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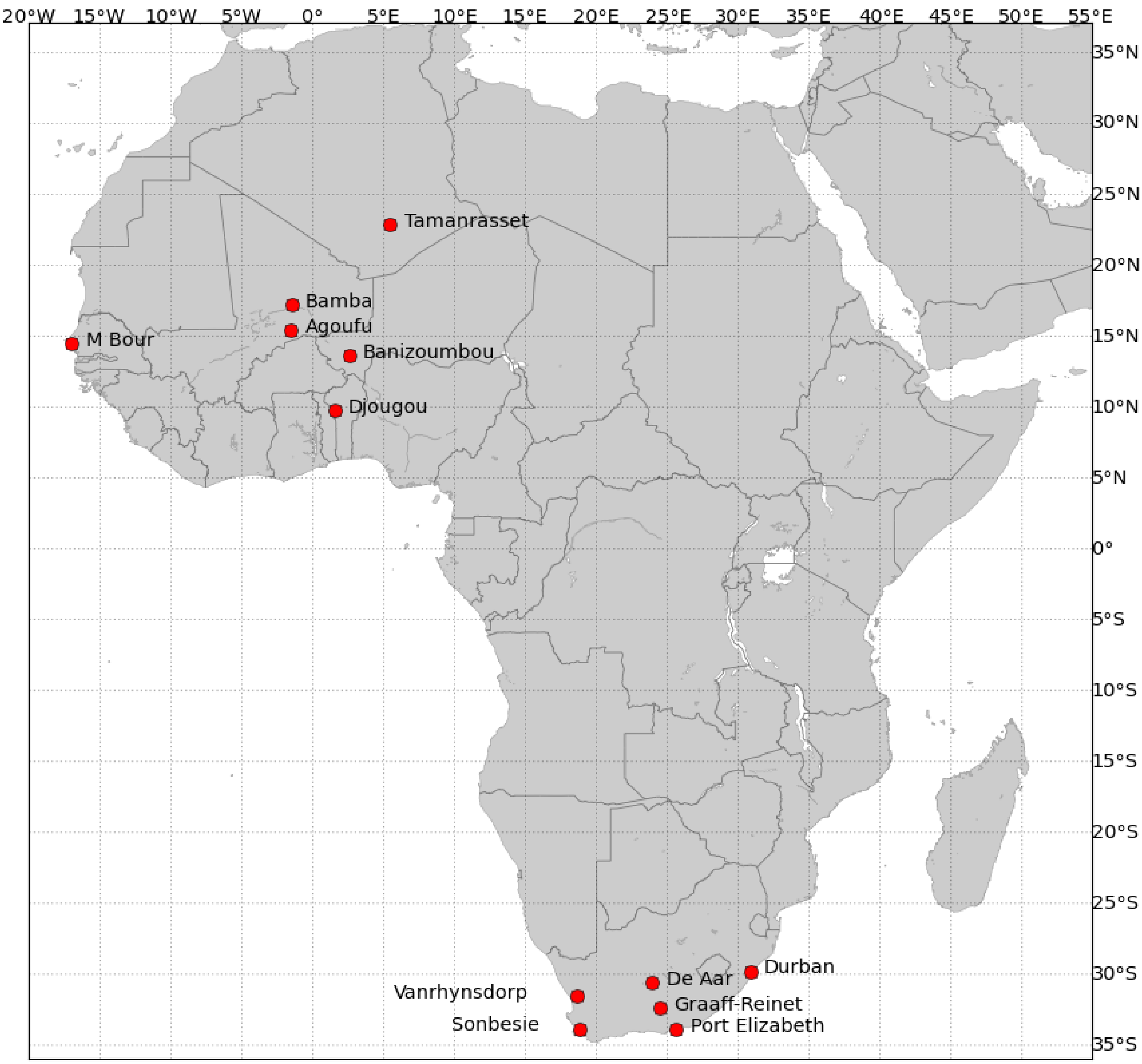
WORLD BANK GROUP

ESMAP
Energy Sector Management Assistance Program

Solar Resource Mapping in Zambia

MODEL VALIDATION REPORT

November 2014



This report was prepared by Marcel Suri, Tomas Cebecauer, Artur Skoczek and Nada Suriova, GeoModel Solar (http://geomodelsolar.eu), under contract to the World Bank Group (WBG).

It is one of several outputs from the solar resource mapping component of the activity '*Renewable Energy Resource Mapping and Geospatial Planning – Zambia* [Project ID: P145271]. This activity is funded and supported by the Energy Sector Management Assistance Program (ESMAP), a multi-donor trust fund administered by the World Bank, under a global initiative on Renewable Energy Resource Mapping. Further details on the initiative can be obtained from the ESMAP website at http://www.esmap.org/.

This document is an **interim output** from the above-mentioned project, and the maps and visualizations presented are **preliminary and unvalidated**. Users are strongly advised to exercise caution when utilizing the information and data contained, as this has not been subject to full peer review. The final, validated, peer reviewed output from this project will be a Zambia Solar Atlas, which will be made available once the project is completed.

ESMAP Solar Resource Mapping for Zambia

Interim Model Validation Report

Renewable Energy Resource Mapping and Geospatial Planning – Zambia [P145271]

November 2014

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ACRONYMS

AERONET	The AERONET (AErosol RObotic NETwork) is a ground-based remote sensing network dedicated to measure atmospheric aerosol properties. It provides a long-term database of aerosol optical, microphysical and radiative parameters.
AOD 670	Aerosol Optical Depth at 670 nm. This is one of atmospheric parameters derived from MACC-II database and used in SolarGIS. It has important impact on accuracy of solar calculations in arid zones.
CFS v2	Climate Forecast System. The meteorological model operated by the US service NOAA (National Oceanic and Atmospheric Administration)
CFSR	Climate Forecast System Reanalysis. The meteorological model operated by the US service NOAA.
DIF	Diffuse Horizontal Irradiation, if integrated solar energy is assumed. Diffuse Horizontal Irradiance, if solar power values are discussed.
DNI	Direct Normal Irradiation, if integrated solar energy is assumed. Direct Normal Irradiance, if solar power values are discussed.
ECMWF	European Centre for Medium-Range Weather Forecasts is independent intergovernmental organisation supported by 34 states, which provide operational medium- and extended-range global forecasts and a computing facility for scientific research.
GFS	Global Forecast System. The meteorological model operated by the US service NOAA.
GHI	Global Horizontal Irradiation, if integrated solar energy is assumed. Global Horizontal Irradiance, if solar power values are discussed.
GTI	Global Tilted (in-plane) Irradiation, if integrated solar energy is assumed. Global Tilted Irradiance, if solar power values are discussed.
MACC	Monitoring Atmospheric Composition and Climate – meteorological model operated by the European service ECMWF (European Centre for Medium-Range Weather Forecasts)
Meteosat MFG and MSG	Meteosat satellites operated by EUMETSAT organization. MSG: Meteosat Second Generation; MFG: Meteosat First Generation
NOAA NCEP	National Oceanic and Atmospheric Administration, National Centre for Environmental Prediction
RSR	Rotating Shadowband Radiometer
TEMP	Air Temperature at 2 metres

GLOSSARY

Aerosols	Small solid or liquid particles suspended in air, for example soil particles, sea salts, pollen or air pollution such as smog or smoke.
Bias	Represents systematic deviation (over- or underestimation) and it is determined by systematic or seasonal issues in cloud identification algorithms, coarse resolution and regional imperfections of atmospheric data (aerosols, water vapour), terrain, sun position, satellite viewing angle, microclimate effects, high mountains, etc.
Root Mean Square Deviation (RMSD)	Represents spread of deviations given by random discrepancies between measured and modelled data and is calculated according to this formula: $$RMSD = \sqrt{\frac{\sum_{k=1}^{n}(X^{k}{}_{measured} - X^{k}_{modeled})^2}{n}}$$ On the modelling side, this could be low accuracy of cloud estimate (e.g. intermediate clouds), under/over estimation of atmospheric input data, terrain, microclimate and other effects, which are not captured by the model. Part of this discrepancy is natural - as satellite monitors large area (of approx. 3 x 4 km), while sensor sees only micro area of approx. 1 sq. centimetre. On the measurement side, the discrepancy may be determined by accuracy/quality and errors of the instrument, pollution of the detector, misalignment, data loggers, insufficient quality control, etc.
Solar irradiance	Solar power (instantaneous energy) falling on a unit area per unit time [W/m^2]. Solar resource or solar radiation is used when considering both irradiance and irradiation.
Solar irradiation	Amount of solar energy falling on a unit area over a stated time interval [Wh/m^2 or kWh/m^2].
Spatial grid resolution	In digital cartography the term applies to the minimum size of the grid cell or in the other words minimal size of the pixels in the digital map
Uncertainty	Is a parameter characterizing the possible dispersion of the values attributed to an estimated irradiance/irradiation values. In this report, uncertainty assessment of the solar resource estimate is based on a detailed understanding of the achievable accuracy of the solar radiation model and its data inputs (satellite, atmospheric and other data), which is confronted by an extensive data validation experience. The second important source of uncertainty information is the understanding of quality issues of ground measuring instruments and methods, as well as the methods correlating the ground-measured and satellite-based data. In this report, the range of uncertainty assumes 80% probability of *occurrence* of values. Thus, the lower boundary (negative value) of uncertainty represents 90% probability of *exceedance*, and it is also used for calculating the P90 value.
Water vapour	Water in the gaseous state. Atmospheric water vapour is the absolute amount of water dissolved in air.

1 SUMMARY

Background

This Model Validation Report shows method and results of preliminary validation of solar resource and meteorological data for the Republic of Zambia, Phase 1 of solar resource mapping and measurement services. The project is a part of technical assistance in renewable energy development implemented by the World Bank in Zambia. It is being undertaken in close coordination with the Ministry of Energy and Water Development of Zambia, Department of Energy, the World Bank's primary country counterpart for this project.

The project is funded by the Energy Sector Management Assistance Program (ESMAP), a global knowledge and technical assistance program administered by the World Bank and supported by 11 bilateral donors. It is part of a major ESMAP initiative in support of renewable energy resource mapping and geospatial planning across multiple countries.

Data and methods

This report documents validation of solar resources calculated by satellite model SolarGIS, and meteorological data derived from the CFSR and CFSv2 models. Inventory in Chapter 3 identifies the existing data sources in the region: solar, aerosol and meteorological data. First, aerosol (Atmospheric Optical Depth, AOD) data from the MACC-II model is evaluated (Chapter 4, this data is used on the input to SolarGIS clear-sky model). Chapter 5 shows relative comparison of SolarGIS GHI and DNI to other modelled databases. Next, validation to high-quality solar resource measurements demonstrates stable performance of SolarGIS in geographic conditions, similar to Zambia. Chapter 6 validates meteorological parameters that are used for site-specific data and for maps. Chapter 7 summarizes validation results in the estimate of uncertainty.

Results

Validation demonstrates stable performance of SolarGIS model in Africa. The validation and previous experience indicate that using high-quality local measurements, the SolarGIS model output have significant potential for reduction of uncertainty in geography of tropical Africa.

2 MODEL QUALITY INDICATORS

The performance of satellite-based models, for a given site, is characterized by the following indicators:

1. **Bias** characterizes systematic model deviation at a given site;
2. **Root Mean Square Deviation** (RMSD), Standard deviation (SD) and Mean Average Deviation (MAD), which indicate spread of error for instantaneous values (typically hourly or sub-hourly);
3. **Kolmogorov-Smirnoff index** (KSI) characterizes representativeness of distribution of values. This indicator is applied only for solar resource data.

Focus of this report is validation and uncertainty assessment of SolarGIS solar resource data that are derived in the form of spatial and site-specific data products. Meteorological data are also validated as they are used in the site-specific times series and Typical Meteorological Year data (TMY). Air temperature is also used as a spatial data product.

Only quality-controlled measurements from high-standard sensors can be used for objective validation of satellite-based solar model, as issues in the ground measured data result in skewed evaluation.

Typically, bias is considered as the first indicator of the model accuracy, however the model should be interpreted analyzing also all other accuracy measures. While knowing bias helps to understand a possible error of longer-term estimate, MAD and RMSD are important for estimating the accuracy of energy simulation and operational calculations (monitoring, forecasting). KSI reveals issues in the model's ability to represent specific solar radiation conditions. This is especially important in the CSP modelling, as the response of these systems is non-linear to irradiance levels.

Even if bias of different satellite-based models is similar, other accuracy characteristics (RMSD, MAD and KSI) may indicate substantial differences in their performance.

Validation statistics for one site may not provide representative picture of the model performance in the given geographical conditions. The reason is that one particular site may be affected by a local microclimate or by hidden issues in the ground-measured data. Therefore, the model should be evaluated at several validation sites. If ability of the model to estimate longterm values, at least two measures are to be considered [1]:

- *Mean bias deviation*, which indicates whether the model has overall tendency to overestimate or to underestimate the measured values.
- *Standard deviation of biases*, which shows the range of deviation of the model estimates (statistically one standard deviation characterizes 68% probability of occurrence).

Good satellite models are consistent in space and time, and thus the validation at several sites within one geography provides a robust indication of the model accuracy in geographically comparable regions elsewhere. Besides bias and RMSD, the ability of the model to simulate representatively sub-hourly values for all conditions (especially high and low light conditions) is very important for optimisation of the solar power plants.

