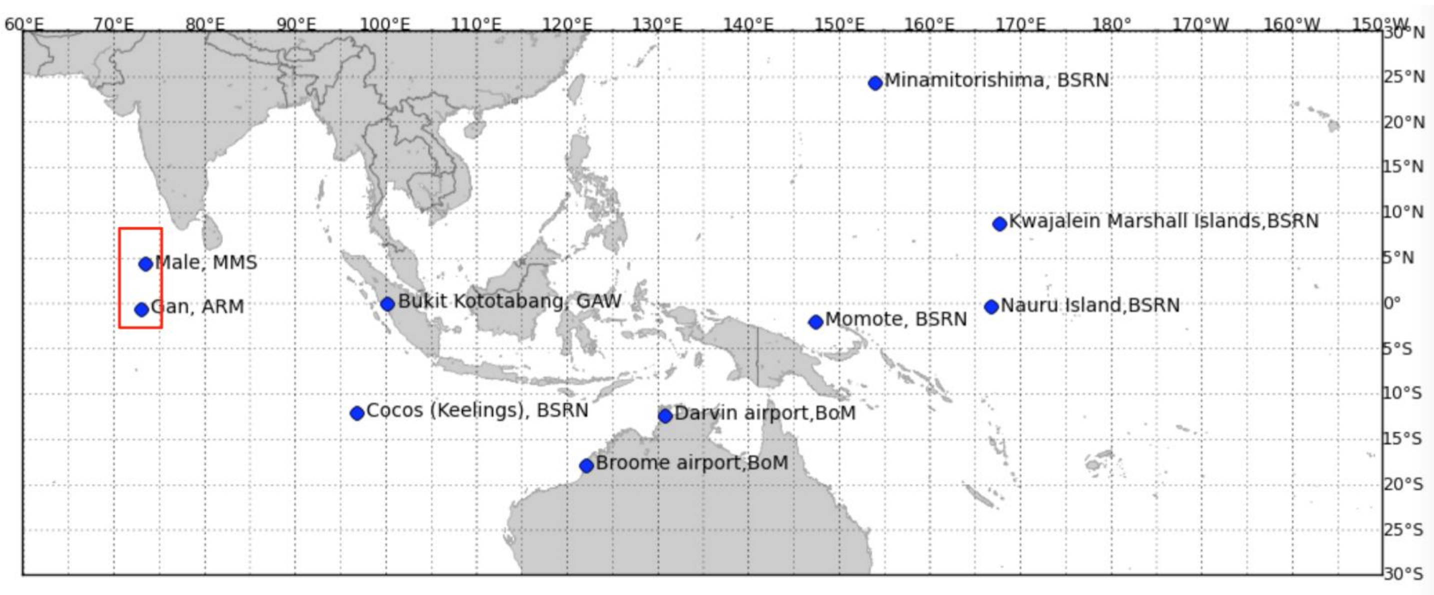
Solar Resource Mapping in the Maldives

MODEL VALIDATION REPORT

JANUARY 2015



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This document is an **interim output** from the above-mentioned project. 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 the Maldives Solar Atlas, which will be published once the project is completed.

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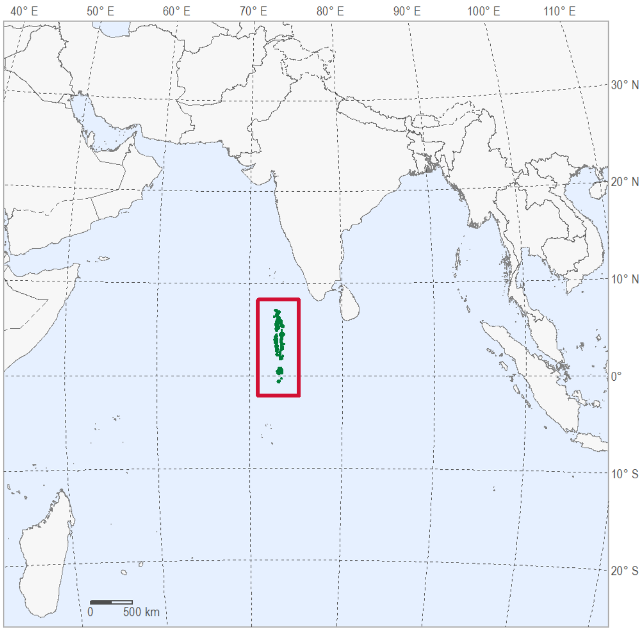

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ACRONYMS

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.
BoM	Bureau of Meteorology, national weather service in Australia
BSRN	Baseline Surface Radiation Network
CFSR/CFSv2	Climate Forecast System Reanalysis (CFSR) and its operational extension, the Climate Forecast System Version 2 (CFSv2), are global meteorological models operated by the US service NOAA.
CMSAF	Satellite Application Facility on Climate Monitoring (CMSAF) aims at the provision of satellite-derived geophysical parameter data sets suitable for climate monitoring. Several cloud parameters, surface albedo, radiation fluxes at the top of the atmosphere and at the surface as well as atmospheric temperature and humidity products form a sound basis for climate monitoring of the atmosphere are available.
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. The Centre provides operational medium- and extended-range global forecasts and a computing facility for scientific research.
GAW	Global Atmosphere Watch. It is a worldwide system established by the World Meteorological Organization to monitor trends in the Earth's atmosphere.
GDPS (GRIB2)	Global Deterministic Forecast System (GDPS, GRIB2) developed by the Meteorological Service of Canada (MSC). It contains data from analysis systems along with output from many of the Canadian Meteorological Centre's Numerical Weather Prediction (NWP) models. The data is free, under standard terms and conditions.
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)
MMS	Maldives Meteorological Service

Meteonorm	Meteonorm is a database with a monthly climate averages from meteorological stations around the world developed by Meteotest. This includes global radiation, temperature, humidity, precipitation, days with precipitation, wind speed and direction and sunshine duration. Data for any geographical location is calculate by spatial interpolation of values from the nearby meteorological stations.
Meteosat IODC	Meteosat satellite operated by EUMETSAT organization over Indian Ocean and Asia
NCDC	NOAA's National Climatic Data Center (NCDC) is responsible for preserving, monitoring, assessing, and providing public access to the climate and historical weather data and information. NCDC database contains mainly collection of data from the national networks belonging to World Meteorological Organization (WMO).
NOAA NCEP	National Oceanic and Atmospheric Administration, National Centre for Environmental Prediction.
PVGIS	Photovoltaic Geographical Information System developed by Joint Research Centre (JRC), the European Commission. Online free solar photovoltaic energy calculator for stand-alone or grid-connected PV systems. PVGIS works for Europe, Africa and Asia. Solar electricity generator simulation and solar radiations maps.
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.
KSI	Kolmogorov-Smirnoff index. It characterizes representativeness of distribution of high frequency (e.g. hourly) values.
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 3 km in Maldives), 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 presents results of preliminary validation of solar resource and meteorological modelled data, within Phase 1 of the project *Renewable Energy Resource Mapping for the Republic of the Maldives*. This part of the project focuses on solar resource mapping and measurement services as part of a technical assistance in the renewable energy development implemented by the World Bank in Maldives. It is being undertaken in close coordination with the Ministry of Environment and Energy (MEE) of Maldives, the World Bank's primary country counterpart for this project.

This project is funded by the *Energy Sector Management Assistance Program* (ESMAP) and *Asia Sustainable and Alternative Energy Program* (ASTAE), both administered by the World Bank and supported by bilateral donors.

Objective, data and methods

The objective of this report is to document validation of solar resources calculated by satellite-based model SolarGIS and validation of meteorological data derived from the numerical weather model CFSR and CFSv2.

Inventory in Chapter 3 identifies the existing data sources in the region: solar, aerosol and meteorological data. Aerosol data (more specifically Aerosol Optical Depth, AOD) from the MACC-II model is evaluated in Chapter 4, as this data is one of the inputs to SolarGIS clear-sky model. Chapter 5 shows relative comparison of SolarGIS GHI and DNI to other modelled databases. This chapter includes also the validation of SolarGIS in respect to solar resource measurements available in tropical climate of Asia. Chapter 6 shows validation of meteorological parameters that are delivered in the form of site-specific data sets and maps. Chapter 7 summarizes validation results in the interim estimate of uncertainty.

Results

Validation shows stable performance of SolarGIS model in the equatorial tropical region, though with higher uncertainty (compared to some other geographical regions). The SolarGIS uncertainty of the model can be reduced in Maldives, providing that high-quality solar resource measurements are available.

The modelling results are presented in the *Solar Modelling Report 129-01/2015.*

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 results.

Typically, bias is considered as the first indicator of the model accuracy. While knowing bias helps to understand a possible error of longer-term estimate, other accuracy indicators should be also considered for a complete understanding of the model performance. Mean Average Deviation (MAD) and Root Mean Square Deviation (RMSD) are important for estimating the accuracy of energy simulation and operational calculations (monitoring, forecasting). Kolmogorov Smirnoff Index (KSI) reveals issues in the model's ability to represent specific solar radiation conditions.

Focusing too much on bias (systematic deviation) may lead to incorrect judgement when comparing different satellite-based models. Even if bias is similar, other accuracy indicators (RMSD, MAD and KSI) may indicate substantial differences in performance of models.

Validation statistics for one site may not provide representative picture of the model performance in a 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. Ability of the model to estimate longterm values should be evaluated analysing two measures for a set of validation points [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 from ground measurements (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 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 Equatorial Asia. 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 − in geographic conditions comparable to those of Maldives − only few sources provide data with sufficient quality required for the model validation (Table 3.1).

Table 3.1: Sources of solar resource validation data

Network	Description
BSRN	Baseline Surface Radiation Network 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 measurements of Global Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance (DIF) and Direct Normal Irradiance (DNI). http://www.bsrn.awi.de/ http://www.bsrn.awi.de/en/data/data_retrieval_via_pangaea/
GAW	Global Atmospheric Watch Program of World Meteorological Organization focuses on better understanding of interactions between the atmosphere, the oceans and the biosphere. It provides solar radiation data for several locations globally. http://www.wmo.int/pages/prog/arep/gaw/gaw_home_en.html http://wrdc.mgo.rssi.ru/
BoM	Easy-available data are also from meteo stations that are part of national meteorological network operated by Bureau of Meteorology, Australia.
ARM	Atmospheric Radiation Measurement program established by U.S. Department of Energy collects data with the aim to improve understanding and representation, in models, of clouds and aerosols and their interactions and coupling with the Earth's surface. Part of the measurement campaign is acquisition data on solar radiation. Data usually include GHI, DIF and DNI measurements. http://www.arm.gov/
MMS	Maldives Meteorological Service provided sunshine hours data from the Campbell–Stokes recorder for Malé, Hulhulé airport for a period from January 2003 to December 2012. This data was used only for indicative comparison with SolarGIS DNI. http://www.meteorology.gov.mv/met/

Before using the ground-measurements for the model validation, they were quality controlled (Chapter 5.1). In general, measurements from networks such as BSRN, GAW, ARM and BoM have quality as they are based on top-accuracy measuring instruments and are well maintained. This allows using them for the model validation.

