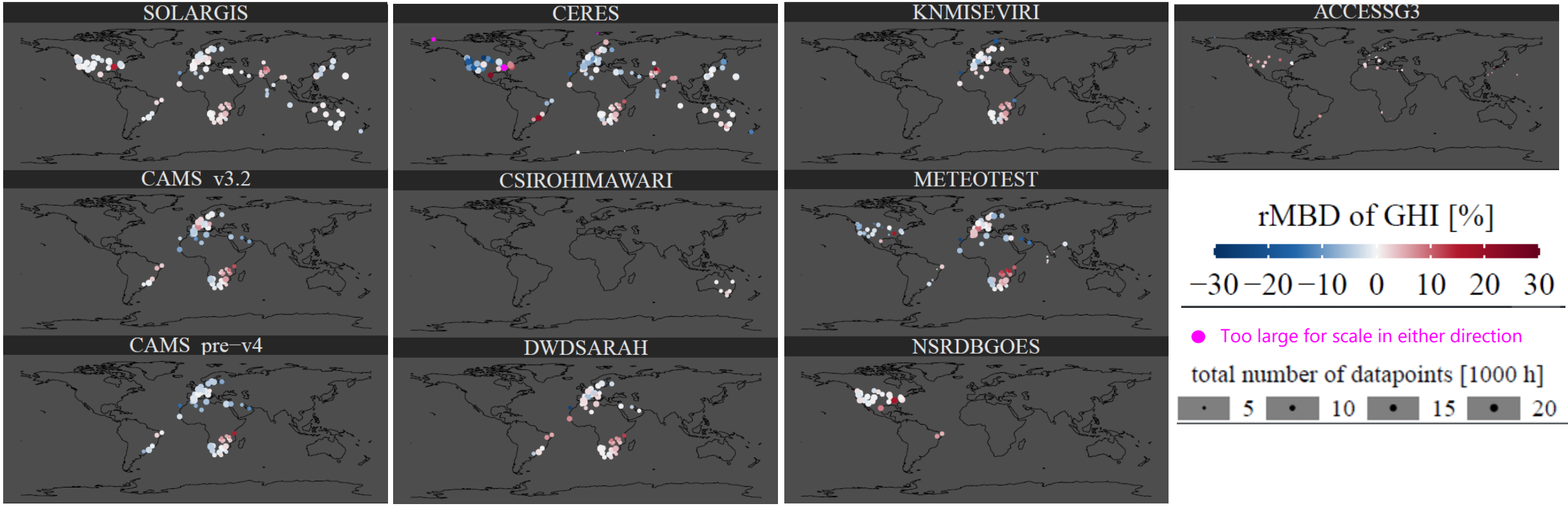
Abbr.	Meaning
MBD, rMBD	Mean bias deviation, relative mean bias deviation
RMSD, rRMSD	Root mean square deviation, relative root mean square deviation
MAD, rRMSD	Mean absolute deviation, relative mean absolute deviation
Stdev	Standard deviation
KSI	Kolmogoroff-Smirnoff Index
CPI	Combined Performance Index
OVER	Relative frequency of exceedance situations

- Relative error metrics normalized to mean of reference ground data (only mean of data points that are used in comparison: valid and >10° solar elevation
- Metrics are summarized as weighted average of each year (weighting: number of valid hours per year)
  - Station years with <1000 h/year are discarded
- Total number of hours per site and data set varies

Results – Global Horizontal Irradiation (GHI)

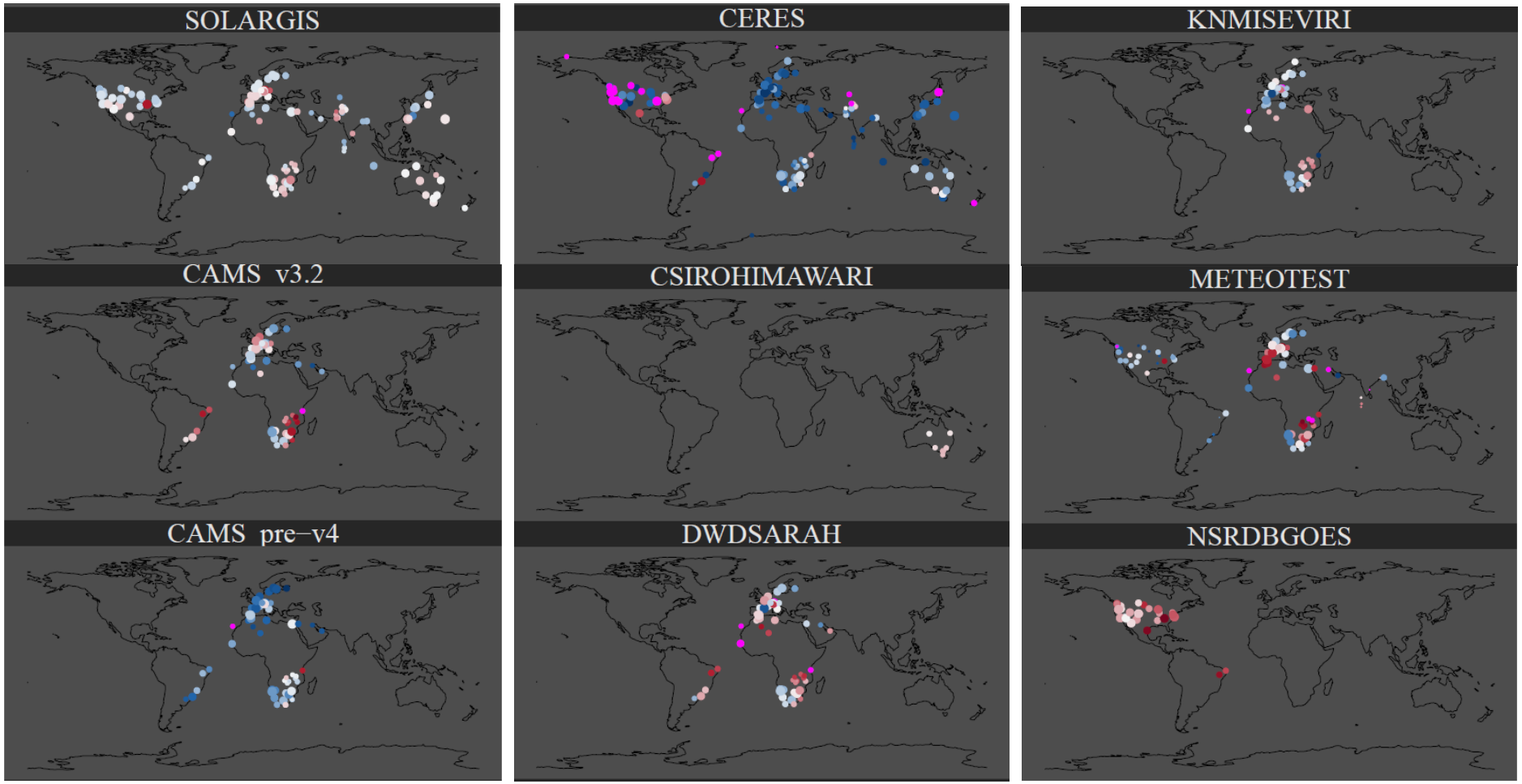


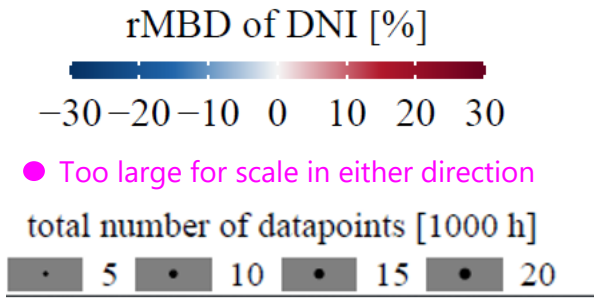
Results – Global Horizontal Irradiation (GHI)



- Different data set size per station and provider
- Performance varies for individual stations
- Some “difficult“ stations for multiple dataset
- Dependency on continent for some dataset

Results – Direct Normal Irradiation (DNI)