Two evaluation studies have been conducted independently by University of Geneva [1, 2]. Both studies analyse features of existing solar radiation models based on processing of satellite data. The studies show that SolarGIS model demonstrates robust and harmonized performance in all indicators.

3 INVENTORY OF SOLAR ATMOSPHERIC AND METEOROLOGICAL VALIDATION DATA

3.1 Solar resource measurements

Public data

Solar radiation, unlike other basic meteorological parameters, is measured only at few meteorological stations in Africa. Solar measurements are collected by various organizations: by international or regional professional networks, meteorological agencies or universities. Access to these data may be restricted by data usage polices. Inventory shows that only few sources provide data with sufficient quality required for the validation of SolarGIS model (Tab 3.1) in geographic conditions comparable to those of Zambia.

Tab. 3.1: Sources of solar resource validation data

Network	Description
AMMA	African Monsoon Multidisciplinary Analyses. AMMA is an international project to improve the knowledge and understanding of the West African Monsoon (WAM) and its variability. http://amma-international.org/
BSRN	Baseline Surface Radiation Network (BSRN) provides near-continuous, long-term, in situ-observed broadband irradiances (solar and thermal infrared) and certain related parameters from a network of more than 50 globally diverse sites. Data usually include GHI, DIF and DNI measurements. Data from De Aar and Tamanrasset meteo stations are used. http://www.bsrn.awi.de/ http://www.bsrn.awi.de/en/data/data_retrieval_via_pangaea/
SASSCAL	Southern African Science Service Centre for Climate Change and Adaptive Land Management in Southern Africa conducts a problem-oriented research in the area of adaptation to climate change and sustainable land management. Solar radiation measurements are part of the project monitoring activities. http://www.sasscal.org/ http://www.sasscalweathernet.org/
SAURAN	SAURAN (Southern African Universities Radiometric Network) is an initiative of the Centre for Renewable and Sustainable Energy Studies (CRSES) at Stellenbosch University and the Group for Solar Energy Thermodynamics (GSET) at the University of KwaZulu-Natal. The network provides high-resolution, ground-based solar radiometric data available from stations located across the Southern African region, including South Africa, Namibia, Botswana and Reunion Island. In this report, four SAURAN data sets were used. http://www.sauran.net/
STERG	Sonbesie is a station operated by STERG (Solar Thermal Energy Research Group), a research group housed in the Department of Mechanical and Mechatronic Engineering in Stellenbosch University and affiliated with the Centre for Renewable and Sustainable Energy Studies, Stellenbosch University. STERG has performed measurements on one site considered in this report. http://weather.sun.ac.za/

Before decision was made if the ground-measurements to be used for the model validation, the data was quality controlled (Chapter 5.1). In general, measurements from networks such as AMMA, BSRN, SAURAN and Sonbesie show quality that allows using them for the model validation. BSRN, SAURAN and Sonbesie produce data in 1 and 10 minute time step, AMMA data are in available hourly time step only.

SASSCAL meteorological network is not focused primarily on high-accuracy solar radiation measurements. The instruments have high uncertainty and our analysis identified higher occurrence of issues, which excluded these measurements from further consideration.

List of public solar resource measuring stations, checked for possible use for validation of SolarGIS model (Chapter 5.2), is summarized in Tabs. 3.2 and 3.3. Their position is shown in Fig. 3.1.

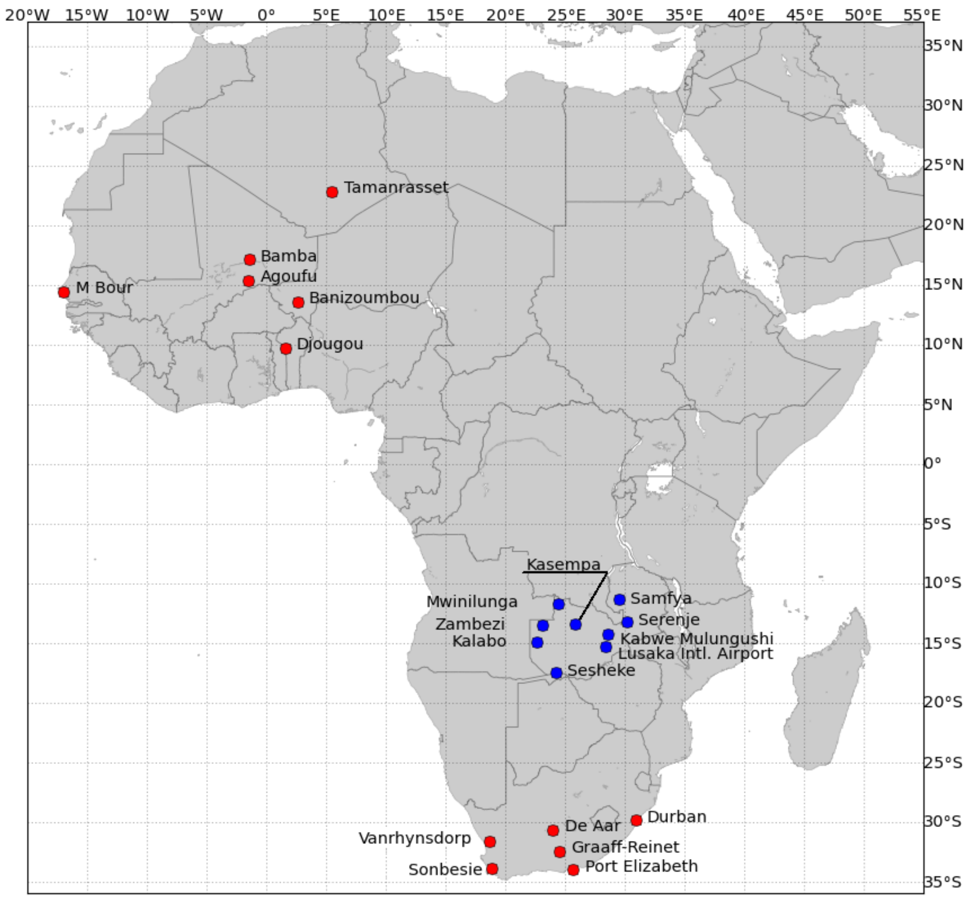


Fig. 3.1: Position of solar validation sites in Africa

Tab. 3.2: Solar measuring stations in Africa, used for validation of SolarGIS

Site name	Country	Source	Latitude [°]	Longitude [°]	Altitude [m a.s.l.]	GHI	DNI	Period
Tamanrasset	Algeria	BSRN	22.7833	5.5137	1378	YES	YES	03/2000 – 12/2006
Bamba	Mali	AMMA	17.0990	-1.4018	272	YES	NO	2006
Agoufu	Mali	AMMA	15.3445	-1.4791	290	YES	NO	2006
M Bour	Senegal	AMMA	14.3940	-16.9590	5	YES	NO	2006
Banizoumbou	Niger	AMMA	13.5311	2.6613	211	YES	NO	2006
Djougou	Benin	AMMA	9.6920	1.6620	438	YES	NO	2006
De Aar	South Africa	BSRN	-30.6667	24.0000	1331	YES	YES	06/2000 – 12/2004
Durban	South Africa	SAURAN	-29.8710	30.9769	150	YES	YES	02/2013 – 07/2014
Graaff-Reinet	South Africa	SAURAN	-32.4855	24.5858	660	YES	YES	12/2013 – 09/2014
Port Elizabeth	South Africa	SAURAN	-34.0086	25.6653	35	YES	YES	12/2012 – 07/2014
Sonbesie	South Africa	STERG	-33.9282	18.8651	144	YES	YES	02/2012 – 07/2014
Vanrhynsdorp	South Africa	SAURAN	-31.6175	18.7383	130	YES	YES	11/2013 – 09/2014

Tab. 3.3: Solar measuring stations operated by SASSCAL network in Zambia

Site name	Country	Source	Latitude [°]	Longitude [°]	Altitude [m a.s.l.]	GHI	DNI	Period
Samfya	Zambia	SASSCAL	-11.3712	29.5606	1194	YES	NO	10/2013 – 10/2013
Mwinilunga	Zambia	SASSCAL	-11.7400	24.4310	1360	YES	NO	12/2103 – 06/2014
Serenje	Zambia	SASSCAL	-13.2267	30.2151	1395	YES	NO	12/2013 – 10/2014
Kasempa	Zambia	SASSCAL	-13.4570	25.8337	1227	YES	NO	12/2013 – 10/2014
Zambezi	Zambia	SASSCAL	-13.5337	23.1079	1066	YES	NO	12/2013 – 10/2014
Kabwe Mulungushi	Zambia	SASSCAL	-14.2926	28.5663	1142	YES	NO	01/2013 – 10/2013
Kalabo	Zambia	SASSCAL	-14.9890	22.6818	1018	YES	NO	12/2013 – 10/2014
Lusaka Int. Airport	Zambia	SASSCAL	-15.3193	28.4405	1149	YES	NO	10/2013 – 10/2014
Lusaka, Uni. Zambia	Zambia	SASSCAL	-15.3912	28.3320	1260	YES	NO	10/2013 – 10/2014
Sesheke	Zambia	SASSCAL	-17.4711	24.3013	944	YES	NO	12/2013 – 10/2014

Private initiatives

A number of solar measuring stations are deployed by companies active in development of solar energy projects in the region. The measured data are used for commercial and technological assessment of solar resource for particular projects and they are not publically available.

3.2 Solar resource modelled data

Public databases

There are several modelled databases available in the region (Tab. 3.4). In general, the databases based on the interpolation of ground-measured data, such as *Meteonorm* [3] are less reliable in areas with sparse availability of meteorological stations. *PVGIS HelioClim-1* [4, 5] is calculated from daily HelioClim-1 data with limited reliability. The global database *NASA SSE* [6] is computed by empirical models from satellite and atmospheric data and shows only global climate patterns at coarse-resolution. *SWERA/NREL* database has medium spatial resolution and is computed using *CSR* model by NREL [7], thus only showing overview perspective. The closest to SolarGIS is satellite-based database *PVGIS CMSAF*, however the data are not updated regularly and are available only as long-term averages [8]. Implementation of these databases is static, and they are not updated regularly.

Tab. 3.4: Inventory of solar resource models for Zambia.

Model	Data source	Data spatial resolution	Parameter	Time resolution of available data	Period
NASA SSE	Satellite + model	110 km x 110 km	GHI, DNI	Long-term monthly	1983 – 2005
Meteonorm 7.1	Ground + satellite	Interpolation and satellite data	GHI, DNI	Long-term monthly	1981 – 2010
PVGIS HelioClim-1	Daily MFG satellite data	30 x 30 km	GHI	Long-term monthly	1985 – 2004
PVGIS CMSAF	MFG and MSG satellites	3 km x 4 km	GHI, DNI	Long-term monthly (hourly)	1998 – 2011
SWERA/NREL	Model	40 km x 40 km	GHI, DNI	Long-term monthly	1985 – 1991
SolarGIS*	MSG/MFG PRIME satellites	3 km x 4 km	GHI, DNI	15 and 30 minutes	1994 – 2013*

** SolarGIS database is continuously updated on daily basis*

Commercial satellite-based databases

On the market there are few solar databases developed and maintained by commercial entities that provide solar radiation data to customers for a fee. Most of these databases are based on the use of satellite data, but they differ in the model implementation and use of input data (e.g. aerosols, water vapour), therefore results may significantly differ. These databases differ also in spatial coverage, spatial and temporal resolution, operational update and other parameters.

Besides quality of data, important for a user is easy access, ability of the system to deliver updated data, and support by services, such as site adaptation, derived data products (e.g. TMY), bankable solar resource assessment, map services and others.

To our understanding, for Zambia, besides SolarGIS, the following commercial databases are available: SOLEMI, 3TIER, IrSOLaV and HelioClim-3. More information about these databases is available in [1, 2].

3.3 Atmospheric data

Along with the clouds, aerosols are the most influential factor controlling GHI and DNI irradiance in the region, especially during cloud-free weather situations. The atmospheric turbidity is mostly influenced by burning biomass, soil particles, locally by human activities (industry, transport and urbanization) and particles transported from other regions.

Complex geography creates specific conditions for local distribution and transport of aerosols. Combined influence of these factors results in varying atmospheric pollution both spatially and temporarily. The accurate description of aerosols is difficult due to several factors:

- Aerosols have high spatial and temporal variability,
- There is insufficient number of aerosol-specialized meteo stations, and often they have only short period of measurements,
- In most of Africa, there are limited possibilities for detailed description of aerosol sources for chemical-transport atmospheric models,
- Arid and semiarid conditions make it difficult to use satellite measurements of aerosols,
- Dynamics of aerosols increases in a complex terrain.

For aerosol characterization a data from chemical transport model MACC-II is used in SolarGIS. The original data with resolution of ca. 85 km and 125 km is post-processed by a) regional adaptation to remove systematic regional deviation of MACC-II database and b) altitude correction to better reflect local terrain conditions.

The understanding of nature of the modelled aerosol data helps to indirectly evaluate the satellite based SolarGIS model. For this purpose a model input aerosol data was compared to aerosol measurements from AERONET [9].