It is to be noted that sunshine recorder has lower accuracy and the data from MMS provides only indicative information when compared to SolarGIS.

List of public solar resource measuring stations, used for validation of SolarGIS model (Chapter 5.2) is summarized in Table 3.2. Their position is shown in Figure 3.1.

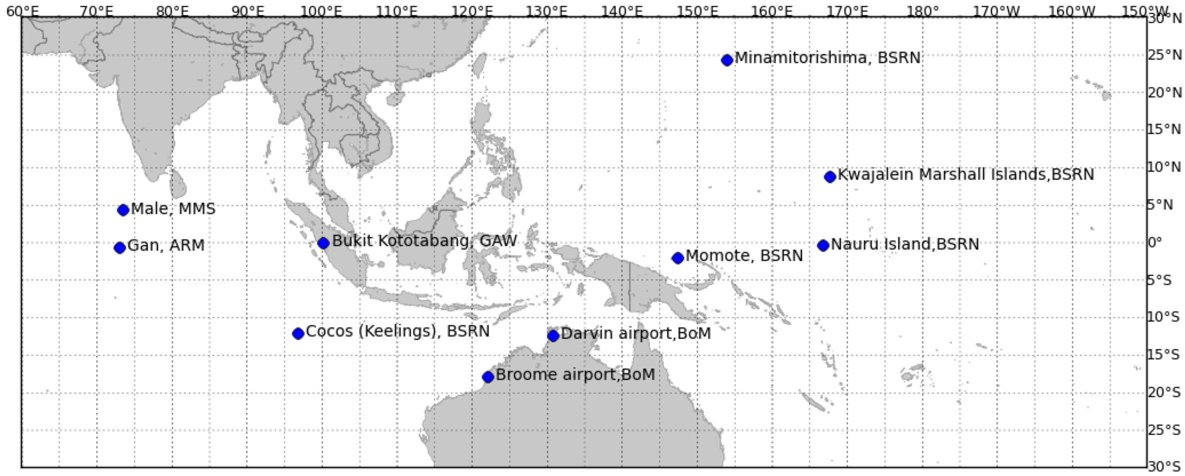

Figure 3.1: Position of sites, for which SolarGIS validation and data comparison was performed

Table 3.2: Solar measuring stations used for SolarGIS validation and data comparison

Site name	Country	Source	Latitude [°]	Longitude [°]	Altitude [m a.s.l.]	GHI	DNI	Period
Gan	Maldives	ARM	-0.69048	73.150048	3	YES	YES	09/2011 – 02/2012
Cocos (Keeling) Islands	(Australia)	BSRN	-12.189	96.8344	3	YES	YES	10/2004 – 12/2008
Momote	Papua New Guinea	BSRN	-2.058	147.425	6	YES	YES	01/2004 – 04/2012
Minamitorishima	Japan	BSRN	24.2883	153.9833	7	YES	YES	04/2010 – 11/2012
Kwajalein	Marshall Islands	BSRN	8.72	167.731	10	YES	YES	04/2007 – 02/2010
Nauru Island	Nauru	BSRN	-0.521	166.9167	7	YES	YES	01/2003 – 12/2008
Darvin airport	Australia	BoM	-12.4239	130.8925	30	YES	YES	01/1999 – 12/2010
Broome airport	Australia	BoM	-17.9475	122.2353	7	YES	YES	01/1999 – 06/2010
Bukit Kototabang	Indonesia	GAW	-0.2019	100.3181	864	YES	YES	01/2000 – 03/2012
*Malé**	*Maldives*	*MMS*	*4.1927*	*73.5281*	*1*	*Sunshine hours*		*01/2003 – 12/2012*

** Sunshine hours from Malé (Hulhulé airport) were used only for indicative comparison.*

Private initiatives

A number of solar measuring stations are deployed by companies active in solar energy project development 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 for Maldives (Table 3.3). In general, the databases based on the interpolation of ground-measured data, such as *Meteonorm* [3] are less reliable in regions with sparse spatial coverage of meteorological stations. The global database *NASA SSE* [4] is computed by empirical models from satellite and atmospheric data with very coarse spatial resolution, which results in coarse and regionally less reliable climate patterns. *SWERA/NREL* database has medium spatial resolution and is computed using *CSR* model by NREL [5, 20], 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 [6]. Implementation of these databases is static, and they are not updated regularly.

Table 3.3: Inventory of solar resource models for Maldives

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 CMSAF	MFG satellite	3 km x 3 km	GHI, DNI	Long-term monthly (hourly)	1999 – 2011
SWERA/NREL	Model	40 km x 40 km	GHI, DNI	Long-term monthly	1985 – 1991
SolarGIS*	MFG satellite	3 km x 3 km	GHI, DNI	30 minutes	1999 – 2015*

** SolarGIS database is continuously updated on daily basis*

Commercial satellite-based databases

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 differ significantly. 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 knowledge, for Maldives, besides SolarGIS, the following commercial databases are available: SOLEMI, 3TIER and IrSOLaV. 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. In general, the atmospheric turbidity is mostly influenced by aerosols in the form of burning biomass, soil particles, locally by human activities (industry, transport and urbanization) and particles transported from other regions.

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 model 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 tropical climate of islands, there are limited possibilities for detailed description of aerosol sources needed by chemical-transport atmospheric models,
- Arid and semiarid conditions make it difficult to use satellite measurements of aerosols,
- In general, dynamics of aerosols increases in a complex terrain (this is not a case of Maldives).

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 (does not apply in Maldives).

Understanding of nature of the modelled aerosol data helps to indirectly evaluate the satellite based SolarGIS model. For this purpose a raster data from aerosol model was compared to point aerosol measurements from AERONET [7]. It must be noted that comparison with AERONET sites is indicative only, but it helps to understand the correlation of point-measured data with a coarser resolution of the modelled data. Such comparison does not constitute fully independent verification of the MACC-II model outputs since the model itself uses this data on the input, as well as tend so f other data sources.

Figure 3.2 shows location of AERONET stations used for atmospheric data validation. Two stations are found in Maldives: Gan and Hanimaadhoo. Fit of aerosol data to ground measurements is important indirect indicator of performance of satellite-based model (for SolarGIS this is evaluated in Chapter 4.2).

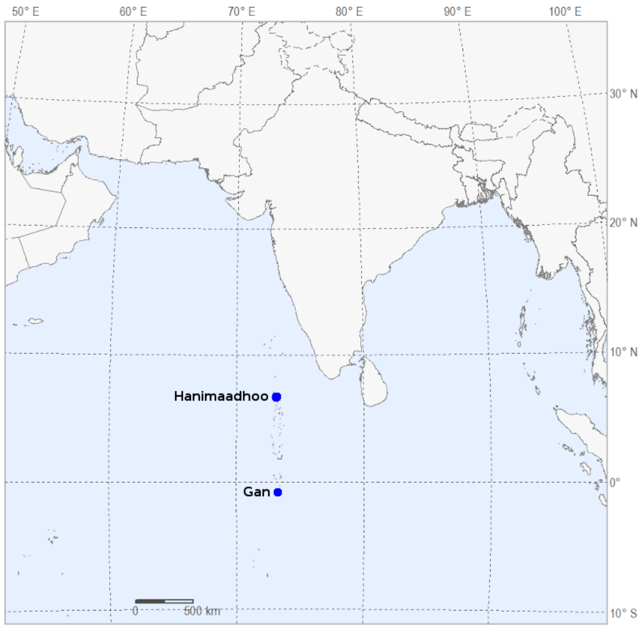

Figure 3.2: Position of two AERONET stations in Maldives

3.4 Meteorological measurements

The validation procedure was carried out by comparison of modelled data with ground-measured data at five sites operated, and kindly provided, by Maldives Meteorological Service (MMS). Also two other meteo sites with similar climate are evaluated (source National Climatic Data Center NCDC provided by NOAA). The position of all selected meteo sites is shown in Figure 3.3. Meteorological data for Malé (Hulhulé airport) station was provided both by MMS (period of 2 years) and also was found in the NCDC network (period of 6 years)

It must be noted that time period of data comparison for the MMS network is relatively short (Table 3.4). Comparison with two other meteo stations in the region is performed for a time period 2008 to 2010 (CFSR model) and for 2011 to 2013 (CFSv2 model) [8, 9].

Table 3.4: Meteo stations in the region considered for validation of CFSR and CFSv2 model outputs

Meteo station	Data source	Time period	Latitude* [°]	Longitude* [°]	Elevation* [m a.s.l.]
NSF Diego Garcia, BIOT	NOAA	01/2008 – 12/2013	-7.3133	72.4111	3
Cocos, Keeling Islands, AU	NOAA	01/2008 – 12/2013	-12.1830	96.8330	4
Malé, Hulhulé, MV	NOAA	01/2008 – 12/2013	4.1927	73.5280	0
Hanimaadhoo, MV	MMS	01/2007 – 12/2008	6.7463	73.1686	2
Malé, Hulhulé, MV	MMS	01/2007 – 12/2008	4.1927	73.5280	0
Kadhdhoo, MV	MMS	01/2007 – 12/2008	1.8583	73.5197	0
Kaadedhdhoo, MV	MMS	01/2007 – 12/2008	0.4883	72.9961	0
Gan, MV	MMS	01/2007 – 12/2008	-0.6905	73.1501	0

* Accurate geographical position and elevation of meteorological station may deviate slightly from the one in the table.