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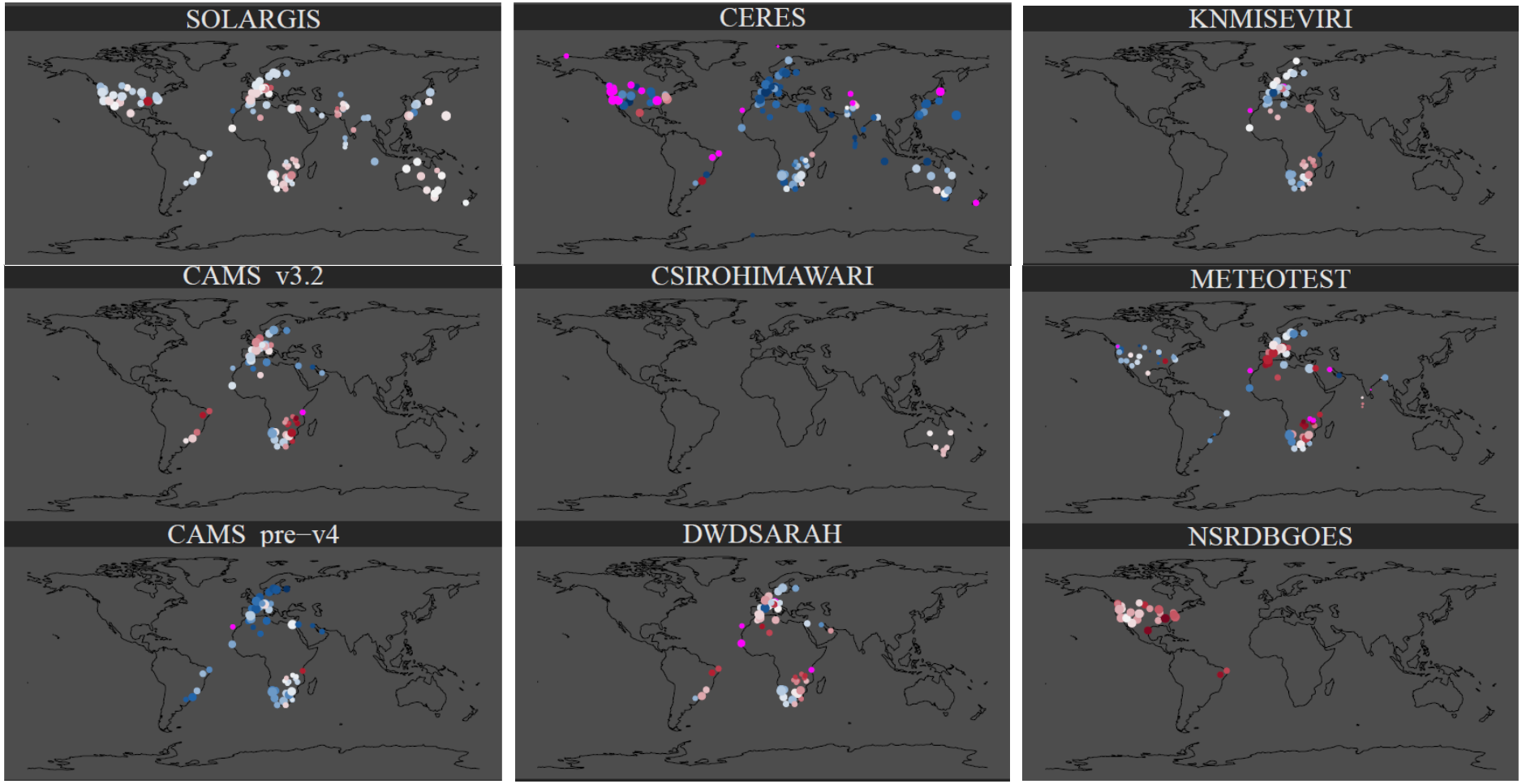
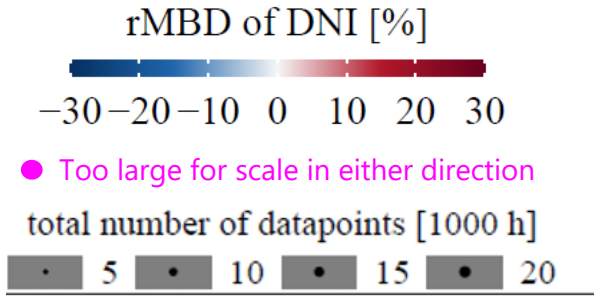
Results – Direct Normal Irradiation (DNI)





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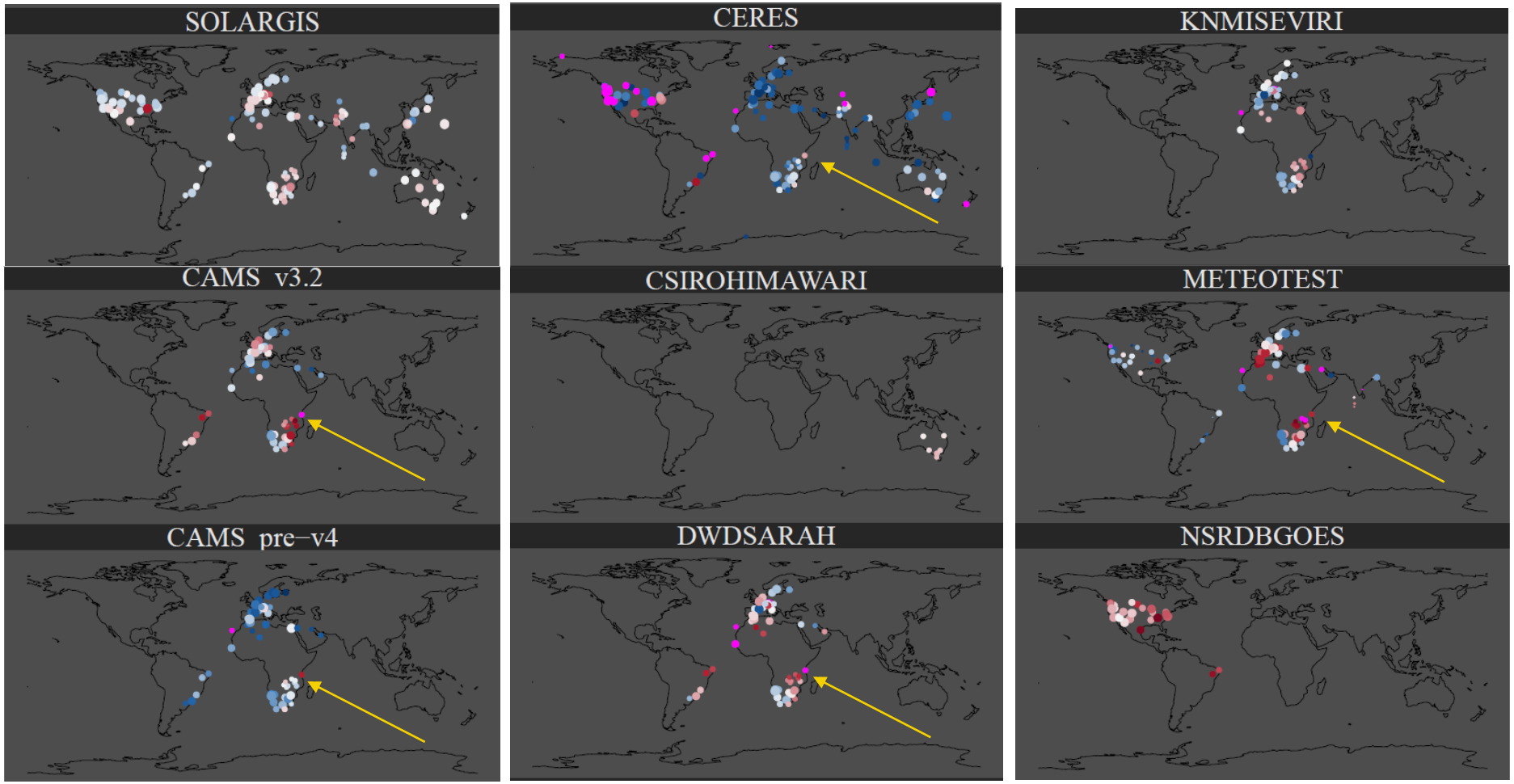
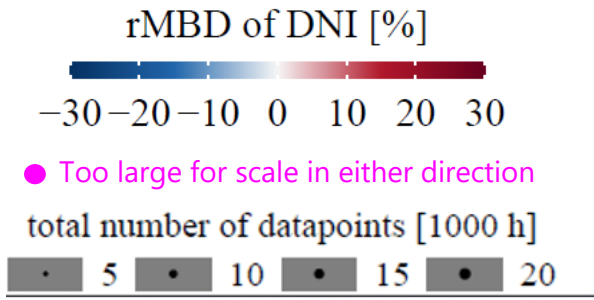
- Larger bias than for GHI
- More „difficult stations“