Fig. 3.2 shows location of the stations used for atmospheric data validation. Only one station is located in Zambia, though several stations exist in the wider region, having reasonably long period of measurements:

- Mongu (Zambia)
- Nairobi (Kenya)
- Malindi (Kenya)
- Mbita (Kenya)
- Gorongosa (Mozambique)
- Skukuza (South Africa)
- Pretoria (South Africa)
- Elandsfontein (South Africa)
- Wits University (South Africa)
- Henties Bay (Namibia)

Fit of aerosol data to ground measurements is important indirect indicator of performance of satellite-based model (for SolarGIS evaluated in Chapter 4.2).

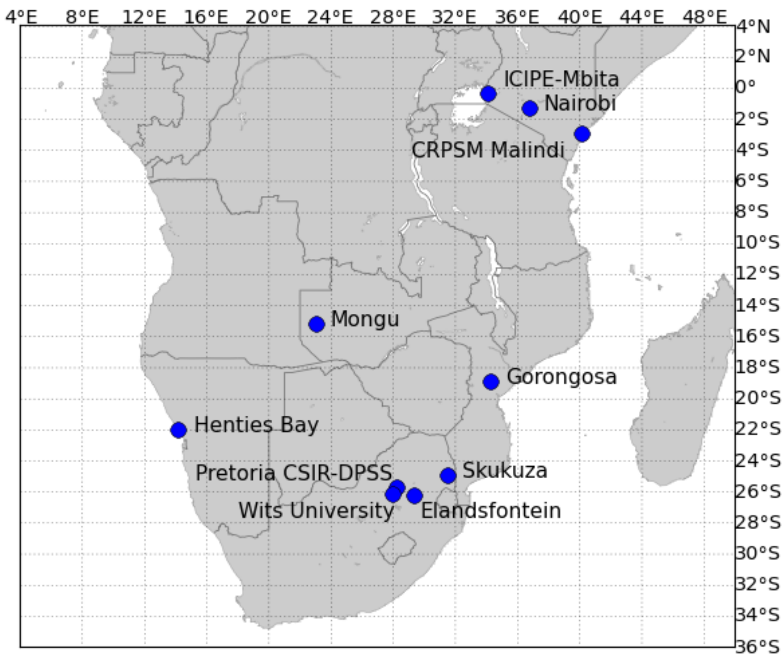


Fig. 3.2: Position of AERONET stations

3.4 Meteorological measurements

The validation procedure was carried out by comparison of modelled data with ground-measured data at eight sites operated by Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL), and also with other six meteo data measured in the region (source NOAA NCDC).

It must be noted that time period of data comparison for the SASSCAL network is relatively short (Tab. 3.5). Comparison with other meteo stations in the region is performed for a time period 2008 to 2010 (CFSR model) and for 2011 to 2013 (CFSv2 model) [11, 12].

Tab. 3.5: Meteo stations in the region considered for validation of CFSR and CFSv2 model outputs

Meteo station	Data source	Time period	Latitude [º]	Longitude [º]	Elevation [m a.s.l.]
Lusaka intl. airport	NOAA	01/2008 – 12/2013	-15.3170	28.4500	1154
Kasane	NOAA	01/2008 – 12/2013	-17.8170	25.1500	1000
Harare, Kutsaga	NOAA	01/2008 – 12/2013	-17.9170	31.1330	1480
Gweru	NOAA	01/2008 – 12/2013	-19.4500	29.8500	1429
Mbeya	NOAA	01/2008 – 12/2013	-8.9330	33.4670	1758
Chimoio	NOAA	01/2008 – 12/2013	-19.1170	33.4670	732
Sesheke	SASSCAL	11/2013 – 10/2014	-17.4711	24.3013	953
Kalabo	SASSCAL	12/2013 – 10/2014	-14.9890	22.6818	1030
Kabwe Mulungushi	SASSCAL	10/2013 – 10/2014	-14.2926	28.5663	1143
Zambezi	SASSCAL	11/2013 – 10/2014	-13.5337	23.1079	1077
Kasempa	SASSCAL	11/2013 – 10/2014	-13.4570	25.8337	1240
Serenje	SASSCAL	12/2013 – 10/2014	-13.2267	30.2151	1390
Mwinilunga	SASSCAL	12/2013 – 10/2014	-11.7400	24.4310	1368
Samfya	SASSCAL	10/2013 – 10/2014	-11.3712	29.5606	1197

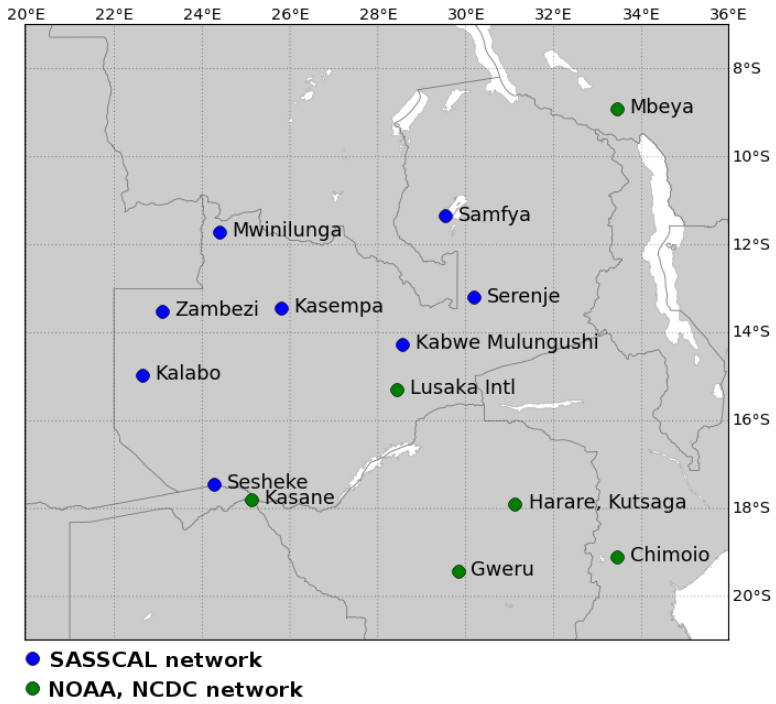


Fig. 3.3: Position of meteo stations considered for validation of CFSR and CFSv2 model outputs

3.5 Meteorological models

Tab. 3.6 gives an overview of selected modelled meteorological data available for the region. Chapter 4.2 of *Interim Solar Modelling Report 128-01/2014* gives more insight into global meteorological models. These models are run by meteorological organisations, such as US National Oceanic and Atmospheric Administration (NOAA), European Center for Medium range Weather Forecasting (ECMWF) or Canadian Meteorological Centre (CMC). Global meteorological models serve for purposes such as weather forecasting, modelling long-term climate processes and helping to understand weather phenomena in a global scale. Accuracy of modelled meteorological data for a specific geographical location cannot compete with the accuracy of well-maintained on-site meteorological sensors. However advantages of the modelled data are numerous: they cover large territories (some are global), they are free of maintenance and calibration issues, in case of reanalysis product they ensure seasonal and long term stability, long history, almost 100% availability both spatially and temporally and they offer data from any location on the Earth. This makes them a good choice for preliminary solar energy simulations.

Tab. 3.6: Selected meteorological models available in the region.

Database name	Source	Spatial resolution	Time resolution	Period
CFSR	NOAA, model	0.312° x 0.312°	1 hour	1979 to 2010
CFSv2	NOAA, model	0.20° x 0.20°	1 hour	2011 to present
GFS	NOAA, model	0.20° x 0.20°	3 to 6 hours	1991 to present
ERA-Interim	ECMWF, model	0.75°x 0.75°	6 hours	1979 to present
GDPS	CMC, model	0.225° x 0.225°	3 hours	2010 to present
Meteonorm	Ground-measurements	Interpolation	Long-term monthly	2000 to 2009

Meteonorm database is also mentioned in Tab. 3.6. It is a different type of weather database, based on ground measurements from a number of (8325) meteorological stations, where site-specific information is calculated by interpolation of monthly averages. Monthly averages are, in the second step statistically disaggregated to synthetic hourly data representing one year. This approach has limitations due to its static character (there is no systematic update) and limited performance in areas with sparse network of meteorological stations. Although this database was historically popular, with today's computing and modelling options, this approach is overcome.

In the delivery for Zambia, the meteorological parameters are derived from CFSR and CFS v2 models. *Water vapour* parameter - for solar resource model - is partially derived also from the GFS database.

4 VALIDATION OF AEROSOL DATA

Along with clouds, aerosol data is one of the most important parameters as it controls accuracy of solar models in arid and semiarid zones. Atmospheric aerosols include liquid and solid particles originating from different sources, e.g. soil particles, sea salts, burning biomass, industrial and traffic pollution and pollen. Aerosols have high spatial and temporal variability and complex behaviour in terms of absorption and scattering of solar irradiance.

Increased aerosol concentrations in the atmosphere can reduce GHI in the range of 0% to 7%, occasionally up to 10%. In case of DNI, the variable aerosols can reduce daily DNI as much as 40% or even more. In solar modelling, aerosols are represented by the parameter called *Atmospheric Optical Depth* (AOD).

4.1 Evaluation of MACC-II Atmospheric Optical Depth data

MACC-II aerosol data [13, 14], used in the SolarGIS model, provide good representation of temporal as well as spatial variability of aerosol load. Despite these qualities, the data may experience systematic deviation in some regions [15]. Here, we evaluate MACC-II AOD data using measurements from AERONET stations [29] located in a wider region (Fig. 3.2). Only one station (Mongu) can be used for direct evaluation in Zambia, other sites show aerosol accuracy in the wider spatial context.

The SolarGIS model is based on aerosol data, which are regionally adapted for larger systematic deviations and they are also adapted for local altitude by empirical height correction. Fig. 4.1 and 4.2 demonstrate an accuracy of the MACC-II database used in the SolarGIS model.

Comparison of post-processed daily MACC-II data and 15-minute AERONET ground measurements for Mongu site shows very good fit. Seasonal profiles, as well as short extreme situations, are well represented. But in conditions with very low aerosol load a slight overestimation of MACC-II AOD is found. On the other hand, for some of high load situations, the modelled AOD may be slightly underestimated. The discrepancy visible in the plot also arises from comparing high frequency (15-min) site-specific AERONET values with daily summaries of regionally-smoothed MACC-II data.

The comparison of AERONET sites in a broader region shows generally good representation of the AOD variability. At some sites higher bias of MACC-II aerosols (Henties Bay, Elandsfontein, Gorongosa, Malindi) may influence resulting accuracy of SolarGIS DNI and GHI irradiation. These sites are relatively far from Zambia, but may indicate issues of the MACC-II model in Eastern Zambia, which is far from the Mongu site.

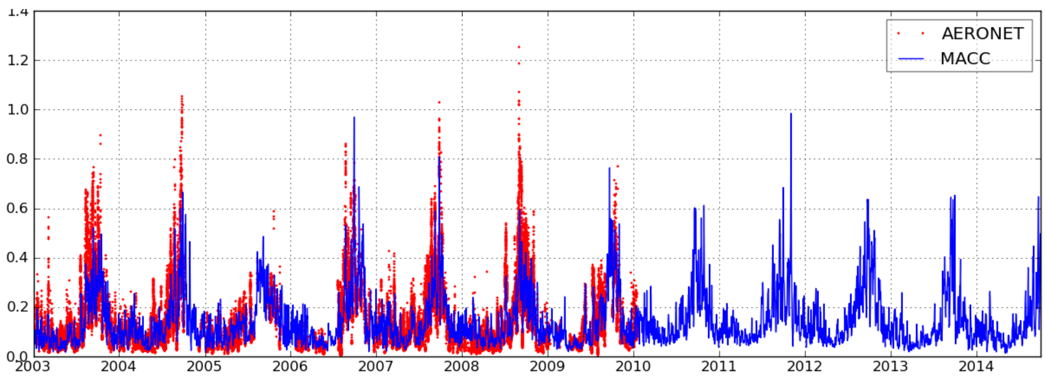
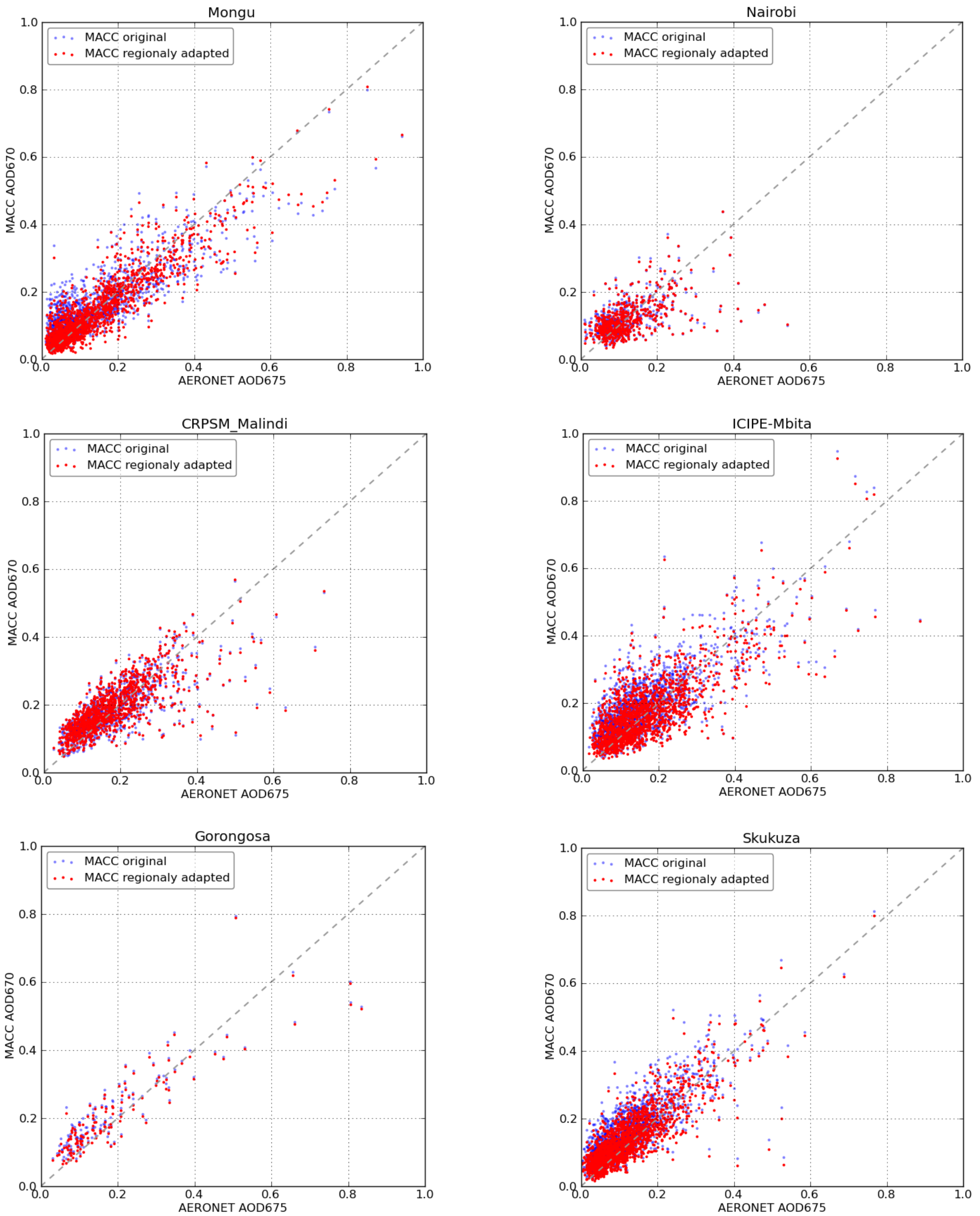