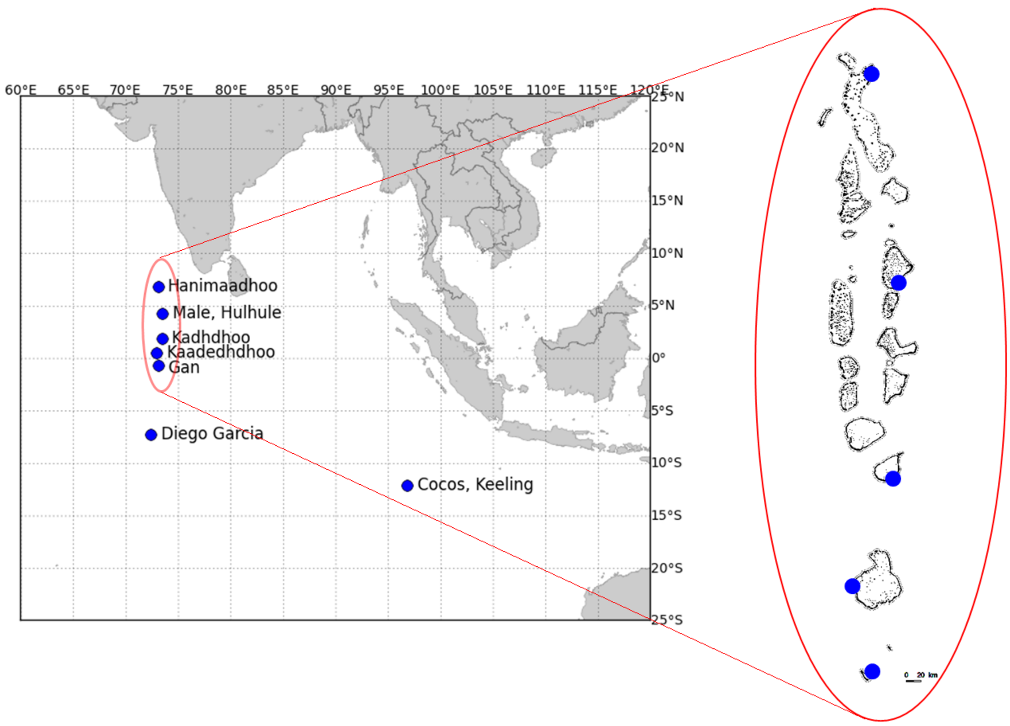

Figure 3.3: Position of meteorological *stations* considered for validation of CFSR and CFSv2 model outputs

3.5 Meteorological models

Table 3.5 gives an overview of selected modelled meteorological data available for the region. Chapter 4.2 in the *Solar Modelling Report 129-01/2015* 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 different purposes like weather forecasting, modelling long-term climate processes and helping to understand weather phenomena in a global scale.

Table 3.5: Some meteorological models available in the region

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

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 products they also ensure seasonal and long term stability, long history, almost 100% availability and they offer data from any location on the Earth. This makes them a good choice for preliminary solar energy simulations.

The Meteonorm database is also mentioned in Table 3.5. 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 Maldives, the meteorological parameters are derived from CFSR and CFS v2 models. *Water vapour* parameter - for solar resource model - is partially derived also from 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 especially in cloudless situations. Atmospheric aerosols represent a complex of 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.

Changing aerosol concentrations in the atmosphere can trigger variability of GHI in the range of 0% to 7%, occasionally up to 10%. In case of DNI, the variable aerosols can trigger day-by-day changes of DNI as much as 40% or even more. In solar modelling, aerosols are represented by the parameter called *Aerosol Optical Depth* (AOD).

4.1 Evaluation of MACC-II Aerosol Optical Depth data

MACC-II aerosol data [10, 11] are used in the SolarGIS model, and they provide good representation of temporal as well as spatial variability of atmospheric load by aerosols. Despite these qualities, the data may experience systematic deviation in some regions [12]. We evaluate MACC-II AOD data using measurements from two AERONET stations [7] located in Gan and Hanimaadhoo (Figure 3.2). Data for Gan is available only for few months, as the measurements were taken during a short scientific experiment. Figure 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 Gan and Hanimaadhoo shows good fit. Seasonal profiles as well as short (several days) extreme situations are well represented, but in situations with very low aerosol concentration a slight overestimation of MACC-II AOD is seen. On the other hand, for some of high concentration situations, the modelled AOD may be slightly underestimated. The discrepancy visible in the plot also arises from high frequency (15-min) site-specific AERONET values that create a natural mismatch when compared with daily summaries of regionally-smoothed MACC-II data.

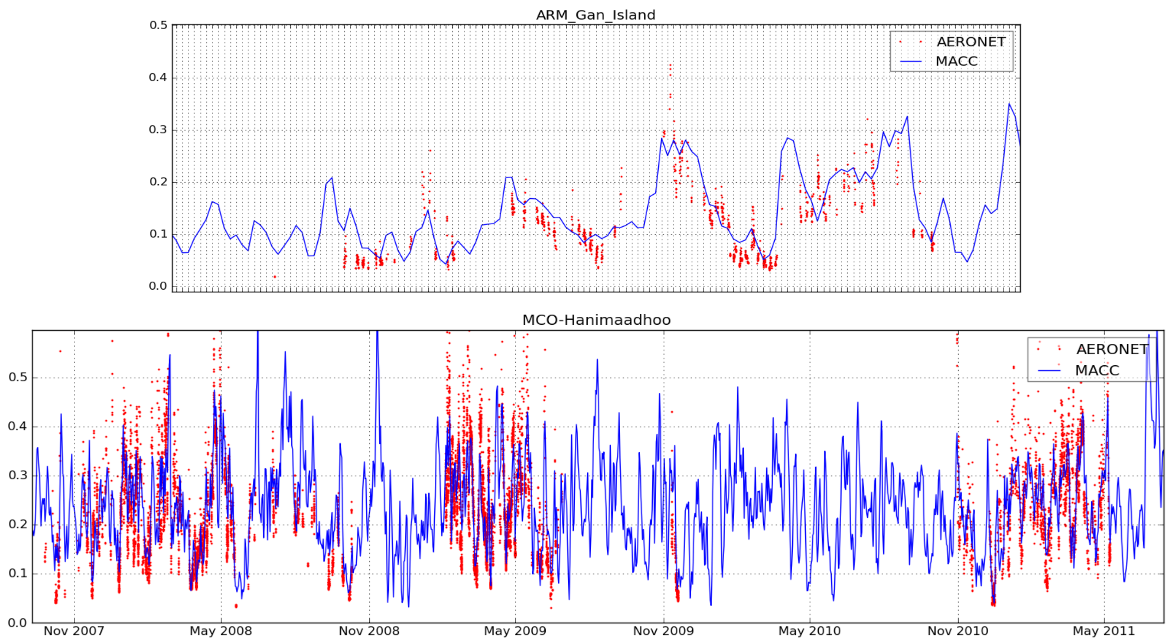

Figure 4.1: Comparison of daily summaries from MACC-II model with 15-min AERONET data.
ARM (Gan) and MCO (Hanimaadhoo) AERONET stations

Some discrepancies and spread of values in the data for both meteo stations are attributed to limited spatial and temporal resolution of the MACC-II database, which not capable to represent with sufficient accuracy higher-frequency changes of the specific local conditions recorded in the AERONET data.

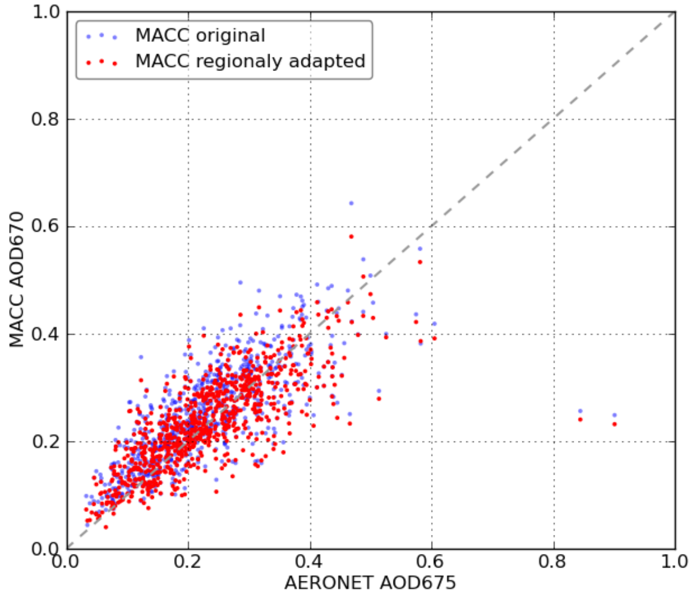

Figure 4.2: Comparison of Aerosol Optical Depth for Hanimaadhoo
AERONET 675 nm (x-axis) and MACC 670 nm (y-axis); blue points: original MACC data;
red points: MACC data regionally-adapted by SolarGIS method

To understand potential issues related to AOD in this region, the MACC-II data for the Malé site were compared with AOD data computed from other satellite missions: Terra MODIS, Aqua MODIS, Terra MISR, Envisat MERIS [13, 14]. While MACC-II model provides systematically daily values, values from satellite databases (MODIS, MERIS, TERRA MISR) have irregular time resolution, determined by the availability of cloudless days (Figure 4.3). All compared databases show the same pattern with relatively stable aerosols over the whole period. Although the range of values in different databases is similar, some differences in high values can be identified.

Limited number of available ground-measured data does not allow in-depth evaluation of the accuracy of the aerosol data. Moreover, the measurements from Gan were available only for a very short period, thus this site gives only limited information. In general, analysis of available AOD data shows good representativeness of the MACC-II database. Small discrepancies could be observed and may be reduced in Phase 2 of this project, by use of high resolution and high quality local solar measurements.