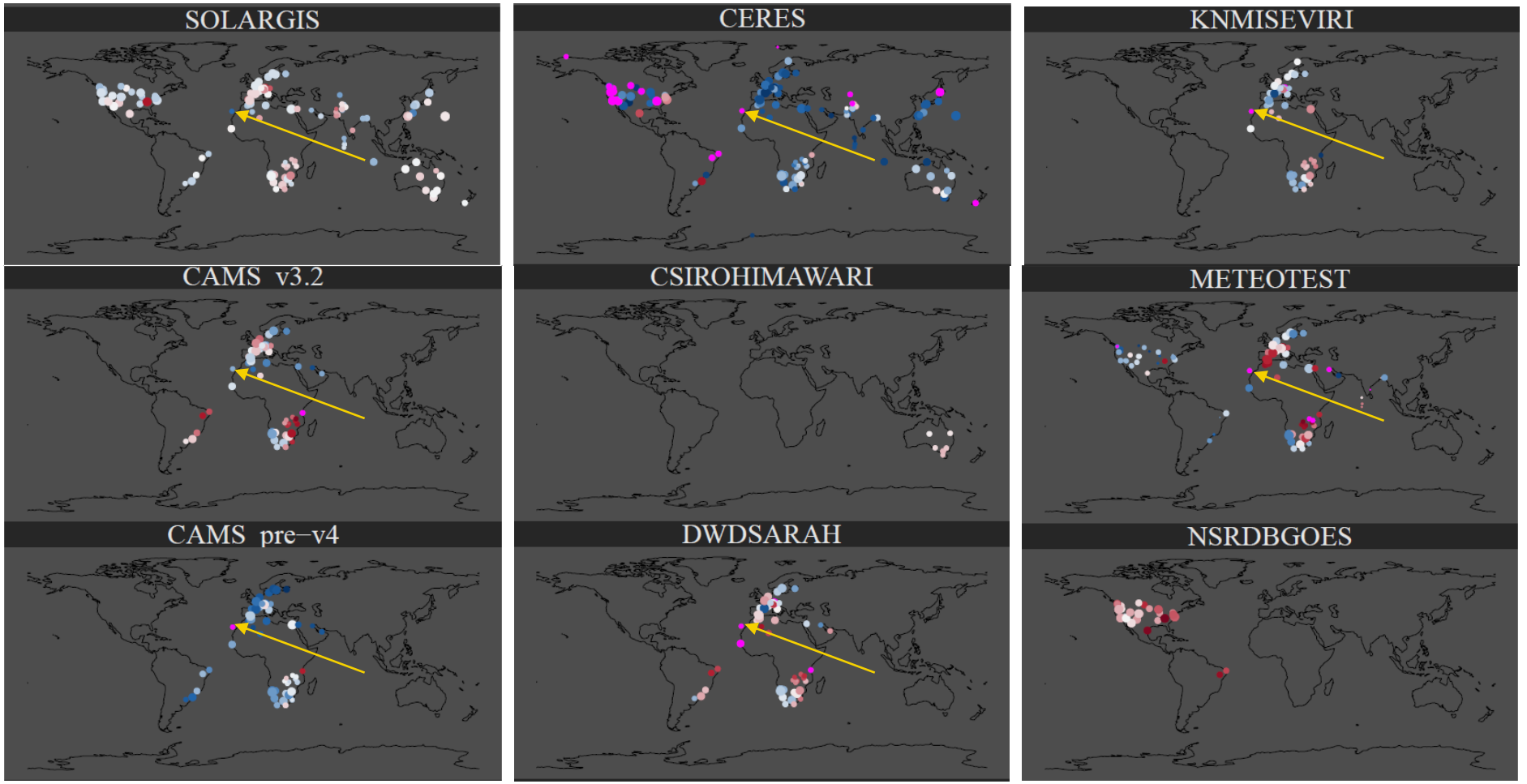
Results – Direct Normal Irradiation (DNI)

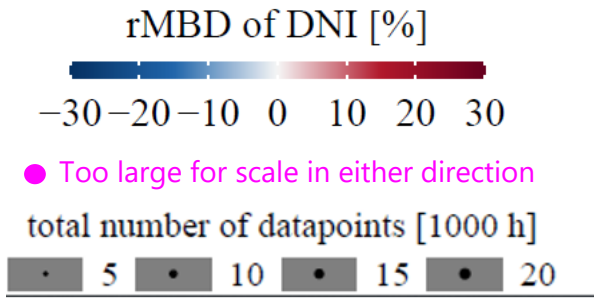




Dar es Salam (Tanzania): often smog

Results – Direct Normal Irradiation





- **Often due to station location (island, mountain, smog)**

Izana (Canary Islands): mountain in the ocean

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Conclusions

- Maps emphasize different data set sizes per test data provider and station
- Data set based on NWP shows almost exclusively positive bias
- Some individual stations show difficulties with multiple data providers
- Dependency on continent for some models
- DNI tendentially larger bias (negative and positive)
- Included global data set derived from polar satellites and geostationary satellites (CERES) has significantly higher deviations than other data sets, at times even higher than the NWP data.
- Benchmark results can be used to identify good data sets for different regions or at times even specific sites, recommendation for procedure will be published

Thank you for your attention!
Thank you to the evaluators & data providers

Contributors (data and review only): CSIRO, DLR/CAMS, DWD, KNMI , Meteotest, NREL, Solargis

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Providers defined how to use their data for (averaged) 60min benchmark

Provider	Model/main data sources	Spatial resolution	Temporal resolution
DWD	SARAH-2.1, MSG satellites, doi: 10.5676/EUM_SAF_CM/SARAH/V002_01	based on **0.05°** gridded sat. data (**~5.5 km**), various resolutions for individual input data	**1 min** (based on 30 min satellite data), 30 min, daily, monthly
CAMS	CAMS v3.2 and experimental pre-v4 APOLLO_NG/Heliosat-4(DLR) method, MSG satellites for clouds, clear sky from CAMS integrated forecasting system	output **interpolated to location of ground station**, input data in various resolutions: 3 to 10 km (sat. pixel), DTM up to ~100 m, aerosol/water vapour/ozone 0.4°, ground albedo 6 km	output: **1 min**, 15 min, 60 min, 1d, monthly; input: 15 min clouds, 3 h aerosols/water vapour/ozone, monthly ground albedo
Meteotest	GOES-16, MSG-4, IODC, HIMAWARI-8, Meteotest MOS	1/16 ° **(~7 km)**	**15 min**
CSIRO	Himawari-8	**2 km**	max **10 min**
NREL (NSRDB)	GOES Model: Physical Solar Model Version 3	GOES: 1998- 2019, gridded segments (4 km) and for 2018 and 2019, **2 km** spatial resolution	GOES: 1998- 2019 30min, 2018 and 2019, 5min for continental US and 10-15 min full disk.
Solargis	Solargis model v2.x; GOES, Meteosat MSG and MFG (PRIME and IODC positions), Himawari and MTSAT satellites; Aerosols from CAMS atmospheric model	Final result **250 m**, satellite data 2-4 km	10 and 15 min depending on satellite, **1** and 5 min on request. **15 min** data used for benchmark
BoM	BoM APS3 ACCESS-G3	**~12 km**	**1 h**, (only 23-07-2019 and 2020)
NASA	CERES MODIS on Terra & Aqua (polar satellites) + geostationary satellites (GOES, Meteosat, MTSAT, Himawari)	1°x1° (**111km**)	**1 h**
KNMI	Input: MSG satellites (SEVIRI data: all channels except HRV); multi-yr mean climatologies of water vapor, ozone and aerosol (ECMWF/CAMS), surface albedo (MODIS). Processing with MSG-CPP algorithm v1.	full disk, satellite pixel size (**~3 km**)	**15** min

Regional model adaptation by providers

- Known stations before the benchmark
- Applied adaptations before the benchmark

Model	Sites used before benchmark	Used adapation
ACCESSG3		
CAMS pre-v4		
CAMS v3.2		Field of view wide bias correction applied
CERES		
CSIROHIMAWARI		Continental wide spatial calibration applied
DWDSARAH		
KNMISEVIRI		
METEOTEST	34	Interpolated linear adaptation
NRELGOES		
SOLARGIS	23	

Benchmark

- Data is used as it was received from the providers (no adaptation)
- All data points evaluated in 60-min resolution
- Treatment of data islands
  - At 5-min resolution, check if at least 3-min time stamps are valid
  - Check if at least 10 5-min intervals in the hour are valid, otherwise discard the hour
- Metrics are summarized as weighted average of each year (weighting: number of valid hours per year)
  - Station years with <1000 h/year are discarded
- Total number of hours per site and data set varies