Fig. 4.1: Comparison of daily summaries from MACC-II model with 15-min AERONET data.
Mongu AERONET station in Zambia

Some discrepancies in individual stations may be attributed to the coarse resolution of MACC-II database, which is not capable representing the specific local conditions recorded in the AERONET data with sufficient accuracy. Also the spread of values may be partially explained by natural differences arising from the comparison of exact point measurements (AERONET) with regionally-averaged values (MACC-II).



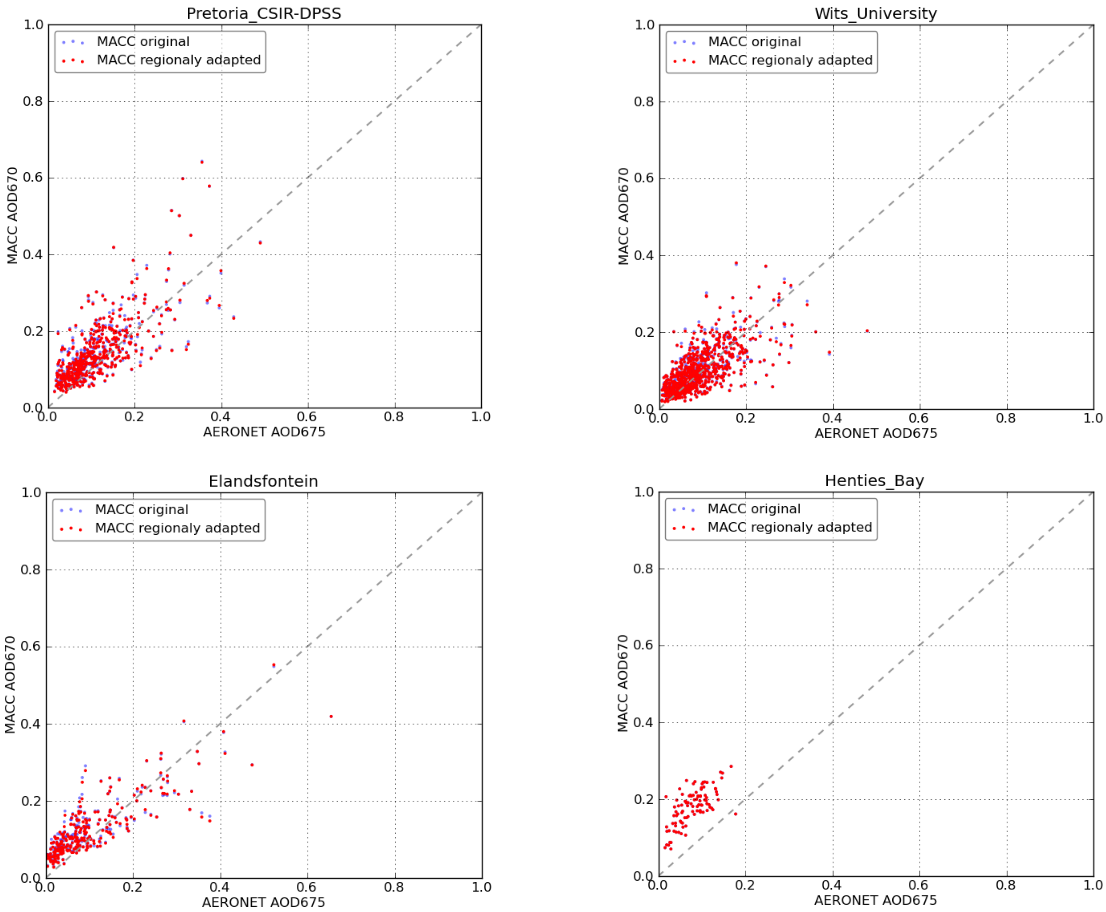


Fig. 4.2: Comparison of Aerosol Optical Depth
AERONET 675 nm (x-axis) and MACC 670 nm (y-axis); blue points: original MACC data;
red points: MACC data regionally-adapted by SolarGIS method

To understand potential issues with AOD in regions, where AERONET data are not available, the MACC-II data for Lusaka were compared with two other data sources (Fig. 4.3):

- Data computed from several satellite missions: Terra MODIS, Aqua MODIS, Terra MISR, Envisat MERIS [16, 17]
- Data computed by chemical transport model GOCART (NASA, Langley ASCD) [18].

All compared databases (except Envisat MERIS) show the same seasonal pattern with increased aerosol load in a period from August to October – the same trend was identified also in the Mongu AERONET station. Range of values between databases is also similar, only differences in extremely high values are identified.

Limited number of ground-measured data does not allow evaluating quality of aerosol data for the whole Zambia. In general, analysis of available AOD data shows good representativeness of MACC-II AOD database in the Mongu site. Discrepancies seen in other sites could be observed in some regions of Zambia. These discrepancies may be reduced or removed in Phase 2 of the ESMAP project, by use of high resolution and high–quality local measurements.

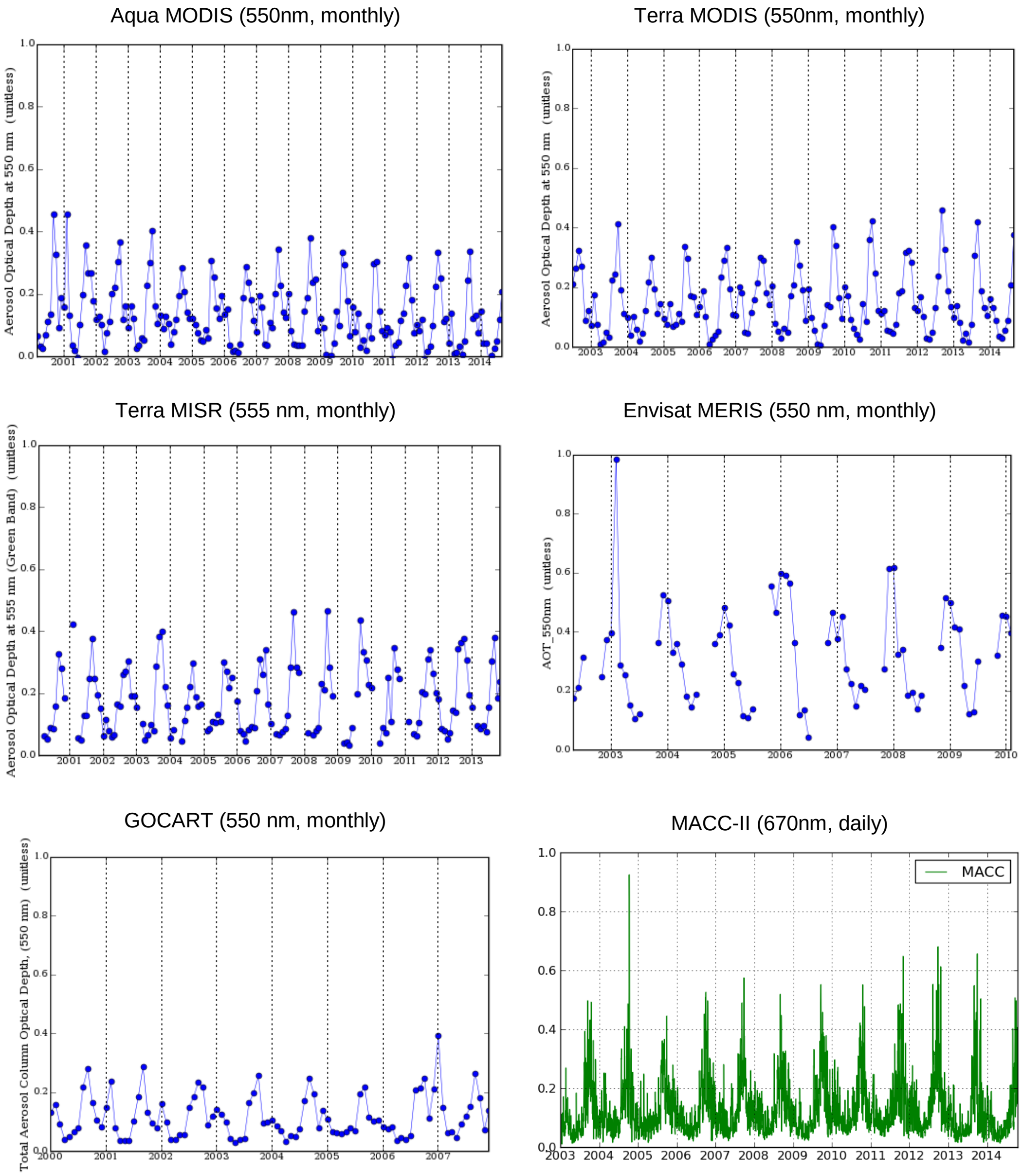


Fig. 4.3: Aerosol Optical Depth for Lusaka from six different AOD databases
Plots of satellite-based data were produced with by Giovanni online data system, NASA Langley ASCD [19]

4.2 Seasonal variability of Atmospheric Optical Depth

SolarGIS uses AOD input data, at the wavelength 670 nm, derived from the MACC-II model. The MACC-II model captures high temporal variability of aerosols, thus it reduces uncertainty of instantaneous GHI and DNI estimates. Fig. 4.4 shows typical monthly variability of aerosols in central and southern Africa. Zambia is located in a transition zone between region with high aerosol load in equatorial and sub-equatorial Africa and regions with low aerosol load in the southern part of continent. The seasonal pattern is influenced by high aerosol load events having their centre outside of the Zambian territory in the Northwest. The lowest aerosol concentration in the atmosphere can be observed from December to June, and the highest in September and October. Highest concentrations are seen in the Western part of the country.

From the global perspective, Zambia is a region with relatively low aerosol load (Fig. 4.5), but still having significant influence on the dynamics of solar resource, especially DNI.

