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Improvement of solar irradiance modelling during cloudy-sky days using measurements

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Abstract

Clouds have a strong influence on the amount of solar irradiance reaching the ground. However, they have large spatio-temporal variations and are difficult to model. The 1D irradiance model of `code_saturne` is used to estimate the global and direct solar irradiances at the ground, taking into account the impact of atmospheric gas, clouds and aerosols. Simulations are conducted and compared to measurements at the French SIRTa observatory (instrumental site for atmospheric remote sensing research), located in Palaiseau, Ile-de-France in August 2009 and in the year 2014. Although irradiance is very well modelled during clear-sky days, it is over-estimated during cloud-sky days. The estimation of irradiance during cloudy-sky days is improved by coupling the model to on-site measurements of cloud parameters from the SIRTa. RMSEs around 59 W m^{-2} and 50 W m^{-2} and MBEs around $+17 \text{ W m}^{-2}$ and -18 W m^{-2} are obtained, respectively, for global and direct irradiances during cloudy-sky days using pyranometer measurements for cloud fraction and microwave radiometric measurements for liquid water path. A sensitivity analysis on the cloud parameters that may lead to the best improvement of simulated irradiance is performed. The cloud optical depth is the most important one, followed by the cloud fraction. The different instruments used for the determination of these parameters are examined. Moreover, hourly values of solar fluxes are analysed to determine and physically understand persistent errors between model and measurements when measured cloud parameters are used.

Keywords: clouds, irradiance modelling, `code_saturne`, cloud optical properties, on-site measurements

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1. Introduction

The energy transition is a pathway toward the decarbonisation of the energy sector. It is necessary to reduce energy-related CO₂ emissions to limit climate change. To do so, energy-efficiency measures and renewable energies are set up. Thus, the expansion of solar energies is an important cornerstone of the energy transition. Solar irradiance is the input power source of photo-voltaic (PV) generators. An accurate prediction of the amount of solar irradiance reaching the ground is necessary to reduce the uncertainty on PV energy-yield assessment, to optimize the performance of PV farms, and to forecast the production at different time scales. The amount of solar irradiance reaching the ground is influenced by different geographical, meteorological and atmospheric parameters. Those parameters have important spatio-temporal variations, leading to difficulties to accurately model solar irradiance.

Depending on the forecast needs, different models have been developed to represent irradiance fluxes at the surface of the Earth (Lorenz and Heinemann, 2012; Diagne et al., 2013). They can be categorized according to the forecasting timescales: for very short time scales (from minutes to few hours), statistical models combined to on-site measured irradiance data can be used (Reikard, 2009). Satellite or cloud-imagery based models are used to derive irradiance forecasts (Lorenz and Heinemann, 2012), but they highly depend on the data availability, which depends for example on the passage of the satellite over the studied area. For longer forecasting times (longer than some hours), Numerical Weather Prediction (NWP) models are the most suitable choice. NWP models are based on the modelling of physical phenomena. They predict the atmospheric variables based on current weather condition by solving the differential equations describing the evolution of these variables, which are required to estimate solar irradiance. Hybrid models have also been developed. They merge different approaches and derive an optimized forecast depending on the forecast horizon that integrates different kinds of input data (Cao and Cao, 2005).

NWP and hybrid models represent the diffuse, direct and global solar irradiances with different levels of complexity: from empirical models (Rigollier et al., 2000) or physics-based models (Xie et al., 2016) to radiative transfer based calculations (Müller et al., 2004) as presented in the overview of (Ine-

36 icken, 2006). An example of an intermediate complexity representation is the
37 two-stream approximation, which solves the transfer of irradiance through
38 a plane parallel atmosphere and integrates irradiance over the zenith angle.
39 Transmission and reflection functions are estimated using two or more spec-
40 tral bands, and integrated over the vertical, like the rapid radiative transfer
41 model (RRTM) (Clough et al., 2005) that uses the DIscrete Ordinate method
42 for Radiative Transfer (DISORT) algorithm (Stamnes et al., 1988) to solve
43 the radiative transfer equation using multiple scattering. In the physics-
44 based model of (Xie et al., 2016), the cloud transmittance and reflectance is
45 estimated using plain exponential functions of solar zenith angle, cloud op-
46 tical thickness and effective particle size. The description of the state of the
47 atmosphere is required as an input of these solar-irradiance models. Atmo-
48 spheric parameters include the optical properties of aerosols (AOP), clouds,
49 water vapor and other gases. Although meteorological parameters may be
50 derived from NWP, this is not always the case for AOPs, which may be de-
51 rived from chemical transport models (Breitkreuz et al., 2009; Sartelet et al.,
52 2018).

53 The direct irradiance is crucial for the economic and energy evaluations of
54 different solar energy applications, like solar concentrating and flate plate
55 systems (Padovan et al., 2014). It can be estimated from the transmission
56 functions in the intermediate complexity models presented above. In empir-
57 ical models, its estimation can be quite complex and decomposition models
58 based on observations are sometimes used to separate the direct normal irra-
59 diance (DNI) from global horizontal irradiance (GHI) (Padovan et al., 2014;
60 Bertrand et al., 2015) or simple methods for correcting the satellite derived
61 DNI data (Polo et al., 2015).