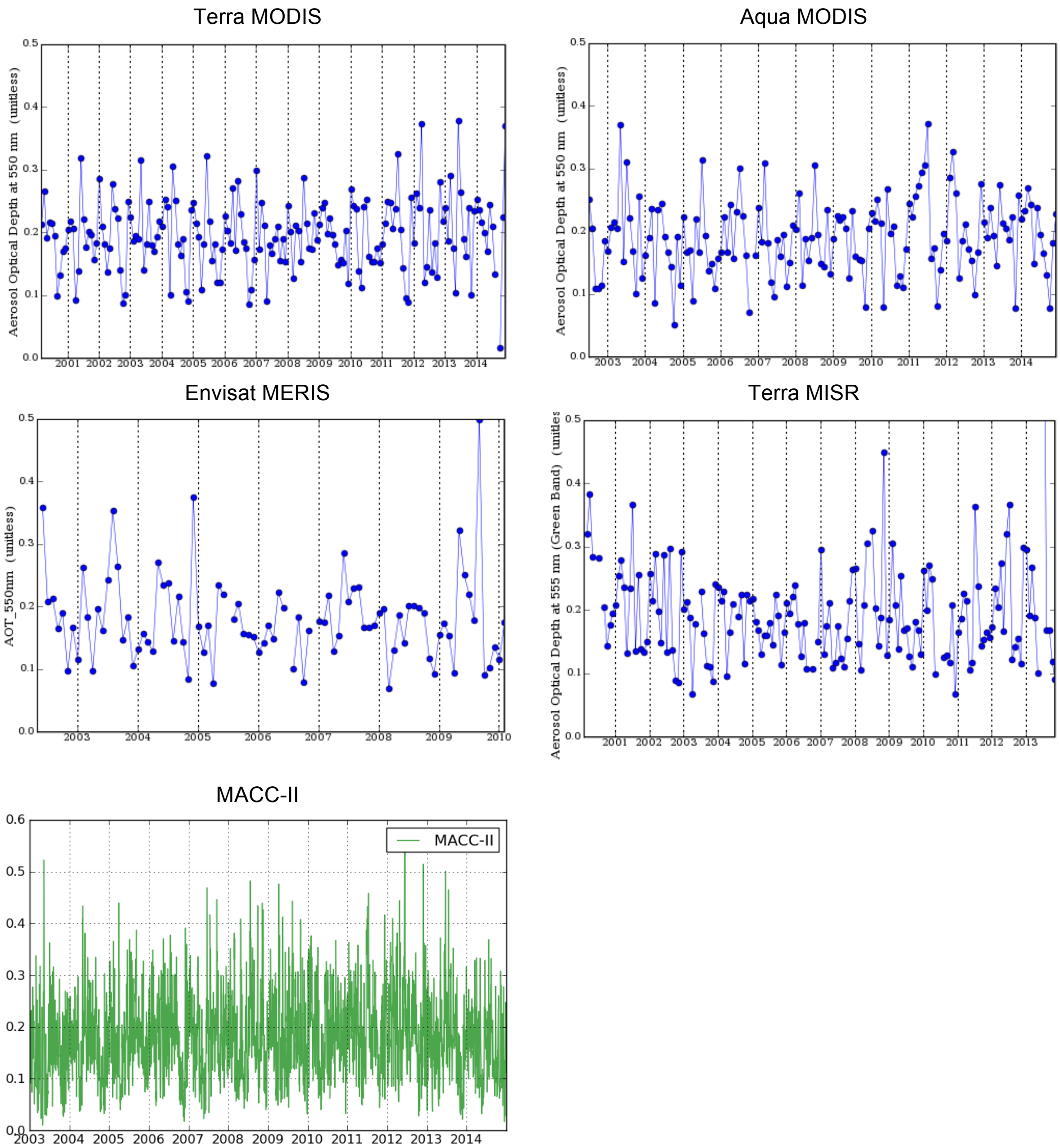

Figure 4.3: Aerosol Optical Depth for Malé from five different AOD databases
Plots of satellite-based data were produced with by Giovanni online data system, NASA Langley ASCD [15]

4.2 Seasonal variability of Aerosol Optical Depth

SolarGIS uses AOD input data, derived from the MACC-II model, for the wavelength 670 nm. The MACC-II model captures high temporal variability of aerosols, thus it reduces uncertainty of instantaneous GHI and DNI estimates. Figure 4.4 shows typical monthly variability of aerosols in central and Northern Indian Ocean. Maldives are located in a central zone with more stable and relatively low aerosol load. Northern Islands may be influenced by increased aerosol load in a period from June to September. The lowest aerosol load in the atmosphere can be observed from December to February. Islands close to the equator have lower seasonal variability. From the global perspective, Maldives is a region with relatively low aerosol load (Figure 4.5), but still having influence on the dynamics of solar resource, especially DNI.

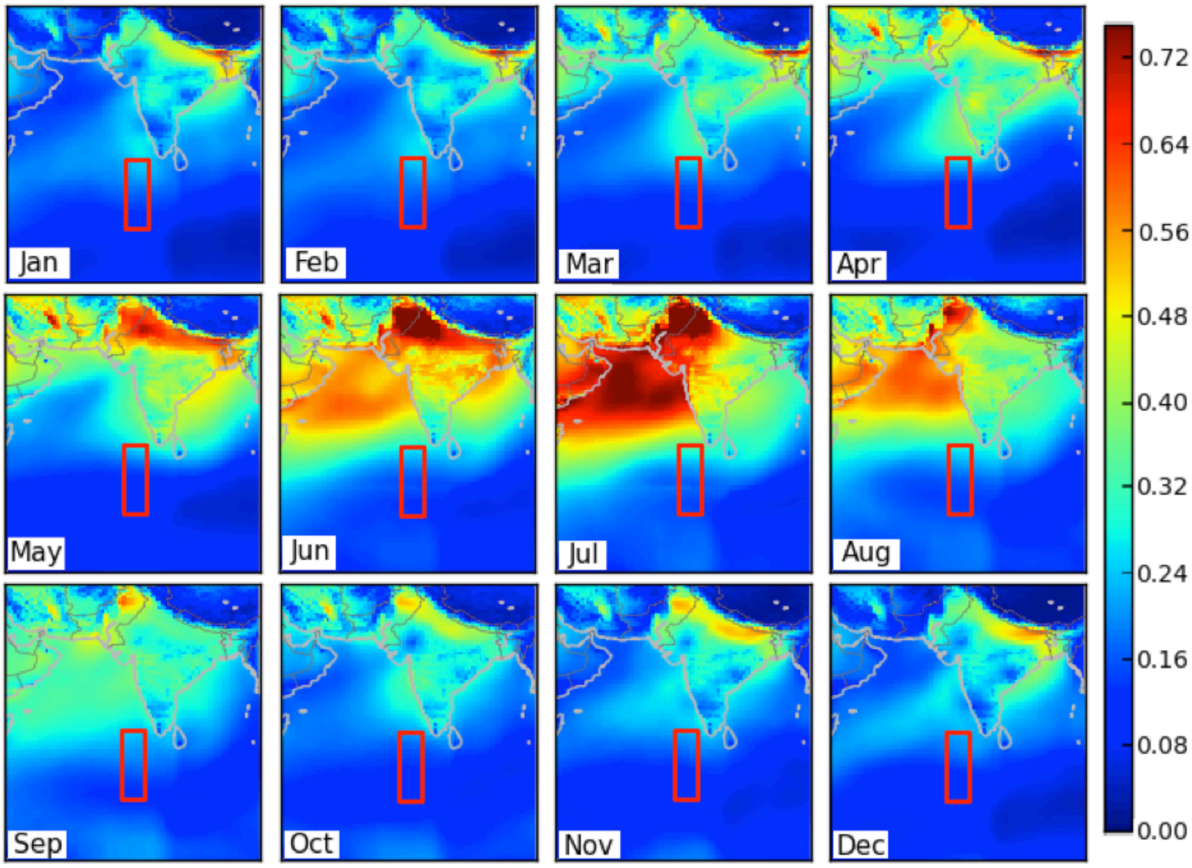

Figure 4.4: Monthly-averaged aerosol maps (AOD 670) derived from the MACC-II database and adapted for the SolarGIS model. Period 2003 to 2013

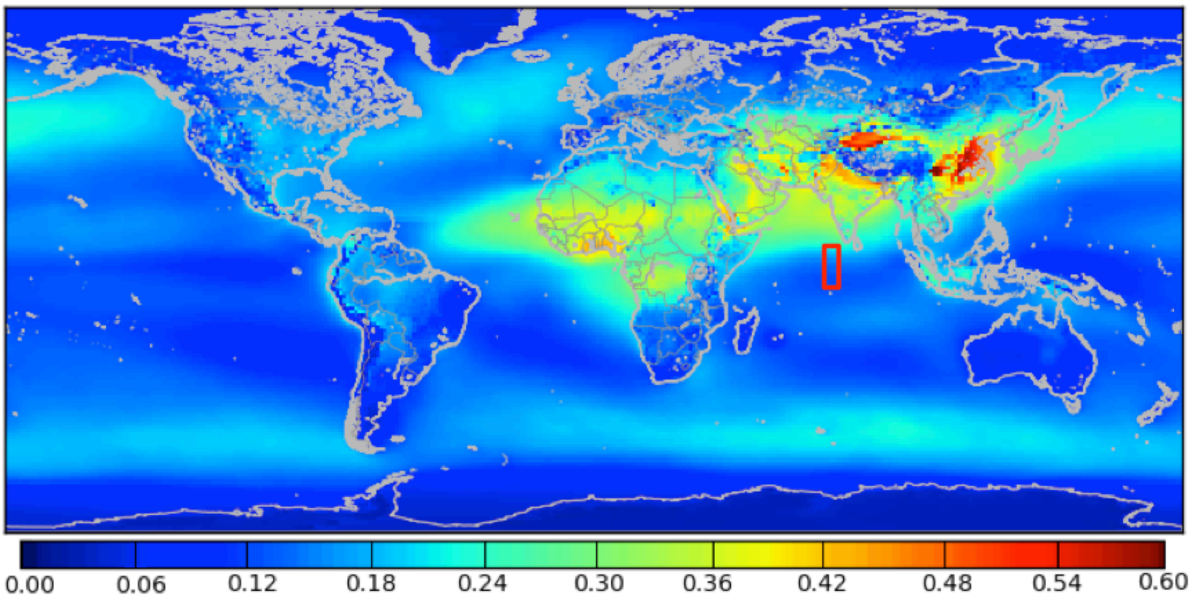

Figure 4.5: Average annual aerosols − Maldives in the global context
AOD 670 nm is computed by the MACC-II model and adapted for SolarGIS.
Period 2003 to 2012. Values are dimensionless.

5 VALIDATION OF SOLAR RESOURCE DATA

5.1 Quality control of solar validation data

5.1.1 Measurements by high accuracy solar sensors

Prior to comparison with satellite-based solar resource data, the ground-measured solar irradiance was quality-controlled by GeoModel Solar. Quality control (QC) was based on methods defined in SERI QC procedures and Younes et al. [16, 17] and also by the GeoModel Solar's in-house developed tests. The ground measurements were inspected also visually, mainly for identification of shading and other regular data error patterns.

As an example, Figure 5.1 shows results of QC in two stations: Cocos (Keeling) Islands and Gan (Maldives). The colours indicate the following flags:

- 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
- Dark grey: other issue.