Tables of results –relative mean bias deviation

Subselection in Africa: GHI, rMBD (%)

site / model	ARA	AUA	CAI	DEA	GOB	KWA	MIS	OUJ	TAT	VUW	ADR	CHI	DAR	Mean	Std	Abs_Mean	Abs_Std
P	-0.7	2.1	-0.2	0.8	-0.3	-2.4	-1.9	0.0	-0.7	4.3	-3.4	4.5		0.6	2.4	1.8	1.6
Q	-0.4	-1.1		-1.0	0.4	3.1	0.3	1.2	3.1	4.4	2.8	3.7	12.3	1.4	2.0	1.9	1.5
R	-2.1	0.8	-1.7	0.2	-0.5	4.0	1.8	1.8	0.7	4.1	-3.3	6.9	10.3	1.8	2.6	2.3	2.1
S	-1.1	-1.1	4.6	-2.7	-0.5	3.4	-0.6	1.9	1.9	6.3	2.1	5.5	-13.0	1.3	3.0	2.5	2.0
T	-5.2	-1.3	-3.4	-1.4	-4.0	-2.5	-4.9	-2.3	-5.3	2.0	-7.5	3.4	14.6	-2.1	3.0	3.2	1.5
U	-4.7	4.2	-5.3	1.7	-4.7	-1.6	4.3	4.2	-4.4	3.9		7.3	9.7	1.0	4.5	4.1	1.6
V	-5.4	1.1		-1.7	-4.3	2.7	-7.2	-2.4	-5.6	6.0	-10.0	7.8	11.0	-0.9	5.1	4.4	2.3
W	2.3		7.6		4.5			4.1	4.5								

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Tables of results –relative mean bias deviation

One table for one continent, component and metric

(abbreviated) Sites evaluated in the continent

Subselection in Africa: GHI, rMBD (%)

site	ARA	AUA	CAI	DEA	GOB	KWA	MIS	OUJ	TAT	VUW	ADR	CHI	DAR	Mean	Std	Abs_Mean	Abs_Std
model																	
P	-0.7	2.1	-0.2	0.8	-0.3	-2.4	-1.9	0.0	-0.7	4.3	-3.4	4.5		0.6	2.4	1.8	1.6
Q	-0.4	-1.1		-1.0	0.4	3.1	0.3	1.2	3.1	4.4	2.8	3.7	12.3	1.4	2.0	1.9	1.5
R	-2.1	0.8	-1.7	0.2	-0.5	4.0	1.8	1.8	0.7	4.1	-3.3	6.9	10.3	1.8	2.6	2.3	2.1
S	-1.1	-1.1	4.6	-2.7	-0.5	3.4	-0.6	1.9	1.9	6.3	2.1	5.5	-13.0	1.3	3.0	2.5	2.0
T	-5.2	-1.3	-3.4	-1.4	-4.0	-2.5	-4.9	-2.3	-5.3	2.0	-7.5	3.4	14.6	-2.1	3.0	3.2	1.5
U	-4.7	4.2	-5.3	1.7	-4.7	-1.6	4.3	4.2	-4.4	3.9		7.3	9.7	1.0	4.5	4.1	1.6
V	-5.4	1.1		-1.7	-4.3	2.7	-7.2	-2.4	-5.6	6.0	-10.0	7.8	11.0	-0.9	5.1	4.4	2.3
W	2.3		7.6		4.5			4.1	4.5								

Test data providers evaluated at the sites (all with sufficient available data)

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Tables of results –relative mean bias deviation

Subselection in Africa: GHI, rMBD (%)

site / model	ARA	AUA	CAI	DEA	GOB	KWA	MIS	OUJ	TAT	VUW	ADR	CHI	DAR	Mean	Std	Abs_Mean	Abs_Std
P	-0.7	2.1	-0.2	0.8	-0.3	-2.4	-1.9	0.0	-0.7	4.3	-3.4	4.5		0.6	2.4	1.8	1.6
Q	-0.4	-1.1		-1.0	0.4	3.1	0.3	1.2	3.1	4.4	2.8	3.7	12.3	1.4	2.0	1.9	1.5
R	-2.1	0.8	-1.7	0.2	-0.5	4.0	1.8	1.8	0.7	4.1	-3.3	6.9	10.3	1.8	2.6	2.3	2.1
S	-1.1	-1.1	4.6	-2.7	-0.5	3.4	-0.6	1.9	1.9	6.3	2.1	5.5	-13.0	1.3	3.0	2.5	2.0
T	-5.2	-1.3	-3.4	-1.4	-4.0	-2.5	-4.9	-2.3	-5.3	2.0	-7.5	3.4	14.6	-2.1	3.0	3.2	1.5
U	-4.7	4.2	-5.3	1.7	-4.7	-1.6	4.3	4.2	-4.4	3.9		7.3	9.7	1.0	4.5	4.1	1.6
V	-5.4	1.1		-1.7	-4.3	2.7	-7.2	-2.4	-5.6	6.0	-10.0	7.8	11.0	-0.9	5.1	4.4	2.3
W	2.3		7.6		4.5			4.1	4.5								

Weighted average of rMBD (%) of each provider at each site

(!) Caution: the same site can have a different number of data points for different providers if the test data contains gaps or covers a different time period

Tables of results –relative mean bias deviation

Subselection in Africa: GHI, rMBD (%)

site / model	ARA	AUA	CAI	DEA	GOB	KWA	MIS	OUJ	TAT	VUW	ADR	CHI	DAR	Mean	Std	Abs_Mean	Abs_Std
P	-0.7	2.1	-0.2	0.8	-0.3	-2.4	-1.9	0.0	-0.7	4.3	-3.4	4.5		0.6	2.4	1.8	1.6
Q	-0.4	-1.1		-1.0	0.4	3.1	0.3	1.2	3.1	4.4	2.8	3.7	12.3	1.4	2.0	1.9	1.5
R	-2.1	0.8	-1.7	0.2	-0.5	4.0	1.8	1.8	0.7	4.1	-3.3	6.9	10.3	1.8	2.6	2.3	2.1
S	-1.1	-1.1	4.6	-2.7	-0.5	3.4	-0.6	1.9	1.9	6.3	2.1	5.5	-13.0	1.3	3.0	2.5	2.0
T	-5.2	-1.3	-3.4	-1.4	-4.0	-2.5	-4.9	-2.3	-5.3	2.0	-7.5	3.4	14.6	-2.1	3.0	3.2	1.5
U	-4.7	4.2	-5.3	1.7	-4.7	-1.6	4.3	4.2	-4.4	3.9		7.3	9.7	1.0	4.5	4.1	1.6
V	-5.4	1.1		-1.7	-4.3	2.7	-7.2	-2.4	-5.6	6.0	-10.0	7.8	11.0	-0.9	5.1	4.4	2.3
W	2.3		7.6		4.5			4.1	4.5								

Calculated mean and standard deviation (Std) of all provided stations (of rMBD and abs(rMDB))

(!) Caution: mean is calculated only if >75% of sites are provided

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Tables of results –relative mean bias deviation

Subselection in Africa: GHI, rMBD (%)

site / model	ARA	AUA	CAI	DEA	GOB	KWA	MIS	OUJ	TAT	VUW	ADR	CHI	DAR	Mean	Std	Abs_Mean	Abs_Std
P	-0.7	2.1	-0.2	0.8	-0.3	-2.4	-1.9	0.0	-0.7	4.3	-3.4	4.5		0.6	2.4	1.8	1.6
Q	-0.4	-1.1		-1.0	0.4	3.1	0.3	1.2	3.1	4.4	2.8	3.7	12.3	1.4	2.0	1.9	1.5
R	-2.1	0.8	-1.7	0.2	-0.5	4.0	1.8	1.8	0.7	4.1	-3.3	6.9	10.3	1.8	2.6	2.3	2.1
S	-1.1	-1.1	4.6	-2.7	-0.5	3.4	-0.6	1.9	1.9	6.3	2.1	5.5	-13.0	1.3	3.0	2.5	2.0
T	-5.2	-1.3	-3.4	-1.4	-4.0	-2.5	-4.9	-2.3	-5.3	2.0	-7.5	3.4	14.6	-2.1	3.0	3.2	1.5
U	-4.7	4.2	-5.3	1.7	-4.7	-1.6	4.3	4.2	-4.4	3.9		7.3	9.7	1.0	4.5	4.1	1.6
V	-5.4	1.1		-1.7	-4.3	2.7	-7.2	-2.4	-5.6	6.0	-10.0	7.8	11.0	-0.9	5.1	4.4	2.3
W	2.3		7.6		4.5			4.1	4.5								