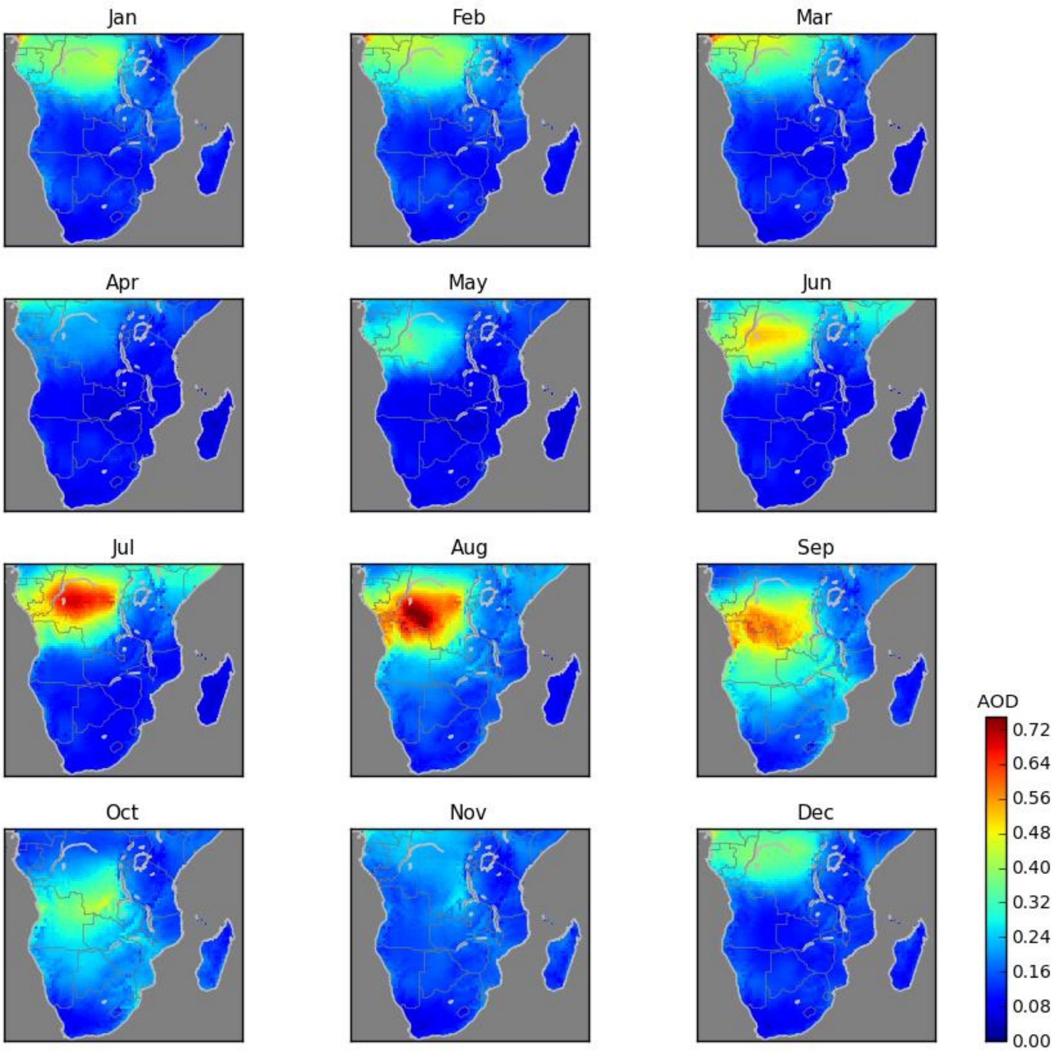


Fig. 4.4: Monthly-averaged aerosol maps (AOD 670) derived from the MACC-II database and adapted for the SolarGIS model. Period 2003 to 2013

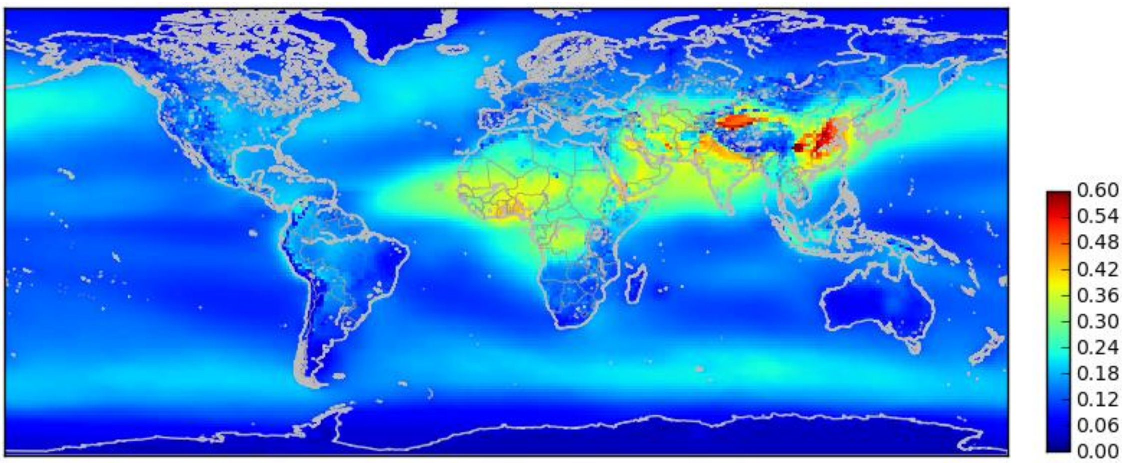


Fig. 4.5: Zambia in the world context – average annual aerosols (represented by AOD 670 nm) computed by the MACC-II model and adapted for SolarGIS. Period 2003 to 2012. Values are dimensionless.

5 VALIDATION OF SOLAR RESOURCE DATA

5.1 Quality control of solar validation data

Prior to comparison with satellite-based solar resource data, the ground-measured irradiance was quality-controlled by GeoModel Solar. Quality control (QC) was based on methods defined in SERI QC procedures and Younes et al. [20, 21] and developed by GeoModel Solar. The ground measurements were inspected also visually, mainly for identification of shading and other regular data error patterns.

Fig. 5.1 shows an example of results of such quality control in one meteo station: Durban (South Africa). The colours indicate the following flags:

- Blue: data excluded by visual inspection - mainly shading, incorrect tracking and calibration issues
- Green: data passed all tests
- Grey: sun below horizon
- White strips: missing data
- Red and violet: GHI, DNI and DIF consistency problem or problems with physical limits

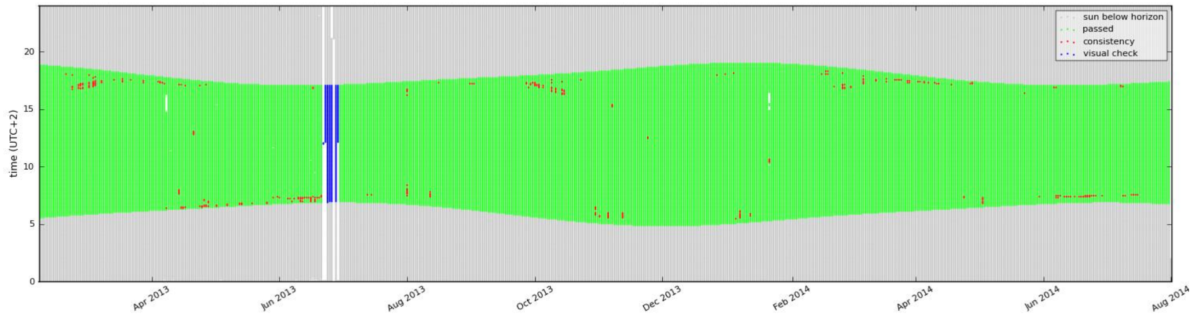


Fig. 5.1: Quality control of data measured at Durban measuring station in South Africa
X-axis: date of measurement, Y-axis: time of measurements; colour – various QC flags.

The example of Durban (Fig. 5.1) shows relatively low occurrence of issues: for short periods we have identified an inconsistency between GHI, DNI and DIF component (red colour); for a short period in June 2013 we identified missing data and non-systematic time shifts.

Quality control shows that all measured solar radiation data is affected by disturbances. The most typical errors are: missing values, inconsistency between the solar components, and occurrence of values out of the physical limits. In many sites shading from surrounding terrain or objects is also observed. These errors were identified, to a various extent, in all stations.

Measurements of all three components (GHI, DNI and DIF) allow performing more complex consistency tests, which help to reveal various issues in data that may otherwise remain hidden (Fig 5.2). Important is also visual control of the data that is used for identification of systematic issues such shading, reflections or problems with calibration of instruments (Fig 5.3).

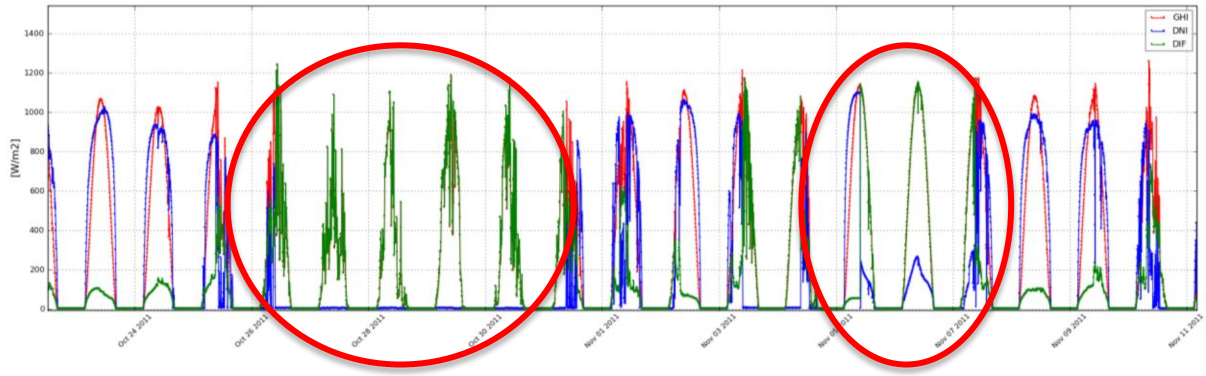


Fig. 5.2: Example of incorrect DNI (DIF) measurements due to problems of sun tracking.

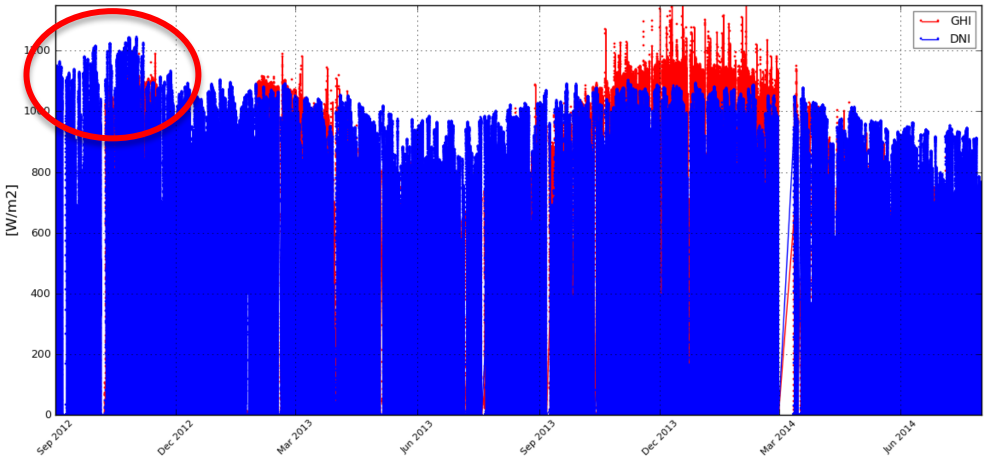


Fig. 5.3: Example of incorrect DNI measurements due to issues with calibration.

For the territory of Zambia the ground measurements were available for eleven locations from the **SASSCAL network**. The data are available through the project web page, however no additional information was available: about instruments, calibration, cleaning plan and maintenance log. Therefore it was difficult to assess nominal accuracy of these measurements. The visual inspection of this data revealed issues, such as shading, missing data, incorrect levelling of instruments (Figs. 5.4 and 5.5). The global horizontal irradiation observations from the SASSCAL network show systematic positive bias for satellite-based yearly GHI, from 4% to 12%, which indicates systematic issues with measured data (instrument levelling and sensor soiling).

Fig. 5.6 shows an example of how issues in ground measurements can be identified when compared to the model data. Two stations show very distinct behaviour. While data from Sonbesie show good fit, the data from Kasempa show high dispersion of values due to lower quality of ground measurements. The performance of the data from the SASSCAL network is variable and cannot be used for objective validation of satellite model performance.

Taking into consideration also fact that these stations are equipped with lower standard sensors, which are not primarily meant for high-accuracy measurements of solar radiation, the data were excluded from further consideration.

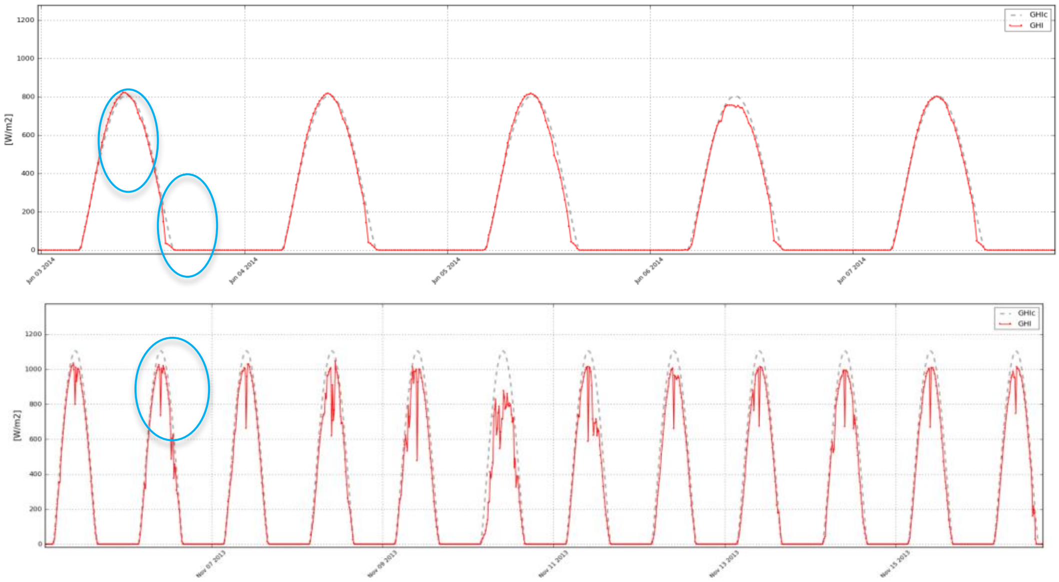


Fig. 5.4: Two examples of data issues identified at meteo stations
Top: asymmetric profile and shading, Bottom: incorrect data.