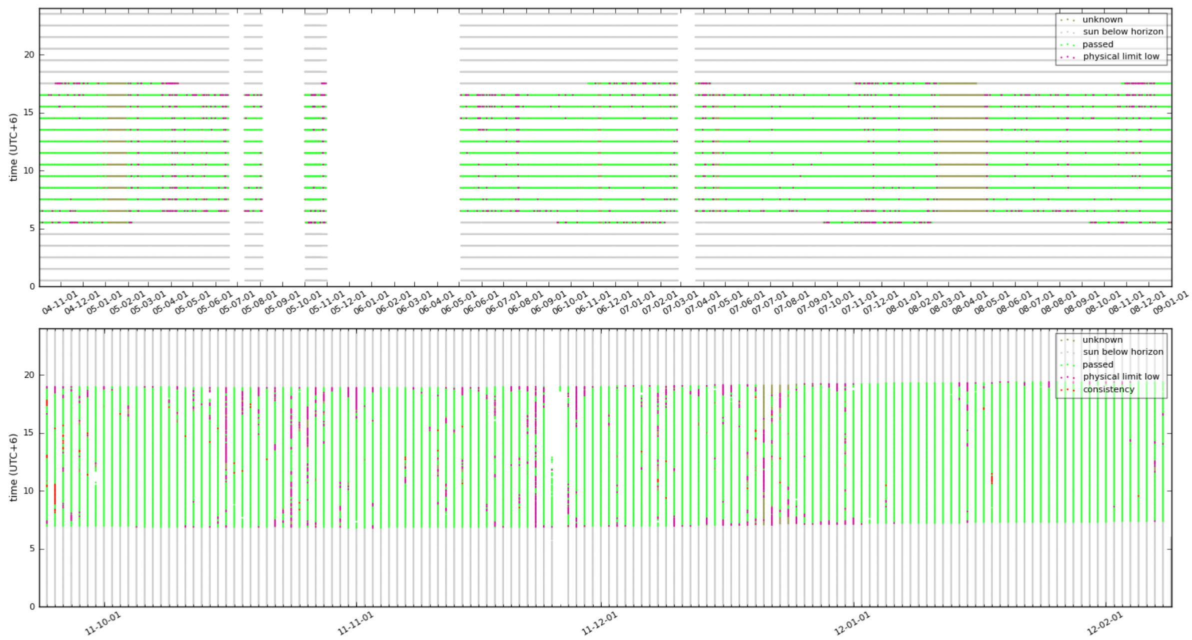

Figure 5.1: Quality control of data measured at Cocos Islands (top) and Gan (bottom) stations
X-axis: date of measurement, Y-axis: time of measurements; colour – various QC flags (read above).

Figure 5.1 shows slightly increased occurrence of issues: for short periods we have identified an inconsistency between GHI, DNI and DIF component (red colour) and measurements outside of physical limits. Data from Cocos Islands contain several periods with gaps; in the Gan station the missing data were identified only for a very short period.

Quality control shows that solar radiation data is often affected by disturbances, which result in various errors. Among typical errors there are missing values, short periods of values with inconsistency between the solar components or values can be out of physical limits. In many stations, also shading from surrounding terrain or objects is observed. These errors were identified, to a various extent, in the data from all solar measuring stations.

Availability of measurements for all three components (GHI, DNI and DIF) allows performing more complex consistency test, which reveals issues in data (such as incorrect sun tracking) that would otherwise remain hidden in the data. Very important is also visual control of the data that helps identifying systematic issues such shading, reflections or miscalibration of instruments.

Quality-control procedures pre-qualified data for the model: the data readings with identified issues were flagged and excluded from further analyses. Table 5.1 summarizes percentage of excluded data by QC tests.

Table 5.1: Data that did not pass through quality control [%]

	Type of test (numbers show percent of total volume of data, assuming 24-hour cycle)				
	Sun below horizon	Test for physical limits	Visual test/other	Consistency test (GHI – DNI – DIF)	Total excluded data samples
Gan	*49.8*	2.9	0.0	0.2	3.1
Cocos (Keeling) Islands	*50.4*	3.4	6.3	0.0	9.7
Momote	*49.4*	8.1	1.2	0.6	9.9
Minamitorishima	*49.1*	7.0	0.1	0.2	7.3
Kwajalein	*49.7*	5.1	0.0	0.0	5.1
Nauru Island	*49.5*	4.1	0.0	2.3	6.4
Darvin airport	*49.8*	3.7	4.2	0.0	7.9
Broome airport	*50.1*	2.6	3.3	0.0	5.9
Bukit Kototabang	*50.0*	11.1	8.5	0.0	19.6

Based on our experience from validating a large number of ground-measured data, here we propose some recommendations to consider during the Phase 2 measuring campaign:

- Data to be used for the model validation must come from high accuracy instruments; technical description of instruments and information on their calibration status must be available. The equipment must be maintained and frequent cleaning of sensors must be applied.
- Use of just one or two sensors (GHI, DNI), without redundant (DIF) measurements does not allow applying (very valuable) redundancy quality control algorithms.
- Solar trackers and instruments should be preferably mounted about 1 m to 1.5 m above ground or roof on a stable concrete or metal platform.
- Data cleaning should be systematic and logged.
- Data should be quality checked on a continuous basis. Some types of logger have software which can automatically pre-flag errors. Data should be provided for processing with flags for above-mentioned problems, to avoid mistaken use of erroneous data.
- Regular scheduled visits on the station every few months could prevent common issues such a tracker misalignment and issues with sensor levelling, with PV power supply or battery.

At this stage of the project accurate long term solar measurements were not available for Maldives, except few months of measurements from the ARM network operating at Gan Island. There is a possibility of having access to solar radiation data measured at the Atmospheric Observatory in Hanimaadhoo Island, if successfully negotiated.

5.1.2 Measurements by Campbell-Stokes recorder

Maldives Meteorological Service provided data from the Campbell–Stokes recorder. We analysed measurements for Malé, Hulhulé airport for a period of 10 complete years (January 2003 to December 2012).

This type of instrument consists of a clear glass sphere that focuses the sun rays onto a strip chart, producing a charred path when there is bright sunshine (Figure 5.2). Data from the sunshine recorder have its limitations, but it is worldwide acceptance as a device for measuring sunshine duration. The installations started in year 1882 and the monitoring lasts till 21st century, ensuring a long record of heliographic data. In 1962, the Campbell-Stokes sunshine recorder was adopted by the World Meteorological Organization (WMO) as the Interim Reference Sunshine. The length of the path determines the bright sunshine duration. The lower limit for bright sunshine (based on a Campbell-Stokes recorder) is between 70 W/m^2 (very dry air) and 280 W/m^2 (very humid air). In 2003, the WMO established its threshold value at 120 W/m^2 and therefore, this value has been set as the sensitivity threshold in electronic sensors.

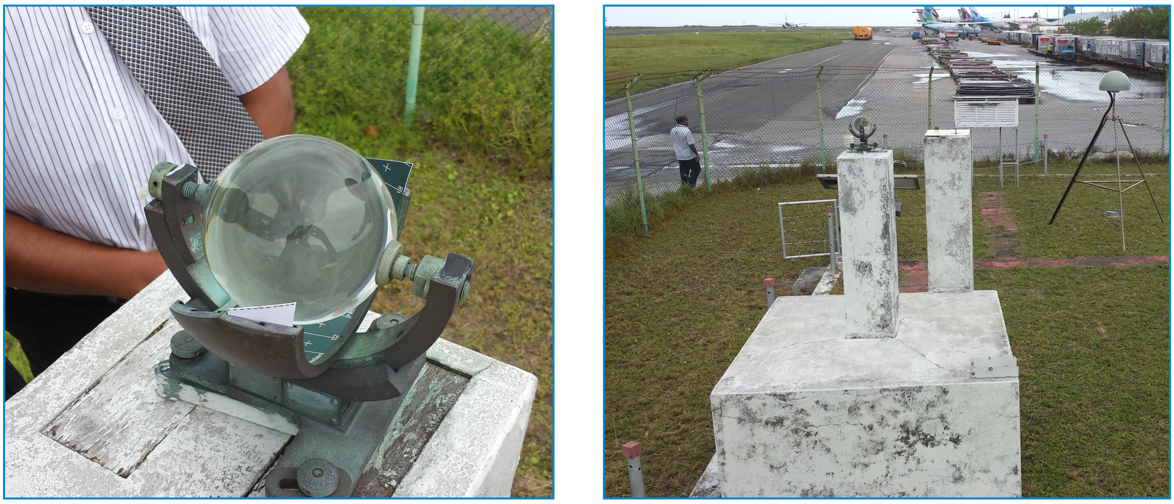

Figure 5.2: Campbell–Stokes recorder mounted at the meteo station at Malé, Hulhulé airport

Climate in Maldives is tropical equatorial with high humidity (the wet season experiencing humidity levels of above 80% on average and the dryer months still as high as 75%) what has an impact on the performance of Campbell–Stokes, namely threshold value of direct irradiation (effective radiation) at which sun rays start to produce path on the paper stripe. This type of device is also very sensitive to precipitation and obtained results are often subjective (depends greatly on to the person analysing the data).

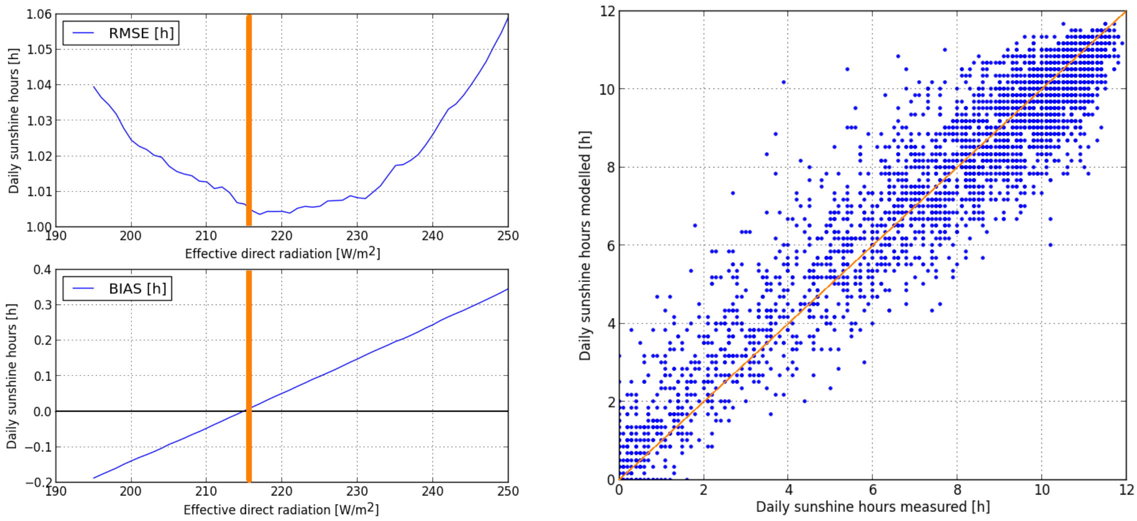

Figure 5.3: Comparison of measured and modelled daily sunshine hours.
Modelled data is based on processed SolarGIS Direct Normal Irradiation with 6-minute time step data (Right) and dependence of fit accuracy on the threshold value (Left).