Calculated mean and standard deviation (Std) of all provided stations (of rMBD and abs(rMDB))

(!) Caution: mean is calculated only if >75% of sites are provided

(!) Caution: stations which are not provided by everyone, who has >75% of sites provided, are excluded from the mean calculation

PVPS

Tables of results –relative mean bias deviation

Sorting according to mean of absolute rMBD

For other metric according to the mean

Subselection in Africa: GHI, rMBD (%)

site / model	ARA	AUA	CAI	DEA	GOB	KWA	MIS	OUJ	TAT	VUW	ADR	CHI	DAR	Mean	Std	Abs_Mean	Abs_Std
P	-0.7	2.1	-0.2	0.8	-0.3	-2.4	-1.9	0.0	-0.7	4.3	-3.4	4.5		0.6	2.4	1.8	1.6
Q	-0.4	-1.1		-1.0	0.4	3.1	0.3	1.2	3.1	4.4	2.8	3.7	12.3	1.4	2.0	1.9	1.5
R	-2.1	0.8	-1.7	0.2	-0.5	4.0	1.8	1.8	0.7	4.1	-3.3	6.9	10.3	1.8	2.6	2.3	2.1
S	-1.1	-1.1	4.6	-2.7	-0.5	3.4	-0.6	1.9	1.9	6.3	2.1	5.5	-13.0	1.3	3.0	2.5	2.0
T	-5.2	-1.3	-3.4	-1.4	-4.0	-2.5	-4.9	-2.3	-5.3	2.0	-7.5	3.4	14.6	-2.1	3.0	3.2	1.5
U	-4.7	4.2	-5.3	1.7	-4.7	-1.6	4.3	4.2	-4.4	3.9		7.3	9.7	1.0	4.5	4.1	1.6
V	-5.4	1.1		-1.7	-4.3	2.7	-7.2	-2.4	-5.6	6.0	-10.0	7.8	11.0	-0.9	5.1	4.4	2.3
W	2.3		7.6		4.5			4.1	4.5								

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Tables of results – relative MBD – use case

Africa: DNI, rMBD (%)

site / model	ALE	ARA	AUA	CAI	DEA	DUR	GAB	GOB	KWA	MIS	OUJ	POR	PRE	STE	TAT	VUW	ADR	CHI	CHL*	CHO*	DAR	IZA	KAA*	KAO*	KAS*	LUS	MBO*	MUT*	MZU*	TAM	Mean	Std	Abs_Mean	Abs_Std
SOLARGIS	1.4	-2.7	4.1	-1.4	2.9	-0.9	4.4	-0.7	-3.4	-5.1	-4.2	4.5	-2.0	-0.1	-4.0	7.5	-5.6	1.5	2.9	3.8		-14.4	3.7	2.4	1.7	2.1	0.4	-3.1	4.4	5.6	0.5	4.5	3.5	2.8
KNMISEVIRI	-6.0	-9.9	-8.2	7.2	-9.5	2.3	-1.4	-8.0	4.2	-6.7	-5.4	2.6	-1.2	-6.2	-6.1	6.8	4.5	8.5	4.3	3.8	-27.8	-41.8	7.1	4.8	7.3	3.2	-0.5	6.2	6.3	4.3	-1.5	10.0	6.8	7.4
CAMS_pre-v4	-9.8	-12.8	-11.9	-0.8	-6.6	-5.1	-4.0	-9.7	-1.7	-15.3	-11.0	2.2	-11.4	-7.9	-15.6	-1.5	-22.0	-4.1	-2.5	-1.6	14.7	-31.2	-0.6	-0.5	-3.4	-3.4	-8.3	3.2	-1.0	-16.4	-7.1	7.3	7.5	6.9
DWDSARAH	-1.6	-6.4	-6.8		-6.0	8.7	0.8	-4.5	8.7	2.4	4.7	4.5	0.9	-3.1	5.2	6.8	17.1	4.5	11.4	7.7	33.3	-42.2	10.9	7.9	11.7	6.8	36.9	13.0	13.7	12.0	4.0	12.7	9.3	9.5
CAMS_v3.2	-4.4	-11.1	1.2		-4.2	14.4	4.0	-8.8	13.9	-11.6	-3.5	6.6	1.7	-3.5	-12.0	16.6	-14.3	18.8	14.5	13.6	39.0	-7.6	10.1	6.3	15.7	11.9	-2.2	7.2	25.6	2.3	4.3	10.5	9.4	6.1
CERES	-20.5	-10.9	-9.5	-14.9	-8.5	-0.1	-8.7	-6.4	3.0	-8.4	-12.1	-18.4	-3.6	-1.8	-14.2	-2.2	-20.7	-6.0	-4.5	-8.0	5.3	-49.3	-10.8	-13.8	-12.9	-5.9	-9.8	-10.6	-1.9	-17.8	-10.1	9.6	10.4	9.4
METEOTEST	-12.1	-12.3	6.2	-4.9	1.0	-5.6	6.9	-12.2	-6.9	19.7	18.2	-1.6	12.9	-3.8	-7.0	5.0		8.9	22.8	19.3	14.1	-37.5	30.5	20.2	22.8	21.3	-12.3	26.3	37.5	11.8	6.7	17.0	14.9	10.1

Africa: GHI, rMBD (%)

site / model	ALE	ARA	AUA	CAI	DEA	DUR	GAB	GOB	KWA	MIS	OUJ	POR	PRE	STE	TAT	VUW	ADR	CHI	CHL*	CHO*	DAR	IZA	KAA*	KAO*	KAS*	LUS	MBO*	MUT*	MZU*	TAM	Mean	Std	Abs_Mean	Abs_Std
SOLARGIS	0.7	-0.7	2.0	-0.2	0.8	0.9	2.4	-0.3	-2.5	-2.2	-0.1	2.6	1.2	1.4	-0.9	4.1	-3.5	4.5	3.9	2.9		-9.4	3.6	2.8	0.5	1.3	0.9	2.6	5.5	-1.8	1.0	2.9	2.3	2.0
CERES	-4.1	-2.1	0.6	-1.7	0.1	4.3	0.0	-0.5	3.8	0.6	1.3	-1.6	1.6	2.6	0.4	4.2	-3.3	6.8	5.5	3.2	10.4	-16.3	3.3	0.2	-0.6	1.2	1.9	2.6	6.7	-4.2	0.8	4.4	3.0	3.3
CAMS_pre-v4	-3.4	-5.2	-1.2	-3.2	-1.4	-0.4	-0.2	-4.1	-2.6	-5.2	-2.5	1.9	-0.3	-1.1	-5.4	1.7	-7.6	3.4	5.7	4.7	14.9	-14.1	5.4	4.2	0.9	2.9	-2.5	6.7	5.6	-6.4	-0.5	4.7	3.7	2.9
KNMISEVIRI	0.2	-1.1	-1.2	4.6	-2.8	4.2	1.6	-0.5	3.4	-0.8	1.9	3.4	2.5	-1.6	1.8	6.4	2.1	5.5	5.9	4.7	-12.8	-21.4	6.7	5.1	2.8	3.4	1.2	7.1	5.0	-1.2	1.6	5.4	3.8	4.1
DWDSARAH	0.4	-0.4	-1.1		-1.0	5.6	1.8	0.5	3.0	-0.2	1.0	1.8	1.9	-0.3	2.9	4.3	2.7	3.7	7.9	6.0	12.5	-25.0	6.8	5.7	3.7	3.8	7.3	8.3	6.4	0.3	2.0	6.1	4.1	4.9
CAMS_v3.2	-1.4	-5.4	1.0		-1.7	4.6	0.8	-4.3	2.7	-7.6	-2.7	0.6	0.6	-1.1	-5.8	6.1	-10.1	7.9	7.4	6.1	11.3	-3.7	4.5	2.5	3.4	3.8	-8.6	3.5	9.1	-5.2	0.6	4.9	4.1	2.6
METEOTEST	-4.1	-4.7	4.0	-5.6	1.7	-0.8	2.9	-4.8	-1.8	3.8	3.9	0.1	5.5	-0.8	-4.7	3.8		7.1	11.4	9.6	9.9	-24.3	13.7	9.2	7.3	8.5	-5.9	11.9	14.2	-3.0	2.4	8.1	6.4	5.3
ACCESSG3		2.3		7.6	5.5			4.6			3.7				4.2																			