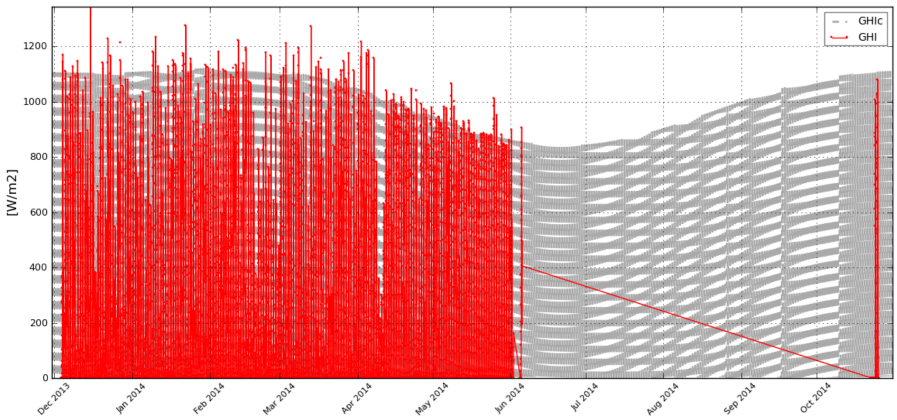


Fig. 5.5: Example of missing data

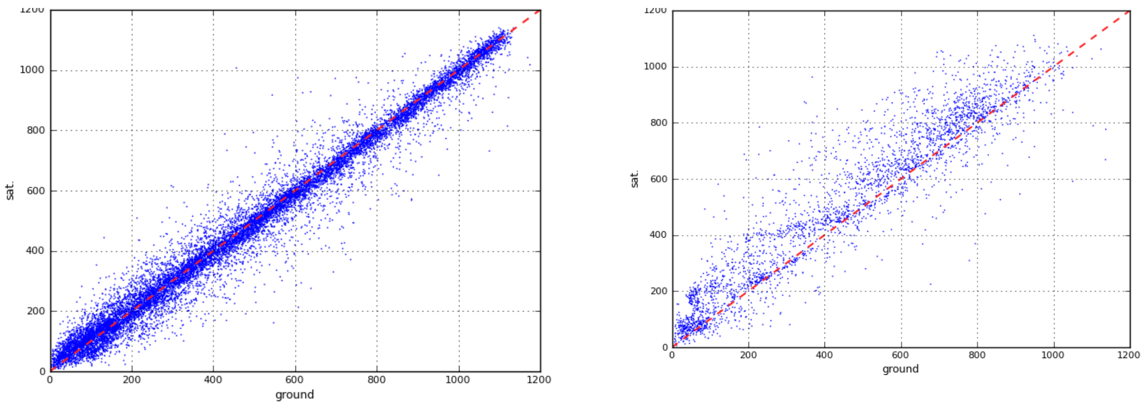


Fig. 5.6: Quality of GHI measurements for two stations
Left: Sonbesie, Stellenbosch, South Africa is an example of good-quality ground measurements;
Right: Kasempa, Zambia shows issues in the measured data.

Quality-control procedures were used for evaluation of those stations that were pre-qualified for validation of the SolarGIS model (data from the SASSCAL network were excluded from further analysis). All affected data readings were flagged for these stations and excluded from further analyses. Tab. 5.1 summarizes percentage of data passed through the quality control tests.

Tab. 5.1: Data for each solar measuring station that did not pass through quality control [%]

	Type of test (numbers show percent of total volume of data)]				
	Sun below horizon	Test for physical limits	Visual test	Consistency test (GHI – DNI – DIF)	Total excluded data samples
Tamanrasset	49.3	0.0	9.3	1.1	10.4
Bamba	49.2	0.5	0.0	0.0	0.5
Agoufu	49.1	0.05	9.0	0.0	9.1
M Bour	49.7	0.3	12.6	0.0	12.9
Banizoumbou	49.7	0.5	0.0	0.0	0.5
Djougou	49.7	0.05	0.0	0.0	0.05
De Aar	48.9	0.1	0.6	5.9	6.6
Sonbesie	49.5	0.0	3.4	0.3	3.7
Durban	50.8	0.0	0.4	0.2	0.6
Graaff-Reinet	50.5	0.0	0.8	0.5	1.3
Port Elizabeth	50.2	0.0	16.1	1.0	17.1
Vanrhynsdorp	50.2	0.0	1.2	0.9	2.1

Based on our experience we propose the following recommendations for running routine measurement campaign:

- Data used for model validation must be measured by high quality instruments; detailed description of instruments must be available. Regular maintenance of sensors must be arranged.
- Use of just one or two sensors (GHI, DNI), without redundant (DIF) measurements does not allow applying valuable quality control algorithms.
- Instruments should be preferably mounted about 1 m to 1.5 m above ground or roof surface on a stable concrete or metal platform.
- Many analysed stations are influenced by shading from surrounding structures. This should be avoided if possible, or affected values should be flagged.
- Data cleaning should be systematic and logged.
- Data should be quality checked on a continuous basis. Some types of data logger have software, which can automatically pre-flag errors. Data should be provided for the end users with flags indicating the above-mentioned problems, to avoid their mistaken use.
- Regular service visits will prevent common issues with tracker misalignment, sensor levelling, PV and battery supply, desiccant exchange, etc.

5.2 Validation of solar resource model

5.2.1 Comparison of SolarGIS to other models

Solar irradiance for Zambia is calculated by the SolarGIS model (Chapter 3.2 *of Interim Solar Modelling Report 128-01/2014*). In this Chapter, the annual SolarGIS average is compared to five other data sources with different temporal and spatial resolution and time coverage (Tab. 3.4). Six representative sites are used, as described in Chapter 6.1 of *Interim Solar Modelling Report 128-01/2014*). Comparison of the databases shows discrepancies (Tab. 5.2 and 5.3), which are determined by their specific characteristics:

- Applied model approaches
- Type and quality of the input data
- Time representation
- Spatial and temporal resolution of the output databases.

In general, higher uncertainties have to be expected when comparing data representing different time periods due to short-term weather variability and climate cycles, but also due to fluctuating atmospheric conditions (e.g. concentration of aerosols). When comparing with ground observations from the previous decades, one has to consider that these may have been measured with instruments of lower accuracy and under application of less-stringent measuring standards.

Tab. 5.2: Comparison of SolarGIS long-term yearly GHI average with five different data sources.

Database	Global Horizontal Irradiation [kWh/m^2]					
	Longe	Lusaka	Misamfu	Mochipapa	Msekera	Mutanda
NASA SSE	2137	2093	2148	2089	2115	2089
Meteonorm 7	2137	1990	2030	2209	2090	2004
PVGIS 3	2144	2086	2286	2071	2078	2129
PVGIS CMSAF	2224	2159	2232	2133	2126	2191
SWERA/NREL	2052	2023	1976	2030	2008	1986
SolarGIS	2200	2120	2170	2137	2071	2150
Standard deviation of GHI annual values	2.8%	3.0%	5.5%	3.0%	2.0%	3.9%
Schematic assessment of GHI uncertainty (80% confidence)	3.6%	3.8%	7.1%	3.8%	2.6%	5.0%
Expected SolarGIS uncertainty (80% confidence)	**6.0%**	**6.0%**	**6.0%**	**6.0%**	**6.0%**	**6.0%**

Tab. 5.3: Comparison of SolarGIS long-term yearly DNI averages with four different data sources.

Database	Direct Normal Irradiation [kWh/m^2]					
	Longe	Lusaka	Misamfu	Mochipapa	Msekera	Mutanda
NASA SSE	2367	2264	2286	2279	2246	2224
Meteonorm 7	2217	1884	1799	2323	2014	1873
PVGIS CMSAF	2290	2129	2188	2129	1980	2170
SWERA/NREL	1822	1778	1586	1828	1730	1652
SolarGIS	2117	2000	1895	2103	1801	1909
Standard deviation of DNI annual values	9.8%	9.6%	14.7%	9.1%	10.3%	11.9%
Schematic assessment of DNI uncertainty (80% confidence)	12.5%	12.3%	18.8%	11.7%	13.2%	15.2%
Expected SolarGIS uncertainty (80% confidence)	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**	**12.0%**

Tabs. 5.2 and 5.3 show dispersion of yearly GHI and DNI values between six different databases, including SolarGIS. This comparative approach is a simplified way how to assess the solar resource uncertainty. Important is to understand the risk of possible great geographical dispersion of the estimates. For comparison we show an uncertainty estimate for SolarGIS based on the available validation data in the region (more in Chapters 5.2.3 and 7.1).

The modern satellite-based models, such as SolarGIS, are more accurate as they are based on modern algorithms, which generate data outputs at high spatial and temporal resolution. However such data should be systematically updated and quality controlled, in order to fulfil all needs of the solar energy industry: during the prefeasibility project stage, design optimisation and financing, as well as for operation and management of solar power plants. In this context, high quality ground measurements play key role for validation and adaptation of satellite-based models: this is planned next step for Phase 2 of this project.

Based on the analysis of sites from Europe, North Africa and Middle East, two intercomparison studies [1, 2] independently analyse the accuracy of satellite-based models, besides SolarGIS, some of them available also for Zambia: 3Tier, SOLEMI, HelioClim-3 and IrSOLaV. Tabs. 5.4 to 5.7 show that SolarGIS has very good performance in all statistical indicators for both Global Horizontal Irradiation and Direct Normal Irradiation. Occasionally, some databases show slightly lower Mean Bias, but this indicator may hide problems (high bias) in individual sites, which may compensate each other in the final figure. From a user's perspective important parameter is Standard Deviation of biases that indicates geographical stability of the model. Full comparison can be found in both studies.

Tab. 5.4: GHI quality indicators related to satellite-based solar radiation models [2]

Global Horizontal Irradiance, GHI	Mean bias		Standard deviation	Standard deviation
	[W/m^2]	[%]	of biases [%]	of hourly values [%]
SolarGIS	3	1	2.7	17
HelioClim v3	4	1	5.3	21
3Tier	4	1	3.4	21
IrSOLaV	1	0	4.0	33

Tab. 5.5: DNI quality indicators related to satellite-based solar radiation models [2]

Direct Normal Irradiance, DNI	Mean bias		Standard deviation	Standard deviation
	[W/m^2]	[%]	of biases [%]	of houry values [%]
SolarGIS	-11	-4	5.9	35
HelioClim v3	25	8	16.1	50
3Tier	17	5	12.1	49
IrSOLaV	-3	-1	-	54

Tab. 5.6: GHI quality indicators related to satellite-based solar radiation models [1]

Global Horizontal Irradiance, GHI	Mean bias		Standard deviation	Standard deviation
	[%]	[%]	of biases [%]	of hourly values [%]
SolarGIS	0	0	2.1	17
HelioClim v3	5	1	5.1	20
SOLEMI (Aerocom aerosols)	6	2	4.8	23
IrSOLaV	2	1	4.2	24

Tab. 5.7: DNI quality indicators related to satellite-based solar radiation models [1]

Direct Normal Irradiance, DNI	Mean bias		Standard deviation	Standard deviation
	[W/m^2]	[%]	of biases [%]	of hourly values[%]
SolarGIS	-6	-2	5.9	34
HelioClim v3	21	6	13.9	47
SOLEMI (Aerocom aerosols)	-40	-11	14.5	49
IrSOLaV	-1	0	12.0	49

5.2.3 Validation at sites with high-quality GHI and DNI measurements

Compared to high-quality ground measurements (Tabs. 5.8 and 5.9) that passed through quality control (Chapter 5.1), the SolarGIS model slightly underestimates DNI in Southern Africa; in other sites and for GHI the bias is more variable. At the level of individual sites, bias (systematic deviation) of the model values is found in a narrow range (typically within ±10% for yearly DNI and ±4% for yearly GHI), thus it correspond to the expected uncertainty of the SolarGIS model [22]. However due to absence of high-quality measurements in tropical Africa, our proposed model uncertainty is rather conservative (see Chapter 7.1).

Terms Bias and RMSD are explained in Glossary. Absolute values of bias are calculated for daytime hours only. Prior to data comparison all data were harmonized into hourly time step. Number of data pairs in Tabs. 5.8 and 5.9 represent all valid hourly daytime data samples from which statistical measures were calculated.