To compare the measurement by Campbell–Stokes with SolarGIS satellite-based data, the SolarGIS Direct Normal Irradiation for Hulhulé airport has been generated with 6-minute time step by time interpolation of the original 30-minute data (to match the temporal resolution of the provided local measurements). To calculate sunshine hours from SolarGIS DNI the variable threshold was applied ranging from 190 to 250 W/m^2 (Figure 5.3 Left).

It was found that the best match (Bias close to 0h and RMSE close to 1h) occurs for the DNI value of 215 to 217 W/m^2. For that DNI value the match between measured and modelled data is very satisfactory (Figure 5.3 Right).

5.2 Validation of solar resource model

5.2.1 Comparison of SolarGIS to other models

Solar irradiance for Maldives is calculated by the SolarGIS model (Chapter 3.2 of the *Solar Modelling Report 128-01/2015*). In this Chapter, the annual SolarGIS average is compared to five other data sources with different temporal and spatial resolution and different time coverage (Table 3.4). Six representative sites are used, as described in Chapter 6.1 of the *Solar Modelling Report 128-01/2014*). Comparison of the databases shows discrepancies (Tables 5.2 and 5.3), which are determined by their different characteristics:

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

Table 5.2: Comparison of SolarGIS long-term yearly GHI average with four different models

Database	Global Horizontal Irradiation [kWh/m^2]			
	Gan	Hanimaadhoo	Hulhulé	Kadhdhoo
NASA SSE	2129	2118	2129	2126
Meteonorm 7	1866	1922	1824	1828
PVGIS CMSAF	1855	2137	2137	2151
NREL	1918	1918	1918	1918
SolarGIS	2065	2040	2059	2062
Standard deviation of GHI annual values	6.3%	5.1%	6.8%	6.9%
Schematic assessment of GHI uncertainty (80% confidence)	8.0%	6.6%	8.8%	8.8%
Expected SolarGIS uncertainty (80% confidence)	**6.0%**	**6.0%**	**6.0%**	**6.0%**

Table 5.3: Comparison of SolarGIS long-term yearly DNI averages with four different models

Database	Direct Normal Irradiation [kWh/m^2]			
	Gan	Hanimaadhoo	Hulhulé	Kadhdhoo
NASA SSE	2111	2126	2126	2104
Meteonorm 7	1405	1429	1264	1338
PVGIS CMSAF	1596	1986	2002	2060
NREL	1734	1734	1734	1734
SolarGIS	1718	1541	1635	1691
Standard deviation of DNI annual values	15.1%	16.6%	19.2%	17.5%
Schematic assessment of DNI uncertainty (80% confidence)	19.3%	21.3%	24.7%	22.4%
Expected SolarGIS uncertainty (80% confidence)	**12.0%**	**12.0%**	**12.0%**	**12.0%**

In general, higher uncertainties may have be expected when comparing data representing different decades due to changes in air pollution and complex climate cycles. In addition, ground observations from the last decades may have been measured with intoruments of lower accuracy and less-stringent measuring standards.

Tables 5.2 and 5.3 show dispersion of yearly GHI and DNI values between five different databases, including SolarGIS. This approach is a schematic way how to assess the solar resource uncertainty. Important is to understand the risk of possible great dispersion of the estimates. For comparison we indicate a conservative uncertainty estimate for SolarGIS (more in Chapters 5.2.3 and 7.1).

The modern satellite-based databases, such as SolarGIS, have high spatial and temporal resolution, they are systematically updated and quality controlled. Modern satellite-based computing approaches are considered as the mainstream source of solar resource information for energy applications - for prefeasibility studies, project optimisation, financing, and for operation and management of solar power plants. In this context, **high quality ground measurements play critical role for validation and adaptation of the satellite-based models.** Therefore installing solar measuring stations is planned for Phase 2 of this project.

Based on the analysis of sites from Europe, North Africa and Middle East, two intercomparison studies by Pierre Ineichen from University of Geneva [1, 2] provide independent analysis of accuracy of commercial satellite-based models. SolarGIS is compared to other databases, three of them available also for Maldives: 3Tier, SOLEMI and IrSOLaV.

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

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

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

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

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

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

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

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

Tables 5.4 to 5.7, show selected information from both studies, and confirm 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 various problems: e.g. high bias can exist in individual sites, but it may compensate when averaged in the final figure. From the 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.

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

Compared to high-quality ground measurements (Tables 5.8 and 5.9) that passed through quality control (Chapter 5.1), the SolarGIS model slightly overestimates DNI in equatorial tropics and the GHI bias is oscillating around zero. At the level of individual sites, bias of the model values (systematic deviation) is found in a narrow range (typically within ±11% for yearly DNI and ±5% for yearly GHI), thus it correspond to the expected uncertainty of the SolarGIS model [18]. Slightly higher bias in Nauru Island may be result inaccurate representation of specific local microclimate by the SolarGIS model data or may indicate also problems with ground measurements. Lower values of the KSI indicator show better match of hourly cumulative distribution of values.

The validation results from the Gan Island show good fit of the model to ground measurements. However, because of only short period of measurements available (approx. 5 months) the results should be considered as indicative. The data may not be representative enough to cover all seasons with diverse weather and solar irradiance patterns.

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

Table 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]	[%]	[%]	[%]	[%]	[-]	
Gan	3	0.5	17.6	7.5	2.6	27	1513
Cocos (Keeling) Islands	-22	-4.8	23.4	13.3	5.7	160	19924
Momote	-12	-2.6	25.3	11.7	3.7	146	19600
Minamitorishima	-1	-0.2	14.2	6.8	1.4	22	10155
Kwajalein	0	0.0	17.7	8.8	1.5	23	8842
Nauru Island	22	4.2	17.9	9.7	4.8	98	7204
Darvin airport	11	2.2	18.6	8.6	3.0	76	11768
Broome airport	-2	-0.3	11.8	5.8	1.9	22	12207
Bukit Kototabang	-1	-0.1	31.0	14.2	2.5	122	20648

Table 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		
	[Wh/m^2]	[%]	[%]	[%]	[%]	[-]	
Gan	11	2.7	36.2	19.3	5.1	92	1497
Cocos (Keeling) Islands	-15	-3.6	45.2	24.1	6.8	156	17055
Momote	12	3.3	48.7	22.9	6.3	180	18248
Minamitorishima	-2	-0.4	27.2	13.4	2.0	113	9458
Kwajalein	-3	-0.8	33.5	16.5	3.1	87	8628
Nauru Island	53	11.1	36.4	21.0	11.8	228	7082
Darvin airport	15	3.0	29.9	15.2	3.9	105	10968
Broome airport	14	2.2	21.3	12.9	4.9	152	11646
Bukit Kototabang	11	5.1	69.2	39.0	6.3	163	14275

Further information about the data and methodology and detailed analysis of uncertainty can be consulted in [18, 19]. Comparison of validation statistics computed for solar meteo sites in equatorial tropics 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

Validation was carried out by comparison of meteorological-model data with ground-measured data for five meteorological stations provided by Maldives Meteorological Services (MMS), and three meteorological stations found in the NOAA NCDC network.

Comparison with the model data is performed for a time period 2008 to 2010 (CFSR model) and for 2011 to 2013 (CFSv2 model). The time period for MMS network covers 2 years only (period 2007 to 2008). For details on the applied model please refer to Chapter 4.2 in *Solar Modelling Report 129-01/2015.* Position of the meteorological stations is shown in Table 3.5 and Figure 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 (Table 6.1). The model data represent larger area that is why they are smoothed and in the case of Maldives it represents air temperature over the surface of an open sea. Therefore the hourly model data is not capable representing exact values of the local microclimate (as measured at a meteorological station). The modelled daily and monthly averages are very close to the measured ones (mean bias), but the hourly variability (amplitude day-time vs. night-time) of the modelled data does not match the hourly variability recorded by the ground measurements. This can be observed in the table as large bias of maximum and minimum diurnal temperature (bias min and max). Parameters bias min and max are calculated as difference between average values of minimum and maximum diurnal temperature respectively. The same effect is visible for other islands (Diego Garcia and Cocos Islands). It was also found that temperature data for Hanimaadhoo station for 2007 is not consistent with 2008 data, and that is why statistics for both years are presented separately.

Figure 6.1 represents data for the Hulhulé airport. It shows that while the amplitude of the measured data is huge (up to 10ºC) the amplitude of modelled data is significantly compressed (up to 4ºC). It is impossible for coarse meteorological model to represent daily variability in Maldives. The reason is that while meteo station monitors air temperature over the nearby land surface, the grid cell of the models by large majority captures air temperature over the ocean.

Table 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
Diego Garcia	0.0	1.4	-1.7	1.2	0.6	0.2	0.0	1.4	-1.7	1.3	0.6	0.0
Malé, Hulhulé	-0.8	0.6	-2.3	1.5	1.0	0.8	-1.0	0.4	-2.6	1.6	1.1	-1.0
Cocos Islands	0.5	2.1	-2.5	2.1	1.2	0.8	0.4	1.9	-2.1	2.0	1.2	0.4
Hanimaadhoo[1]	3.6	4.2	3.0	3.7	3.6	3.6	-	-	-	-	-	-
Hanimaadhoo[2]	-0.1	1.6	-2.0	1.7	0.6	0.2	-	-	-	-	-	-
Malé, Hulhulé	-0.6	0.8	-2.3	1.5	0.9	0.6	-	-	-	-	-	-
Kadhdhoo	-0.3	1.5	-2.2	1.7	0.7	0.4	-	-	-	-	-	-
Kaadedhdhoo	-0.5	1.6	-2.2	1.9	0.9	0.6	-	-	-	-	-	-
Gan	-0.1	1.7	-2.0	1.7	0.7	0.2	-	-	-	-	-	-

* Time period for MMS network is shown in Table 3.5
[1] Measurements for the year 2007
[2] Measurements for the year 2008

Bias is expressed as a difference between the modelled and measured average values. Even that bias is low, the distribution of hourly values shows mismatch, which is determined by the low spatial resolution of the weather model. The model is not capable to describe the daily amplitude of air temperature at the islands (small piece of land in a large mass of ocean. On the other hand, the daily amplitude in the islands is relatively low.