PVPS

Tables of results – relative MBD – use case

Africa: DNI, rMBD (%)

site / model	ALE	ARA	AUA	CAI	DEA	DUR	GAB	GOB	KWA	MIS	OUJ	POR	PRE	STE	TAT	VUW	ADR	CHI	CHL*	CHO*	DAR	IZA	KAA*	KAO*	KAS*	LUS	MBO*	MUT*	MZU*	TAM	Mean	Std	Abs_Mean	Abs_Std
SOLARGIS	1.4	-2.7	4.1	-1.4	2.9	-0.9	4.4	-0.7	-3.4	-5.1	-4.2	4.5	-2.0	-0.1	-4.0	7.5	-5.6	1.5	2.9	3.8		-14.4	3.7	2.4	1.7	2.1	0.4	-3.1	4.4	5.6	0.5	4.5	3.5	2.8
KNMISEVIRI	-6.0	-9.9	-8.2	7.2	-9.5	2.3	-1.4	-8.0	4.2	-6.7	-5.4	2.6	-1.2	-6.2	-6.1	6.8	4.5	8.5	4.3	3.8	-27.8	-41.8	7.1	4.8	7.3	3.2	-0.5	6.2	6.3	4.3	-1.5	10.0	6.8	7.4
CAMS_pre-v4	-9.8	-12.8	-11.9	-0.8	-6.6	-5.1	-4.0	-9.7	-1.7	-15.3	-11.0	2.2	-11.4	-7.9	-15.6	-1.5	-22.0	-4.1	-2.5	-1.6	14.7	-31.2	-0.6	-0.5	-3.4	-3.4	8.3	3.2	-1.0	-16.4	-7.1	7.3	7.5	6.9
DWDSARAH	-1.6	-6.4	-6.8		-6.0	8.7	0.8	-4.5	8.7	2.4	4.7	4.5	0.9	-3.1	5.2	6.8	17.1	4.5	11.4	7.7	33.3	-42.2	10.9	7.9	11.7	6.8	36.9	13.0	13.7	12.0	4.0	12.7	9.3	9.5
CAMS_v3.2	-4.4	-11.1	1.2		-4.2	14.4	4.0	-8.8	13.9	-11.6	-3.5	6.6	1.7	-3.5	-12.0	16.6	-14.3	18.8	14.5	13.6	39.0	-7.6	10.1	6.3	15.7	11.9	-2.2	7.2	25.6	2.3	4.3	10.5	9.4	6.1
CERES	-20.5	-10.9	-9.5	-14.9	-8.5	-0.1	-8.7	-6.4	3.0	-8.4	-12.1	-18.4	-3.6	-1.8	-14.2	-2.2	-20.7	-6.0	-4.5	-8.0	5.3	-49.3	-10.8	-13.8	-12.9	-5.9	-9.8	-10.6	-1.9	-17.8	-10.1	9.6	10.4	9.4
METEOTEST	-12.1	-12.3	6.2	-4.9	1.0	-5.6	6.9	-12.2	-6.9	19.7	18.2	-1.6	12.9	-3.8	-7.0	5.0		8.9	22.8	19.3	14.1	-37.5	30.5	20.2	22.8	21.3	-12.3	26.3	37.5	11.8	6.7	17.0	14.9	10.1

Africa: GHI, rMBD (%)

site / model	ALE	ARA	AUA	CAI	DEA	DUR	GAB	GOB	KWA	MIS	OUJ	POR	PRE	STE	TAT	VUW	ADR	CHI	CHL*	CHO*	DAR	IZA	KAA*	KAO*	KAS*	LUS	MBO*	MUT*	MZU*	TAM	Mean	Std	Abs_Mean	Abs_Std
SOLARGIS	0.7	-0.7	2.0	-0.2	0.8	0.9	2.4	-0.3	-2.5	-2.2	-0.1	2.6	1.2	1.4	-0.9	4.1	-3.5	4.5	3.9	2.9		-9.4	3.6	2.8	0.5	1.3	0.9	2.6	5.5	-1.8	1.0	2.9	2.3	2.0
CERES	-4.1	-2.1	0.6	-1.7	0.1	4.3	0.0	-0.5	3.8	0.6	1.3	-1.6	1.6	2.6	0.4	4.2	-3.3	6.8	5.5	3.2	10.4	-16.3	3.3	0.2	-0.6	1.2	1.9	2.6	6.7	-4.2	0.8	4.4	3.0	3.3
CAMS_pre-v4	-3.4	-5.2	-1.2	-3.2	-1.4	-0.4	-0.2	-4.1	-2.6	-5.2	-2.5	1.9	-0.3	-1.1	-5.4	1.7	-7.6	3.4	5.7	4.7	14.9	-14.1	5.4	4.2	0.9	2.9	-2.5	6.7	5.6	-6.4	-0.5	4.7	3.7	2.9
KNMISEVIRI	0.2	-1.1	-1.2	4.6	-2.8	4.2	1.6	-0.5	3.4	-0.8	1.9	3.4	2.5	-1.6	1.8	6.4	2.1	5.5	5.9	4.7	-12.8	-21.4	6.7	5.1	2.8	3.4	1.2	7.1	5.0	-1.2	1.6	5.4	3.8	4.1
DWDSARAH	0.4	-0.4	-1.1		-1.0	5.6	1.8	0.5	3.0	-0.2	1.0	1.8	1.9	-0.3	2.9	4.3	2.7	3.7	7.9	6.0	12.5	-25.0	6.8	5.7	3.7	3.8	7.3	8.3	6.4	0.3	2.0	6.1	4.1	4.9
CAMS_v3.2	-1.4	-5.4	1.0		-1.7	4.6	0.8	-4.3	2.7	-7.6	-2.7	0.6	0.6	-1.1	-5.8	6.1	-10.1	7.9	7.4	6.1	11.3	-3.7	4.5	2.5	3.4	3.8	-8.6	3.5	9.1	-5.2	0.6	4.9	4.1	2.6
METEOTEST	-4.1	-4.7	4.0	-5.6	1.7	-0.8	2.9	-4.8	-1.8	3.8	3.9	0.1	5.5	-0.8	-4.7	3.8		7.1	11.4	9.6	9.9	-24.3	13.7	9.2	7.3	8.5	-5.9	11.9	14.2	-3.0	2.4	8.1	6.4	5.3
ACCESSG3		2.3		7.6	5.5			4.6			3.7				4.2																			

Stations with *

- Tier 2 stations
  - Not all QC tests
  - Higher uncertainty

PVPS

Tables of results – relative MBD – use case

Africa: DNI, rMBD (%)

site / model	ALE	ARA	AUA	CAI	DEA	DUR	GAB	GOB	KWA	MIS	OUJ	POR	PRE	STE	TAT	VUW	ADR	CHI	CHL*	CHO*	DAR	IZA	KAA*	KAO*	KAS*	LUS	MBO*	MUT*	MZU*	TAM	Mean	Std	Abs_Mean	Abs_Std
SOLARGIS	1.4	-2.7	4.1	-1.4	2.9	-0.9	4.4	-0.7	-3.4	-5.1	-4.2	4.5	-2.0	-0.1	-4.0	7.5	-5.6	1.5	2.9	3.8		-14.4	3.7	2.4	1.7	2.1	0.4	-3.1	4.4	5.6	0.5	4.5	3.5	2.8
KNMISEVIRI	-6.0	-9.9	-8.2	7.2	-9.5	2.3	-1.4	-8.0	4.2	-6.7	-5.4	2.6	-1.2	-6.2	-6.1	6.8	4.5	8.5	4.3	3.8	-27.8	-41.8	7.1	4.8	7.3	3.2	-0.5	6.2	6.3	4.3	-1.5	10.0	6.8	7.4
CAMS_pre-v4	-9.8	-12.8	-11.9	-0.8	-6.6	-5.1	-4.0	-9.7	-1.7	-15.3	-11.0	2.2	-11.4	-7.9	-15.6	-1.5	-22.0	-4.1	-2.5	-1.6	14.7	-31.2	-0.6	-0.5	-3.4	-3.4	-8.3	3.2	-1.0	-16.4	-7.1	7.3	7.5	6.9
DWDSARAH	-1.6	-6.4	-6.8		-6.0	8.7	0.8	-4.5	8.7	2.4	4.7	4.5	0.9	-3.1	5.2	6.8	17.1	4.5	11.4	7.7	33.3	-42.2	10.9	7.9	11.7	6.8	36.9	13.0	13.7	12.0	4.0	12.7	9.3	9.5
CAMS_v3.2	-4.4	-11.1	1.2		-4.2	14.4	4.0	-8.8	13.9	-11.6	-3.5	6.6	1.7	-3.5	-12.0	16.6	-14.3	18.8	14.5	13.6	39.0	-7.6	10.1	6.3	15.7	11.9	-2.2	7.2	25.6	2.3	4.3	10.5	9.4	6.1
CERES	-20.5	-10.9	-9.5	-14.9	-8.5	-0.1	-8.7	-6.4	3.0	-8.4	-12.1	-18.4	-3.6	-1.8	-14.2	-2.2	-20.7	-6.0	-4.5	-8.0	5.3	-49.3	-10.8	-13.8	-12.9	-5.9	-9.8	-10.6	-1.9	-17.8	-10.1	9.6	10.4	9.4
METEOTEST	-12.1	-12.3	6.2	-4.9	1.0	-5.6	6.9	-12.2	-6.9	19.7	18.2	-1.6	12.9	-3.8	-7.0	5.0		8.9	22.8	19.3	14.1	-37.5	30.5	20.2	22.8	21.3	-12.3	26.3	37.5	11.8	6.7	17.0	14.9	10.1