Tab. 5.8: Global Horizontal Irradiance: bias and RMSD for validation sites

Site name		Bias		Root Mean Square Deviation (RMSD)			KSI	Data pairs
				Hourly	Daily	Monthly		
		[W/m^2]	[%]	[%]	[%]	[%]	[-]	
Tamanrasset	Algeria	0	0.0	8.5	4.6	1.8		10 216
M Bour	Senegal		1.9	11.2	6.4	3.3		3 293
Bamba	Mali		-2.2	12.0	7.7	5.1		4 403
Agoufu	Mali		-1.0	10.9	6.1	2.9		3 660
Banizoumbou	Niger		-1.8	12.3	7.5	4.8		4 360
Djougou	Benin		2.7	16.8	9.6	5.4		4 330
De Aar	South Africa	8	1.8	11.5	6.9	2.5		2 729
Durban	South Africa	-13	-3.3	17.4	9.1	4.6	70	5 756
Sonbesie	South Africa	-6	-1.2	10.5	4.8	2.2	49	13 981
Vanrhynsdorp	South Africa	-4	-0.8	8.8	3.5	1.3	23	3 279
Port Elizabeth	South Africa	-9	-2.3	11.8	5.8	3.7	21	4 484
Graaff-Reinet	South Africa	-1	-0.3	11.6	4.9	0.9	11	2 975

Tab. 5.9: Direct Normal Irradiance: bias and RMSD for validation sites

Site name		Bias		Root Mean Square Deviation (RMSD)			KSI	Data pairs
				Hourly	Daily	Monthly		
		[kWh/m^2]	[%]	[%]	[%]	[%]	[-]	
Tamanrasset	Algeria	24	3.9	21.6	16.4	5.6		10 216
De Aar	South Africa	-6	-1.0	16.8	9.9	2.4		2 729
Aggeneys	South Africa	-36	-4.9	16.1	10.7	6.3	203	5 743
Durban	South Africa	-41	-9.7	30.2	18.1	10.2	187	5 756
Port Elizabeth	South Africa	-9	-2.0	23.5	13.7	5.5	75	4 484
Sonbesie	South Africa	-23	-4.2	24.3	17.8	6.3	292	13 981
Vanrhynsdorp	South Africa	-29	-4.6	18.7	12.8	5.7	114	3 279
Graaff-Reinet	South Africa	-32	-5.5	21.2	11.6	6.2	79	2 975

Further information about the data and methodology and detailed analysis of uncertainty can be consulted in [23, 24]. Comparison of validation statistics computed for solar meteo sites in Africa with similar geographical conditions shows stability of the SolarGIS model outputs, and provides confidence about the estimated uncertainty of GHI and DNI.

6 VALIDATION OF METEOROLOGICAL DATA

6.1 Validation sites

The validation procedure was carried out by comparison of meteorological-model data with ground-measured data at the selected meteorological stations in the region. The validation data come from two different databases: NOAA NCDC and SASSCAL.

Comparison is performed for a time period 2008 to 2010 (CFSR model) and for 2011 to 2014 (CFSv2 model). The time period for SASSCAL network covers up to 1 year only. For details on the applied meteorological models please refer to Chapter 4.2 in *Interim Solar Modelling Report 128-01/2014.* Position of the meteorological stations is shown in Tab. 3.5 and Fig. 3.3.

6.2 Air temperature at 2 metres

Air temperature is derived from both meteorological models by postprocessing and disaggregation from the original model resolution to 1-km grid (Tab. 6.1). Considering spatial and time interpolation, the deviation of the model values compared to ground observations is acceptable. Variability of the modelled data matches the variability recorded by the ground measurements. However, it is to be noted that the model data represent larger area, they are smoothed and therefore they are not capable to represent exact values of the local microclimate (as measured on a meteo station).

Tab. 6.1: Air temperature at 2 m: accuracy indicators of the meteorological model [ºC].

	CFSR model (2008 to 2010)						CFSv2 model (2011 to 2013)*					
	Bias mean	Bias min	Bias max	RMSD hourly	RMSD daily	RMSD monthly	Bias mean	Bias min	Bias max	RMSD hourly	RMSD daily	RMSD monthly
Lusaka Intl.	0.7	2.3	-0.1	4.4	2.7	1.4	-1.3	-1.2	-0.9	2.5	1.7	1.3
Kasane	0.6	0.7	1.0	2.7	1.8	1.0	-0.4	-0.6	0.5	2.7	1.6	0.8
Harare, Kutsaga	-0.5	-1.5	1.0	2.6	1.3	0.7	-1.3	-2.1	0.1	2.8	1.7	1.4
Gweru	0.3	-0.2	1.0	2.2	1.6	0.6	-0.6	-1.3	0.2	2.3	1.4	1.0
Mbeya	-0.5	0.6	-0.8	2.3	1.4	0.9	-1.5	0.1	-2.1	2.7	1.9	1.6
Chimoio	-0.4	-2.0	0.9	3.0	1.5	0.6	-1.3	-2.9	-0.3	3.2	2.3	1.5
Sesheke							0.7	2.0	-0.1	2.9	1.6	0.8
Kalabo							-0.5	-0.2	0.0	2.5	1.7	0.6
Kabwe							-1.0	0.2	-1.8	2.7	1.9	1.2
Zambezi							0.3	1.3	-0.3	2.4	1.4	1.0
Kasempa							-0.8	0.2	-1.0	2.5	1.5	1.0
Serenje							-1.8	-1.5	-1.9	2.7	2.2	2.0
Mwinilunga							-1.3	-0.1	-1.4	2.6	1.7	1.7
Samfya							-1.8	-1.3	-1.7	2.5	2.1	2.0

* Time period for SASSCAL network is shown in Tab. 3.5

The difference in yearly average maximum temperature between modelled and measured data is relatively small. For the minimum night temperature the meteorological models show bias -2.9ºC, in the worst case (model temperature is lower than ground measurement) for one meteorological station. The daytime temperature is represented with much better accuracy: with bias below ±2ºC for all but one meteorological station. It can be observed that accuracy of the model air temperature in the region is good. Both daily and seasonal variability is well represented.

Fig. 6.1 shows the data fit for the Lusaka airport meteo station.

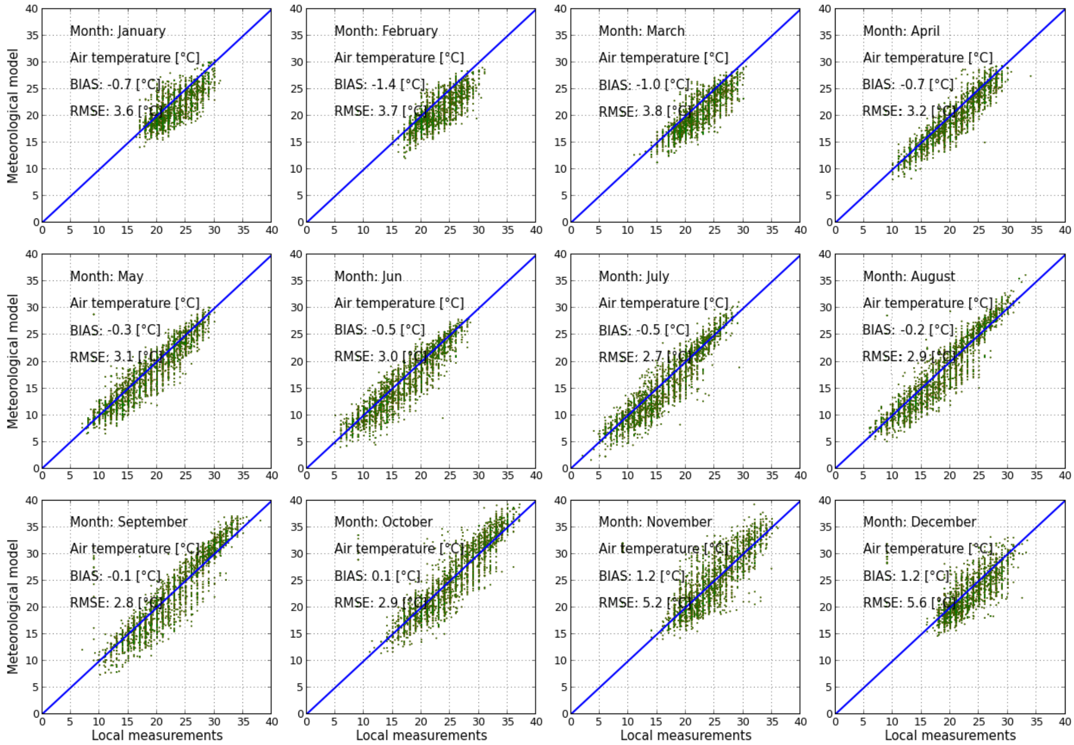


Fig. 6.1: Scatterplots of air temperature at 2 m at the Lusaka airport meteo station.
Measured values (horizontal axis) and meteorological model values (vertical axis)

6.3 Relative humidity

Relative humidity for a period 1999 to 2014 is calculated from the specific humidity, air pressure and air temperature. Original time resolution is 1-hour. The indirect calculation of relative humidity from the meteorological models may result in higher deviation, especially for the night values with high relative humidity. The validation results are summarized in Tab. 6.2.

Similarly to the case of air temperature, relative humidity exhibits higher bias for average maximum values (night time), as it is a temperature-dependent meteorological variable. Daytime values are represented with better accuracy. Accuracy of the modelled data is relatively stable throughout the year.

Fig. 6.2 shows the data fit for the Lusaka airport meteo station.

Tab. 6.2: Relative humidity: accuracy indicators of the model outputs [%].

	CFSR model (2008 to 2010)						CFSv2 model (2011 to 2013)*					
	Bias mean	Bias min	Bias max	RMSD hourly	RMSD daily	RMSD monthly	Bias mean	Bias min	Bias max	RMSD hourly	RMSD daily	RMSD monthly
Lusaka Intl.	-13	-5	-13	20	16	14	-8	-4	-9	14	11	9
Kasane	-10	-6	-15	16	14	11	-7	-5	-9	14	11	8
Harare, Kutsaga	-2	-4	1	13	8	4	0	-1	0	12	7	4
Gweru	-7	-6	-6	13	11	8	-3	-3	-2	12	8	4
Mbeya	0	3	-3	14	10	7	3	7	-2	12	8	6
Chimoio	-10	-11	-8	16	13	11	-5	-4	-4	14	10	6
Sesheke							-11	-4	-15	17	13	11
Kalabo							-6	-3	-9	14	11	7
Kabwe							-1	4	-8	14	11	7
Zambezi							-9	-3	-13	16	12	10
Kasempa							-3	-1	-7	13	9	5
Serenje							4	5	2	11	8	5
Mwinilunga							-1	2	-8	11	6	2
Samfya							-2	-1	-3	10	7	5

* Time period for SASSCAL network is shown in Tab. 3.5

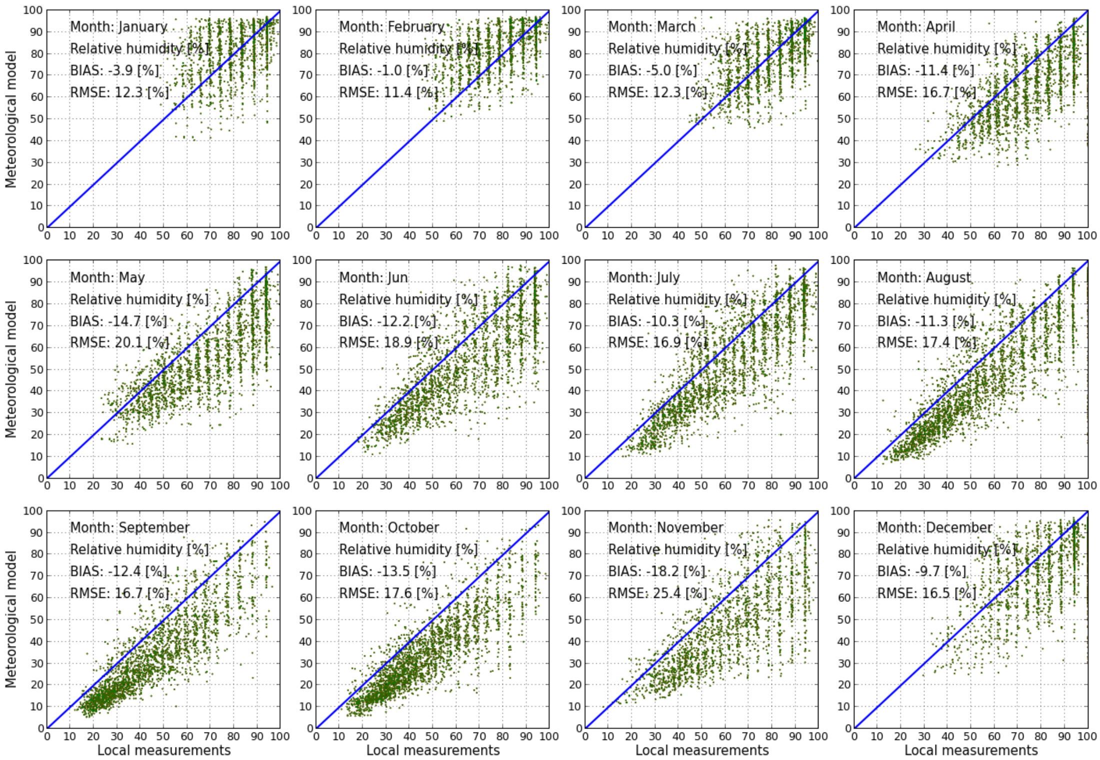


Fig. 6.2: Scatterplots of relative humidity at 2 m at the Lusaka airport meteo station. Measured values (horizontal axis) and meteorological model values (vertical axis)

6.4 Wind speed

Wind speed for the period 1999 to 2014 is calculated from the CFSR and CFSv2 models, from 10-metre wind u- and v- components with the original 1 hourly time step resolution. The results of comparison of modelled wind speed with on-site ground measurements are summarized in Tab. 6.3 and Fig. 6.4.

Tab. 6.3: Wind speed: accuracy indicators of the model outputs [m/s].