Bias min and bias max show average systematic deviation of minimum daily values (typically early morning) and maximum daily values (typically early afternoon). The same applies for the RH, WS and WD parameters discussed in Chapters below.

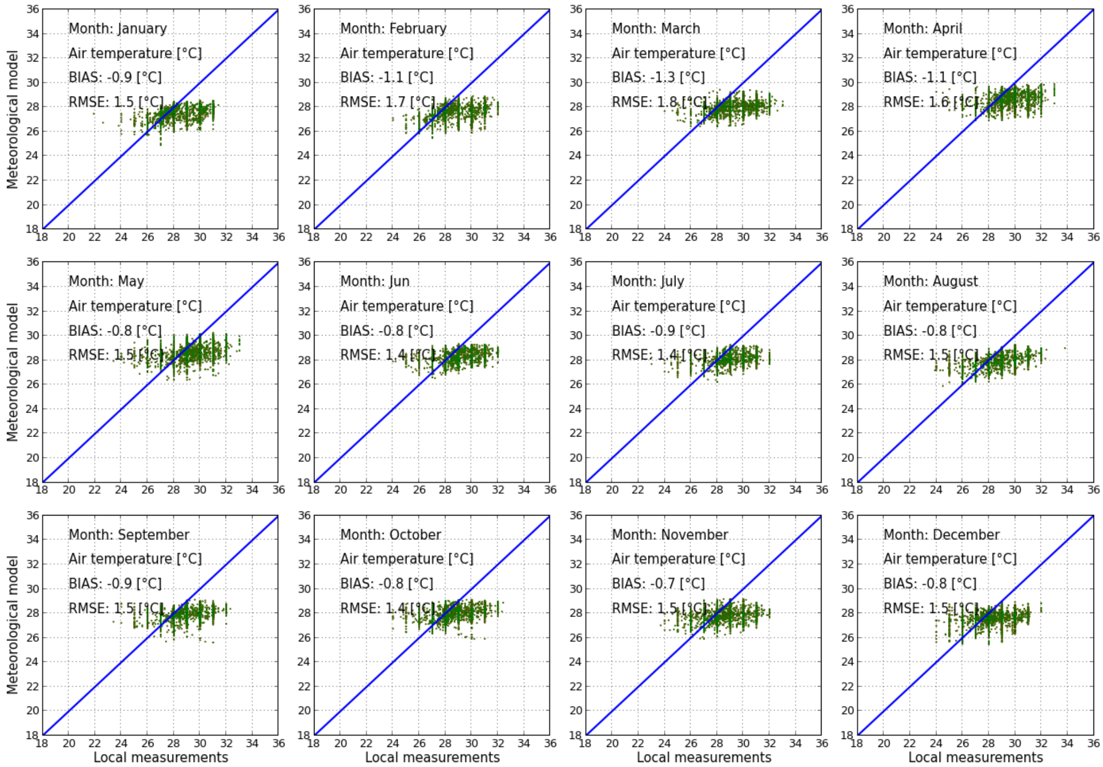

Figure 6.1: Scatterplots of air temperature at 2 m at Hulhulé airport.
Measured values (horizontal axis) and meteorological model values (vertical axis)

6.3 Relative humidity

Modelled relative humidity 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 when compared to meteorological measurements. The validation results are summarized in Table 6.2. Similarly to the case of air temperature, relative humidity exhibits good match in terms of daily and monthly averages, however the diurnal variations are not represented well by hourly model data. Figure 6.2 shows the data for the Hulhulé airport. The amplitude of diurnal changes is significantly lower in comparison to the measured data.

Table 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
Diego Garcia	-8	1	-14	11	10	8	-10	0	-16	15	13	10
Malé, Hulhulé	-4	3	-11	8	6	4	-4	2	-11	8	6	4
Cocos Islands	-2	6	-10	7	5	2	-3	4	-11	8	5	4
Hanimaadhoo	-6	2	-14	10	7	-6	-	-	-	-	-	-
Malé, Hulhulé	-6	1	-12	9	7	-6	-	-	-	-	-	-
Kadhdhoo	-5	2	-13	9	6	-5	-	-	-	-	-	-
Kaadedhdhoo	-5	1	-13	9	7	-5	-	-	-	-	-	-
Gan	-7	1	-14	10	8	-7	-	-	-	-	-	-

* Time period for MMS network is shown in Table 3.5

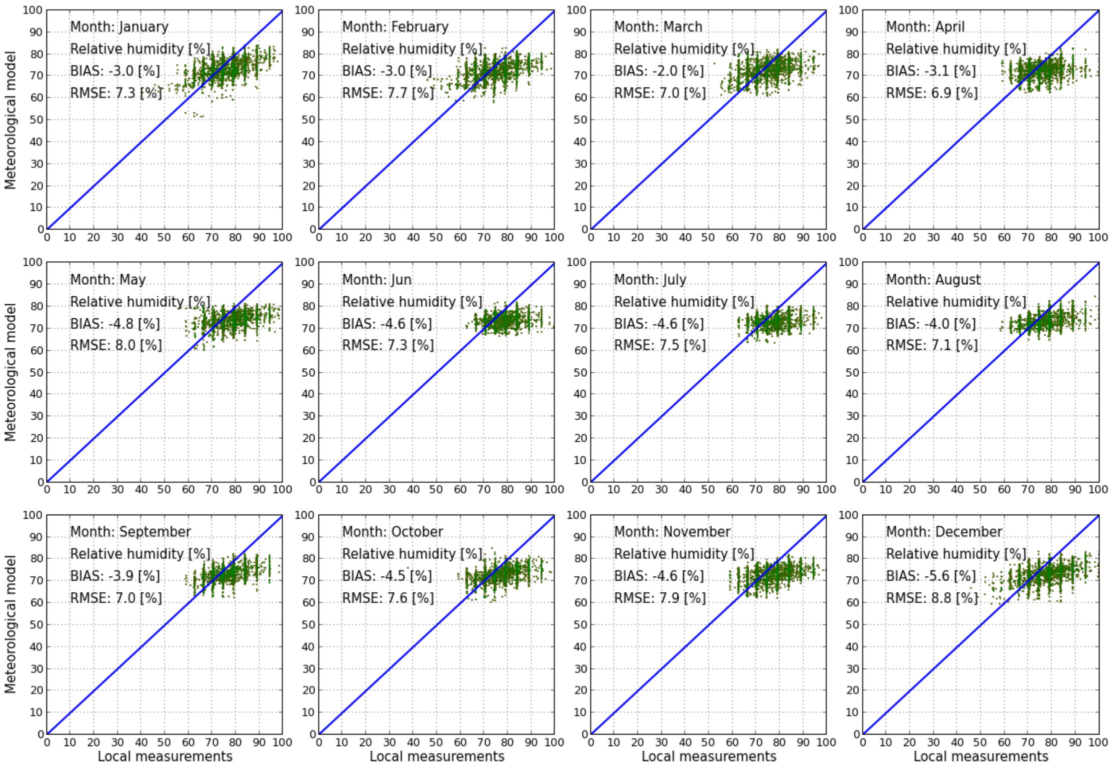

Figure 6.2: Scatterplots of relative humidity at 2 m at Hulhulé airport.
Measured values (horizontal axis) and meteorological model values (vertical axis)

6.4 Wind speed

Wind speed is calculated from the CFSR and CFSv2 models, from 10-metre wind u- and v- components with the original 1-hourly time step resolution. Comparison of the model wind speed with on-site ground measurements is summarized in Table 6.3 and Figure 6.5. The model represents regional values for 10 m height. Figure 6.3 compares wind speed from the CFSR and CFSv2 models with the measurements. Wind direction and wind speed are strongly determined by local microclimate. Maldives are flat, that is why the modelled wind speed and wind direction fit quite well the measured values.

Table 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
Diego Garcia	1.3	2.3	0.2	2.1	1.6	1.3	1.0	2.0	-0.1	1.9	1.4	1.1
Malé, Hulhulé	0.4	1.1	-0.6	1.6	1.1	0.6	0.3	1.1	-0.7	1.5	1.0	0.3
Cocos Islands	0.6	1.2	-0.4	2.9	2.4	1.1	0.0	0.9	-1.2	2.5	2.1	0.8
Hanimaadhoo	1.1	1.6	-0.8	2.9	2.4	1.6	-	-	-	-	-	-
Malé, Hulhulé	0.3	2.0	-3.1	3.8	3.0	0.7	-	-	-	-	-	-
Kadhdhoo	0.9	1.7	-1.4	2.8	2.2	1.0	-	-	-	-	-	-
Kaadedhdhoo	1.1	1.7	-0.6	2.7	2.2	1.2	-	-	-	-	-	-
Gan	0.9	1.7	-1.5	2.8	2.2	1.1	-	-	-	-	-	-

* Time period for MMS network is shown in Table 3.5

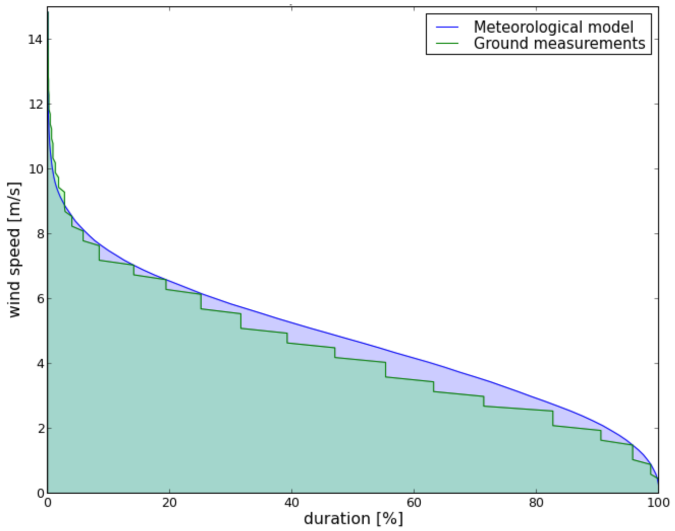

Figure 6.3: Duration curves of wind speed at Hulhulé airport.
CFSR/CFSv2 model versus local measurements