Africa: GHI, rMBD (%)

site / model	ALE	ARA	AUA	CAI	DEA	DUR	GAB	GOB	KWA	MIS	OUJ	POR	PRE	STE	TAT	VUW	ADR	CHI	CHL*	CHO*	DAR	IZA	KAA*	KAO*	KAS*	LUS	MBO*	MUT*	MZU*	TAM	Mean	Std	Abs_Mean	Abs_Std
SOLARGIS	0.7	-0.7	2.0	-0.2	0.8	0.9	2.4	-0.3	-2.5	-2.2	-0.1	2.6	1.2	1.4	-0.9	4.1	-3.5	4.5	3.9	2.9		-9.4	3.6	2.8	0.5	1.3	0.9	2.6	5.5	-1.8	1.0	2.9	2.3	2.0
CERES	-4.1	-2.1	0.6	-1.7	0.1	4.3	0.0	-0.5	3.8	0.6	1.3	-1.6	1.6	2.6	0.4	4.2	-3.3	6.8	5.5	3.2	10.4	-16.3	3.3	0.2	-0.6	1.2	1.9	2.6	6.7	-4.2	0.8	4.4	3.0	3.3
CAMS_pre-v4	-3.4	-5.2	-1.2	-3.2	-1.4	-0.4	-0.2	-4.1	-2.6	-5.2	-2.5	1.9	-0.3	-1.1	-5.4	1.7	-7.6	3.4	5.7	4.7	14.9	-14.1	5.4	4.2	0.9	2.9	-2.5	6.7	5.6	-6.4	-0.5	4.7	3.7	2.9
KNMISEVIRI	0.2	-1.1	-1.2	4.6	-2.8	4.2	1.6	-0.5	3.4	-0.8	1.9	3.4	2.5	-1.6	1.8	6.4	2.1	5.5	5.9	4.7	-12.8	-21.4	6.7	5.1	2.8	3.4	1.2	7.1	5.0	-1.2	1.6	5.4	3.8	4.1
DWDSARAH	0.4	-0.4	-1.1		-1.0	5.6	1.8	0.5	3.0	-0.2	1.0	1.8	1.9	-0.3	2.9	4.3	2.7	3.7	7.9	6.0	12.5	-25.0	6.8	5.7	3.7	3.8	7.3	8.3	6.4	0.3	2.0	6.1	4.1	4.9
CAMS_v3.2	-1.4	-5.4	1.0		-1.7	4.6	0.8	-4.3	2.7	-7.6	-2.7	0.6	0.6	-1.1	-5.8	6.1	-10.1	7.9	7.4	6.1	11.3	-3.7	4.5	2.5	3.4	3.8	-8.6	3.5	9.1	-5.2	0.6	4.9	4.1	2.6
METEOTEST	-4.1	-4.7	4.0	-5.6	1.7	-0.8	2.9	-4.8	-1.8	3.8	3.9	0.1	5.5	-0.8	-4.7	3.8		7.1	11.4	9.6	9.9	-24.3	13.7	9.2	7.3	8.5	-5.9	11.9	14.2	-3.0	2.4	8.1	6.4	5.3
ACCESSG3		2.3		7.6	5.5			4.6			3.7				4.2																			

Stations with *

- Tier 2 stations
  - Not all QC tests
  - Higher uncertainty

Discussed stations (smog, island)

PVPS

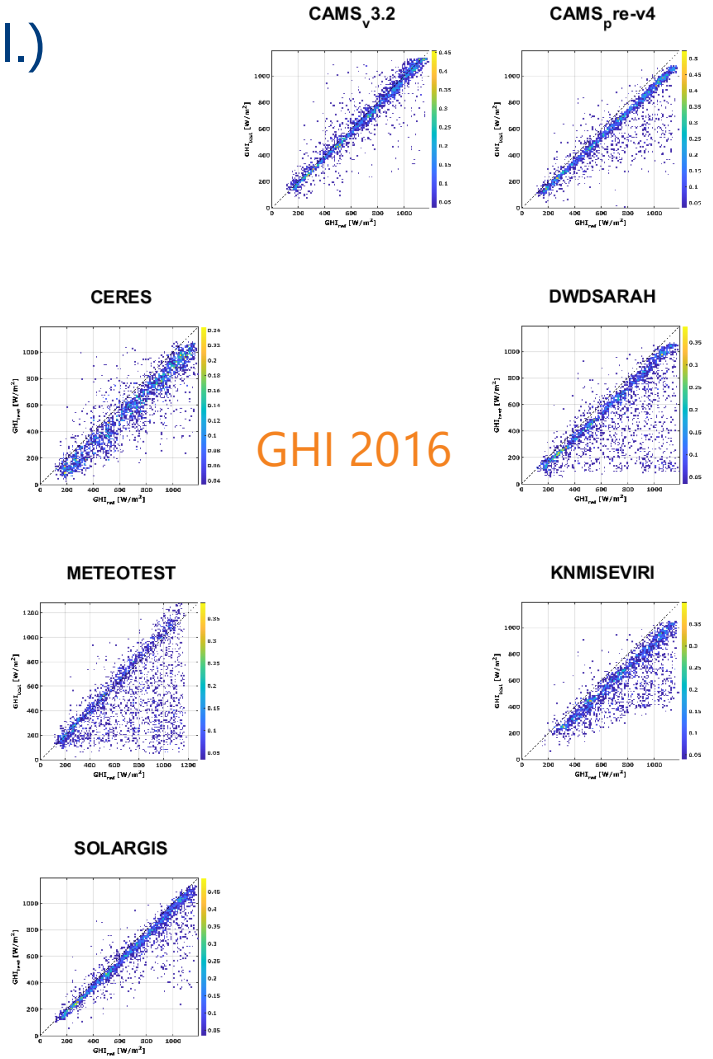
Example - IZA

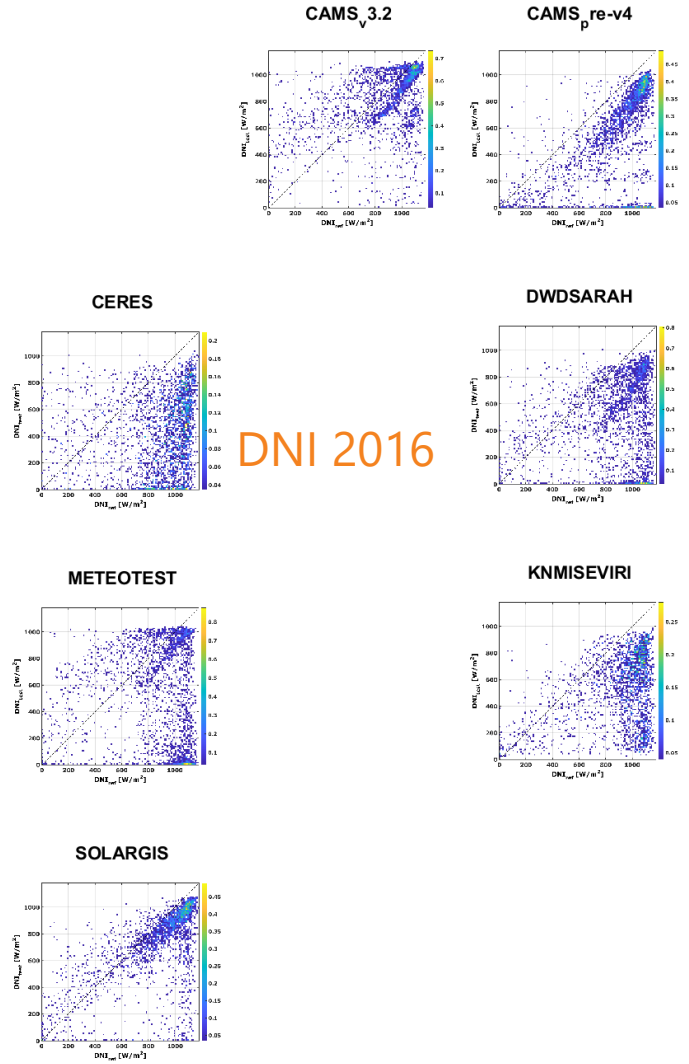
- Izana, Canary Islands (2373 m a.m.s.l.)
- Is station below or above clouds?
- Snow cover or cloud cover?