	CFSR model (2008 to 2010)						CFSv2 model (2011 to 2013)*					
	Bias mean	Bias min	Bias max	RMSD hourly	RMSD daily	RMSD monthly	Bias mean	Bias min	Bias max	RMSD hourly	RMSD daily	RMSD monthly
Lusaka Intl	0.9	1.0	-0.1	1.9	1.5	1.2	0.4	0.6	-0.3	1.6	1.2	0.8
Kasane	-0.9	0.3	-2.5	1.8	1.2	0.9	-1.1	0.0	-2.6	1.8	1.3	1.1
Harare, Kutsaga	-0.5	0.4	-2.0	1.6	1.0	0.6	-0.9	0.0	-2.1	1.6	1.1	0.9
Gweru	0.7	0.9	0.1	2.1	1.5	0.8	0.6	0.9	0.0	2.0	1.4	0.7
Mbeya	-1.0	0.2	-3.1	2.6	2.0	1.4	-2.0	-0.7	-3.6	2.9	2.4	2.0
Chimoio	-0.5	-0.5	-0.6	2.0	1.5	0.6	-1.2	-1.0	-1.4	1.9	1.7	1.2
Sesheke							0.0	0.7	-1.3	1.2	0.5	0.1
Kalabo							0.3	0.6	-0.2	1.1	0.7	0.4
Kabwe							1.6	1.6	0.8	2.0	1.8	1.7
Zambezi							-0.5	0.0	-1.7	1.2	0.7	0.5
Kasempa							0.9	1.1	0.0	1.3	1.1	0.9
Serenje							-0.4	0.3	-1.2	1.2	0.7	0.5
Mwinilunga							-0.4	0.3	-0.9	4.0	3.7	1.0
Samfya							-0.6	0.2	-2.1	1.7	0.9	0.7

* Time period for SASSCAL network is shown in Tab. 3.5

Wind direction (together with wind speed) parameter is strongly determined by the local microclimate. From the comparison it can be seen that modelled wind speed and wind direction do not fit well the measured values. Fig. 6.3 compares wind speed from the CFSv2 model with the measurements. The model represents regional values for 10 m height. The **modelled wind speed deviates from the measured data**.

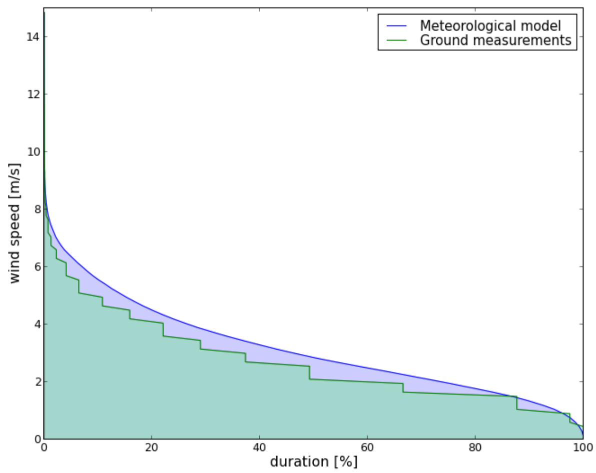


Fig. 6.3: Comparison of duration curves of wind speed data at the Lusaka airport meteorological station. CFSR/CFSv2 model versus local measurements (data represent period 2008 to 2013).

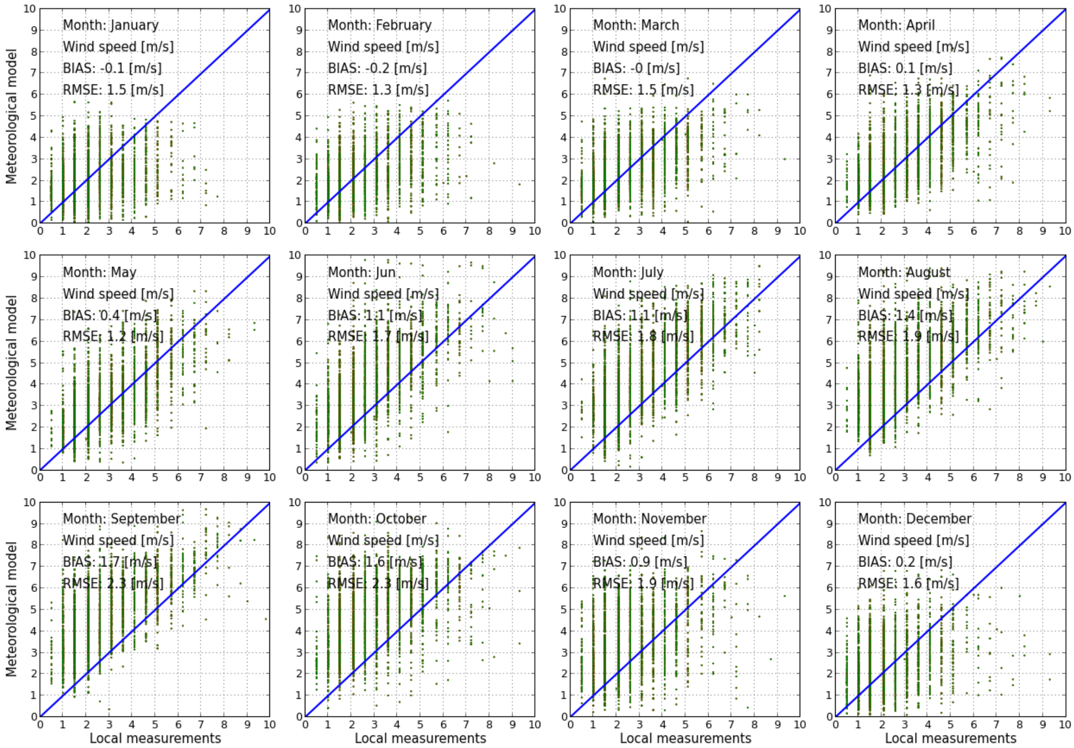


Fig. 6.4: Scatterplots of wind speed at 2 m at Lusaka airport meteo station.
Measured values (horizontal axis) and meteorological model values (vertical axis)

Wind direction (together with wind speed) is represented by wind rose, and this parameter is strongly determined by local microclimate (Fig. 6.5). From the comparison it can be seen that modelled wind speed and wind direction deviate from the measured values. Wind speed data for the other meteorological stations exhibit similar characteristics, with the annual bias below 1 m/s.

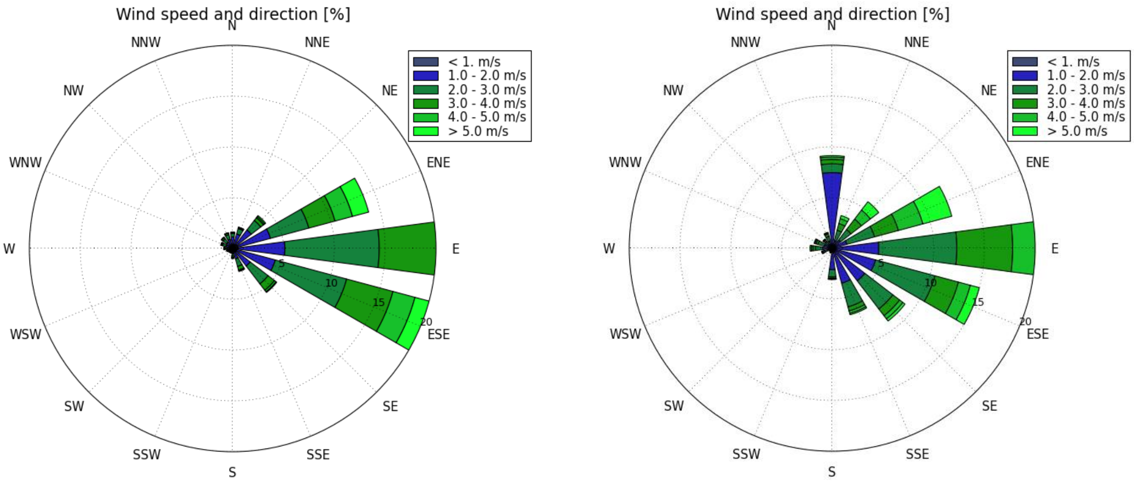


Fig. 6.5: Comparison of wind direction derived from the CFSv2 modes (left)
with local measurements (right) at the Lusaka meteorological station
(data represent period 01/2008 to 12/2013).

The reason why the model wind speed values differ from the measured data is low spatial resolution of the CFSR and CFSv2 meteorological models, which represents only regional effects, while data at micro-scale may differ from the regional scale. Since meteorological model represent larger area, the highest wind speed modelled are not present in the measured data.

7 UNCERTAINTY OF THE MODEL ESTIMATES

7.1 Solar resource parameters

In Zambia, the **uncertainty of DNI and GHI** is determined by the combined uncertainty of the SolarGIS model and of the ground measurements [22], more specifically:

1. Parameterization of **numerical models integrated in SolarGIS** for the specific data inputs and their ability to generate accurate results for various geographical conditions:
    - Data inputs into SolarGIS model (accuracy of satellite data, aerosols, water vapour and terrain).
    - Clear-sky model and its capability to properly characterize various states of the atmosphere
    - Simulation accuracy of the satellite model and cloud transmittance algorithms, being able to properly distinguish different types of surface, clouds, fog, vegetation, occasional flooding, etc.
    - Diffuse and direct decomposition models
2. Uncertainty of the **ground-measurements**, which is determined by:
    - Accuracy of the instruments
    - Maintenance practices, including sensor cleaning, calibration
    - Data post-processing and quality control procedures.

Statistics, such as bias and RMSD (Chapter 5.2.3) characterize accuracy of SolarGIS model in a given validation points, relative to the ground measurements. The validation results are determined by local geography and by quality and reliability of the ground-measured data. It is to be noted that validation for one single site can provide only indicative information. Consistent understanding of the model performance and uncertainty can only be developed by analysis of several validation sites representing similar geographic conditions.

From the user's perspective, the information about the model uncertainty has probabilistic nature, which can be considered at different confidence levels. Tabs. 7.1 and 7.2 show expert estimate of the model uncertainty assumed at 80% probability of occurrence (an equivalent to 90% exceedance) of values.

Tab. 7.1: Interim uncertainty of SolarGIS model estimate for GHI, GTI and DNI

	Yearly uncertainty	Monthly uncertainty
Global Horizontal Irradiation (GHI)	±6%	±8%
Global Tilted Irradiation (GTI)	±7%	±9%
Direct Normal Irradiation (DNI)	±12%	±15%

Tab. 7.2: Uncertainty of estimate of yearly solar resources: ground instruments vs. SolarGIS model

	Best sensors and professional maintenance[1]	SolarGIS data[2]
DNI: Rotating Shadowband Radiometer (RSR)	±3.5%	±12%
DNI: First class pyrheliometer	±1%	
GHI: Rotating Shadowband Radiometer (RSR)	±3.5%	±6%
GHI: Secondary standard pyranometer	±2%	

[1] Range of uncertainty depends on climate, measurements practices and post-processing
[2] Depends on the geographical ability of SolarGIS model and input data to reflect the local solar climate

7.2 Meteorological data

The quality of the modelled meteorological parameters stored in the SolarGIS database was assessed by comparison with ground measurements in the geographic region. Model meteorological data are derived from two different numerical models covering periods from 1994 to 2010 (CFSR model) and 2011 to 2014 (CFSv2). Taking into account the results of the comparison, the uncertainty is estimated in Tab. 7.3.

It was found that the modelled air temperature fits quite well the measured data with occasional larger discrepancies in minimum night-time or maximum day-time temperature.

Wind speed and wind direction data from the meteorological model represent larger region and are smoothed in a comparison to the site measurements at a meteorological station. Although modelled wind speed and wind direction usually fit the patterns of the site-measured data, the maximum values are often not present accurately in the modelled data.

Tab. 7.3: Expected uncertainty of modelled meteorological parameters in region.

	Annual	Monthly	Hourly
Air temperature at 2 m [°C]	<1.5	<2.0	<3.0 (night time) <2.0 (day time)
Relative humidity at 2 m [%]	< 10	<15	<25 (night time) <15 (day time)
Average wind speed at 10 m [m/s]	<1.0	<1.5	<2.0

8 LIST OF FIGURES

9 LIST OF TABLES

10 REFERENCES

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11 BACKGROUND ON GEOMODEL SOLAR

Primary business of GeoModel Solar is in providing support to the site qualification, planning, financing and operation of solar energy systems. We are committed to increase efficiency and reliability of solar technology by expert consultancy and access to our databases and customer-oriented services.

The Company builds on 25 years of expertise in geoinformatics and environmental modelling, and 14 years in solar energy and photovoltaics. We strive for development and operation of new generation high-resolution quality-assessed global databases with focus on solar resource and energy-related weather parameters. We are developing simulation, management and control tools, map products, and services for fast access to high quality information needed for system planning, performance assessment, forecasting and management of distributed power generation.

Members of the team have long-term experience in R&D and are active in the activities of International Energy Agency, Solar Heating and Cooling Program, Task 46 Solar Resource Assessment and Forecasting.

GeoModel Solar operates a set of online services, integrated within SolarGIS® information system, which includes data, maps, software, and geoinformation services for solar energy.

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ISO 9001
LL-C (Certification)

GeoModel Solar is ISO 9001:2008 certified company for quality management.