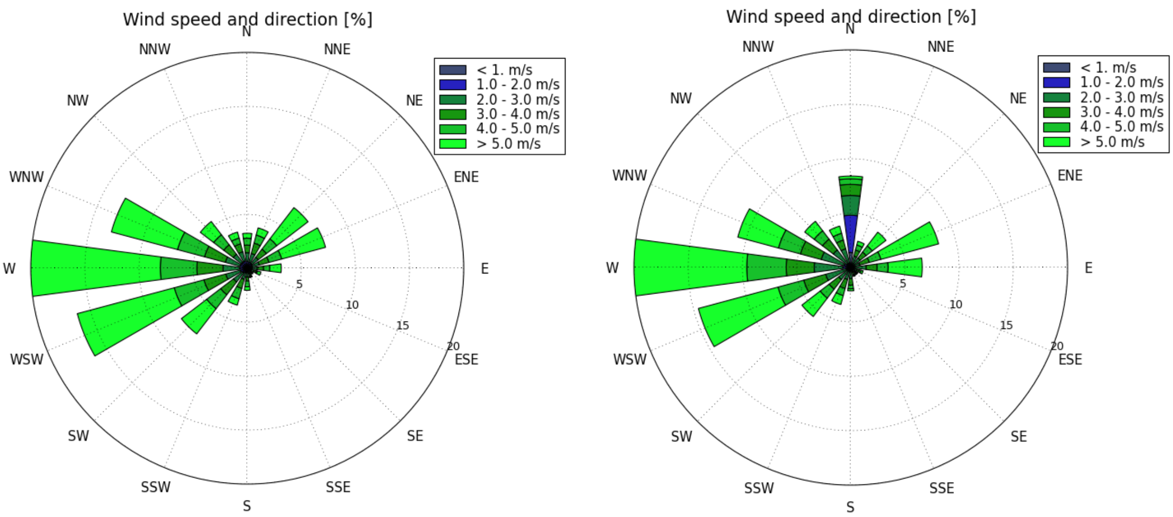

Figure 6.4: Comparison of wind direction derived from the CFSR/CFSv2 models (left) with local measurements (right) at Malé, Hulhulé meteorological station.

Wind direction (together with wind speed) is represented by wind rose, and this parameter is strongly determined by local microclimate (Figure 6.4). The 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 1.5 m/s.

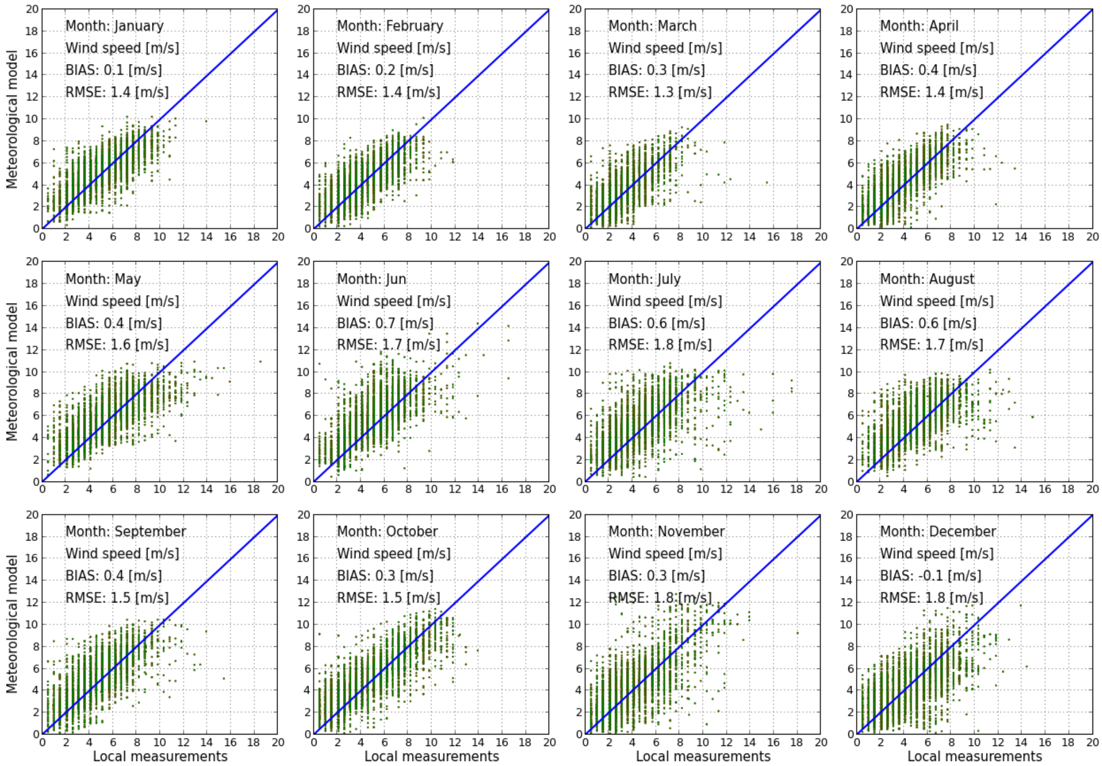

Figure 6.5 Scatterplots of wind speed at 10 m at Hulhulé airport.
Measured values (horizontal axis) and CFSR/CFSv2 meteorological model values (vertical axis)

The reason why the model wind speed values slightly differs from the measured data is low spatial resolution of the CFSR and CFSv2 meteorological models, which represents mainly wind over the surface of open sea, 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.

6.5 Precipitation

Similarly to the other meteorological parameters precipitation is strongly determined by the microclimate. Not only modelling of precipitation is difficult task but also precise measurements of rainfall require systematic maintenance of rain gauges. Rain gauges have also their limitations. Attempting to collect rain data in a hurricane can be nearly impossible and unreliable (even if the equipment survives) due to wind extremes.

Table 6.4 and Figure 6.6 compare the average monthly precipitation measured at meteorological stations with the modelled data. It can be noticed that meteorological model tends to underestimate precipitation but the monthly trend is very similar. In terms of PV systems the high annual precipitation in Maldives ensures low soiling losses even without periodical cleaning of the modules.

Table 6.4: Precipitation: Average monthly sums of precipitation [mm]

Precipitation [mm]		Jan	Feb	Mar	Arp	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum
Hanimaadhoo	Measured	290	11	35	168	213	196	170	121	168	318	199	417	2307
	Model	155	22	87	185	238	65	129	158	149	236	113	191	1730
Malé, Hulhulé	Measured	43	26	99	168	213	210	167	187	154	292	94	233	1885
	Model	141	17	90	155	208	124	161	149	197	177	87	192	1697
Kadhdhoo	Measured	6	73	87	105	239	228	356	138	141	234	69	159	1835
	Model	64	59	69	80	225	266	272	151	244	139	66	134	1770
Kaadedhdhoo	Measured	159	9	106	224	168	99	210	163	187	251	165	283	2025
	Model	130	16	93	180	224	80	180	146	160	218	111	225	1763
Gan	Measured	252	20	126	150	213	64	254	188	145	274	135	212	2031
	Model	206	70	114	202	248	71	146	150	164	274	170	177	1992

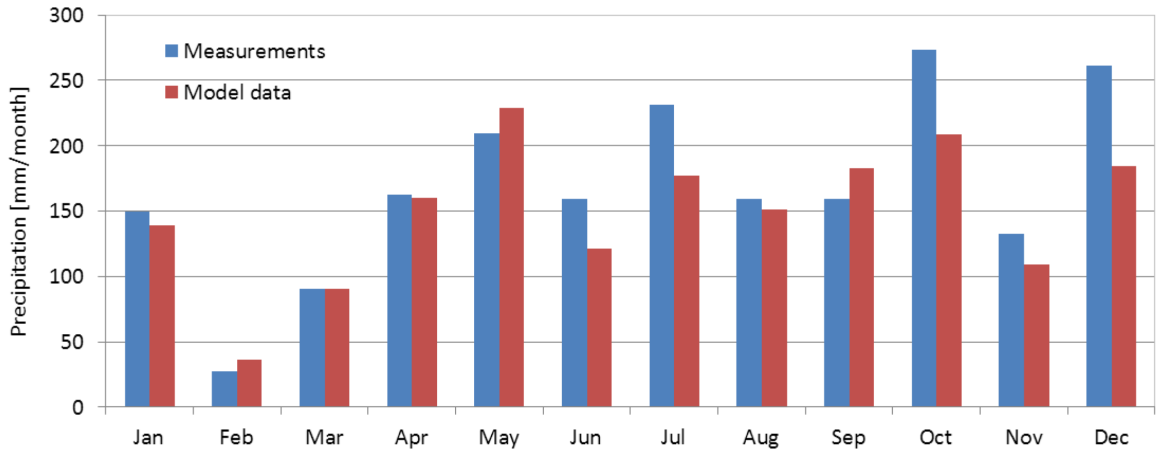

Figure 6.6: Comparison of average monthly precipitation from the CFSR model with local measurements mean value for all stations shown in Table 6.4

7 UNCERTAINTY OF THE MODEL ESTIMATES

7.1 Solar resource parameters

In Maldives, the uncertainty of Direct Normal Irradiation (DNI) and Global Horizontal Irradiation (GHI) is determined by uncertainty of the SolarGIS model and ground measurements [18], 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).
   - Solis clear-sky model and its capability to properly characterize various states of the atmosphere
   - Simulation accuracy of the SolarGIS 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 by Perez et al.
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. Therefore validation for one single site represents the performance of the model only in a limited geographical extent. Only if validation for several sites is available, more consistent information about the model uncertainty can be created. From the user's perspective, the information about the model uncertainty has probabilistic nature, which is considered at different confidence levels. Tables 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. Table 7.2 shows that installation of measuring stations in Maldives give a good base for reducing model uncertainty.

Table 7.1: Uncertainty of the preliminary SolarGIS model estimates

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

Table 7.2: Uncertainty of estimate of the 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

Accuracy of the modelled meteorological parameters stored in the SolarGIS database was assessed by comparison with ground measurements in the geographic region. Meteorological data are derived from two different numerical models covering periods from 1999 to 2010 (CFSR model) and 2011 to 2014 (CFSv2). Taking into account the results of the comparison, the uncertainty is estimated in Table. 7.3.

It was found that the modelled air temperature fits quite well the measured data in terms of monthly averages but minimum and maximum values are not represented well due to small size of the islands and coarse spatial resolution of the models.

Similarly to air temperature and relative humidity, the modelled wind speed and wind direction represent larger region and are geographically smoothed in a comparison to the site measurements at a meteorological station.

Table 7.3: Expected uncertainty of modelled meteorological parameters in region

	Annual	Monthly	Hourly
Air temperature at 2 m	<1°C	<1.5°C	<2.5°C
Relative humidity at 2 m	< 8%	<10%	<15%
Average wind speed at 10 m	<1.5 m/s	<1.5 m/s	<3 m/s

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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
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GeoModel Solar is ISO 9001:2008 certified company for quality management since 2011.