➢Special station

➢Helpful for comparing model performance in similar locations (mountain sites)

➢To estimate model performance for surrounding areas the above issues have to be considered (maybe not comparable).





PVPS

Tables of results – relative MBD – use case

User can select suitable datasets for the continent or climate zone of interest

Tropical_Zone: DNI, rMBD (%)

site / model	ARA	AUA	BRO	CAC	COI	DRW	FEN	HOW	NAT*	PET	ROC	TIR	TOW	VUW	CHI	CHL*	CHO*	DAR	KAA*	KAO*	KAS*	LUS	MBO*	MUT*	MZU*	TAM	COC	DWN	GAN*	HAN*	KDO*	MLE*	Mean	Std	Abs_Mean	Abs_Std
SOLARGIS	-2.7	4.1	-0.1	-0.5	-6.7	0.7	-5.9	-6.3	-4.4	0.1	0.2	5.9	4.0	7.5	1.5	2.9	3.8		3.7	2.4	1.7	2.1	0.4	-3.1	4.4	5.6	-4.4	-0.6	-2.2	-7.0	-2.7	-6.9	1.7	3.2	3.0	1.9
CAMS_pre-v4	-12.8	-11.9		-6.5					-11.3	-6.5				-1.5	-4.1	-2.5	-1.6	14.7	-0.6	-0.5	-3.4	-3.4	-8.3	3.2	-1.0	-16.4							-5.2	5.3	5.6	4.9
DWDSARAH	-6.4	-6.8		4.0					12.2	14.5				6.8	4.5	11.4	7.7	33.3	10.9	7.9	11.7	6.8	36.9	13.0	13.7	12.0							9.5	9.4	11.0	7.4
CAMS_v3.2	-11.1	1.2		9.1					11.5	15.9				16.6	18.8	14.5	13.6	39.0	10.1	6.3	15.7	11.9	-2.2	7.2	25.6	2.3							9.8	8.8	11.4	6.4
CERES	-10.9	-9.5	-4.2	-24.5	-24.4	-24.3	-3.6	-18.4	-34.2	-36.6	-3.5	-20.6	-7.2	-2.2	-6.0	-4.5	-8.0	5.3	-10.8	-13.8	-12.9	-5.9	-9.8	-10.6	-1.9	-17.8	-26.9	-25.9	-21.3	-26.8	-21.4	-26.5	-12.9	10.1	12.9	10.1
METEOTEST	-12.3	6.2		-15.7			-9.3	3.4	-3.1	-9.8		37.3		5.0	8.9	22.8	19.3	14.1	30.5	20.2	22.8	21.3	-12.3	26.3	37.5	11.8			8.0	1.7	8.1		10.5	16.5	16.8	9.5
CSIROHIMAWARI											1.3																									
KNMISEVIRI	-9.9	-8.2												6.8	8.5	4.3	3.8	-27.8	7.1	4.8	7.3	3.2	-0.5	6.2	6.3	4.3										
NSRDBGOES									11.9	20.5																										

Ranking different for GHI and DNI

Tropical_Zone: GHI, rMBD (%)

site / model	ARA	AUA	BRO	CAC	COI	DRW	FEN	HOW	NAT*	PET	ROC	TIR	TOW	VUW	CHI	CHL*	CHO*	DAR	KAA*	KAO*	KAS*	LUS	MBO*	MUT*	MZU*	TAM	COC	DWN	GAN*	HAN*	KDO*	MLE*	Mean	Std	Abs_Mean	Abs_Std
SOLARGIS	-0.7	2.0	1.0	-1.4	-2.6	1.5	1.6	2.5	1.0	1.9	0.1	-1.8	0.9	4.1	4.5	3.9	2.9		3.6	2.8	0.5	1.3	0.9	2.6	5.5	-1.8	-1.8	0.7	-3.1	-3.7	-4.6	-4.7	2.0	2.1	2.4	1.5
CERES	-2.1	0.6	0.6	2.3	-0.4	0.0	5.8	6.4	-3.7	-6.7	0.1	1.7	-2.0	4.2	6.8	5.5	3.2	10.4	3.3	0.2	-0.6	1.2	1.9	2.6	6.7	-4.2	-2.3	-2.7	-4.6	-6.5	-5.4	-5.4	1.3	3.8	3.3	2.2
CAMS_pre-v4	-5.2	-1.2		-1.0					0.4	2.2				1.7	3.4	5.7	4.7	14.9	5.4	4.2	0.9	2.9	-2.5	6.7	5.6	-6.4							1.6	3.9	3.5	2.1
DWDSARAH	-0.4	-1.1		0.2					5.1	6.6				4.3	3.7	7.9	6.0	12.5	6.8	5.7	3.7	3.8	7.3	8.3	6.4	0.3							4.4	3.0	4.6	2.7
CAMS_v3.2	-5.4	1.0		2.9					2.6	4.2				6.1	7.9	7.4	6.1	11.3	4.5	2.5	3.4	3.8	-8.6	3.5	9.1	-5.2							2.7	4.9	4.9	2.3
METEOTEST	-4.7	4.0		-5.2			-1.8	6.9	2.9	0.4		3.9		3.8	7.1	11.4	9.6	9.9	13.7	9.2	7.3	8.5	-5.9	11.9	14.2	-3.0			2.7	-1.7	0.2		5.0	6.7	7.2	4.0
ACCESSG3	2.3																																			
CSIROHIMAWARI											-0.7																									
KNMISEVIRI	-1.1	-1.2												6.4	5.5	5.9	4.7	-12.8	6.7	5.1	2.8	3.4	1.2	7.1	5.0	-1.2										
NSRDBGOES									4.6	6.3																										

Ranking different for single station

How to use the results and plots

Objective: estimate data quality for	Plots to look at
A specific continent in general	Table plots, and maps
A site that is close to or similar to a site used in this benchmark	Table and scatter plots of this site (multiplot with all test data sets)
A specific climate	Table plots for climate zone (not shown here), and maps
A specific geography (mountain, coast, other)	Table plots for this geography (not shown here), and maps
…	…

Conclusion

- Deviations between data sets and errors in general are much higher for DNI compared to GHI
- NWP data set often shows positive bias (ACCESSG3)
- Included global data set derived from polar satellites and geostationary satellites (CERES) has significantly higher deviations than other data sets, at times even higher than the NWP data.
  - Reason is very coarse resolution (1°), so that pixels (cells) are much larger than those of the other databases. For DNI the difference to the other satellite data sets is much more pronounced.
- Significant deviations between performance of different satellite-derived radiation data sets
- Most appropriate data set depends on site and also on continent and climate zone of interest
- Some stations are challenging for some models as high deviations are observed for several data sets (e.g. high mountains, smog)
- Benchmark results can be used to identify good data sets for different regions or at times even specific sites, recommendation for procedure will be published

Planned tasks

- Benchmark for site adapted data (one adaptation for all)
  - Planned for November 2022
- Histograms of deviation of yearly sums at all stations for each provider
  - Planned for November 2022
- Writing of Report
  - Q4 2022

Publication plan

Topic	Time frame
Presentations: PVPMC Workshop (by Adam) EMS 2022 (by Anne) WCPEC-8 (by Elena) SolarPACES (by Anne)	 2022-08-23--24 2022-09-06 **2022-09-26 -- 30** **2022-09-26 -- 30**
IEA PVPS report "R1.4.2 Report on benchmarking results for satellite- and model-derived data sets [M72]" -QC can be summarized, use ref. to QC paper	**End 2022** **(report due by Q2 2023 according to task work plan)**
Paper Benchmark with focus on conclusion on data sets, as a condensed version of the report (optional)	**After report is finalized**