62 Clear-sky irradiance is often accurately modelled (Psiloglou and Kambezidis,
63 2007; Blanc et al., 2011; Lefèvre et al., 2013; Kambezidis et al., 2016; Sartelet
64 et al., 2018), especially when the influence of aerosols is taken into account.
65 Sartelet et al. (2018) (referred to as KS18) showed that irradiance fluxes at
66 the surface are strongly improved during clear-sky days when AOP are es-
67 timated from the aerosol concentrations simulated by a chemistry-transport
68 model.

69 However, the modelling of irradiance during cloudy-sky days is a common
70 problem for the various numerical models (Morcrette, 1991; Morcrette et al.,
71 2008; Lorenz and Heinemann, 2012; Diagne et al., 2013), KS18. Clouds have
72 a strong influence on solar irradiance at the surface but they are extremely
73 variable in space and time. The parameterisation of clouds requires the deter-

74 mination of the cloud fraction at the ground, which requires the knowledge of
75 the overlapping of the different vertical cloud layers (Räisänen, 1998), as well
76 as cloud optical properties such as cloud optical depth (COD), single scat-
77 tering albedo, and asymmetry factor (Stephens, 1978; Stephens et al., 1984;
78 Nielsen et al., 2014). In particular, low clouds are found in nearly all types
79 of convecting systems and are misrepresented in climate models (Naud et al.,
80 2010; Haynes et al., 2011; Gregow et al., 2020). Satellite measurements have
81 been used to improve the representation of cloud properties and irradiance .
82 For example, geostationary satellite-derived cloud properties have been used
83 to derive surface solar irradiance under cloudy sky (Schillings et al., 2004).
84 The brightness measurements from GOES satellite images have been used
85 to derive the bulk effect of clouds, the cloud albedo and absorption (Gautier
86 et al., 1980). To better forecast irradiance, different methods are used. The
87 description of clouds and irradiance in NWP models may be improved using
88 satellite and/or in-situ measurements and data assimilation, as detailed in
89 (Kurzrock et al., 2018) and (Gregow et al., 2020): as satellite irradiances
90 contain information on clouds, they may be directly assimilated; or retrieved
91 cloud properties may be used to adjust the initial state of the NWP model.
92 Other methods exists in literature. For example, in (Roy et al., 2001), a
93 neural network approach is used to derive cloud coverage in the sky. In
94 (Moncada et al., 2018), an artificial intelligence method is combined to sky
95 imager data to forecast irradiance.
96 The goal of the current study is to improve the estimation of irradiance
97 during cloudy-sky days by coupling a solar-irradiance model with on-site
98 measurements, and to compare the added-value of different measurements.
99 Because irradiance on cloudy-sky days is strongly influenced by the cloud
100 fraction and the cloud optical depth (COD) (Lorenz and Heinemann, 2012),
101 their representation using different parameterisations and measurements will
102 be compared to determine the most efficient ones.
103 The 1D irradiance model included in the 3D CFD (Computational Fluids
104 Dynamics) model `code_saturne`¹, described in KS18, is used in this study to
105 represent the global and direct solar irradiances. Meteorological data from
106 the WRF model and aerosol’s concentrations from the air-quality modelling
107 platform *Polyphemus* are used as input data (Sartelet et al., 2018; André
108 et al., 2020). The measurements of cloud properties are obtained from dif-

¹<https://www.code-saturne.org/cms/>

109 ferent instruments of the French observatory SIRTa (Haeffelin et al., 2005),
110 located in the southern suburbs of Paris. The article is structured as follows:
111 first, the methodology and configuration of the simulation are detailed. Sec-
112 ond, the modelling of irradiance during clear-sky days and cloudy days is
113 briefly evaluated. Third, the impact of using different measured parame-
114 ters to improve the modelling during cloudy days is estimated. Finally, an
115 analysis of errors conforming to cloud properties is presented.

116 2. Methodology

117 2.1. The solar irradiance scheme of `code_saturne`

118 `code_saturne` is an open source CFD software. It solves the Navier-Stokes
119 equations for 2D, 2D-axisymmetric and 3D flows. In this study, the stan-
120 dalone 1D irradiance model of `code_saturne` is used to estimate, every hour,
121 the total solar irradiance and its direct and diffuse horizontal components at
122 the surface of the Earth (KS18).

123

124 This model parameterises the attenuation of irradiance from gas, aerosol
125 and clouds present in the atmosphere above the location studied. The so-
126 lar irradiance flux is computed by considering irradiance from two spectral
127 bands: the ultraviolet–visible (UV–vis) band (300–700 nm) and the solar
128 infrared (SIR) band (700–3000 nm). In these two spectral bands, the solar
129 irradiance is influenced by different processes:

- 130 • In the UV-vis band, solar irradiance is absorbed by ozone in the strato-
131 sphere and is scattered by air molecules (Rayleigh scattering), aerosols
132 and clouds in the troposphere.
- 133 • In the SIR band, the absorption by water vapour dominates the ozone
134 absorption in the troposphere.

135 The calculation of the irradiance is done at the ground surface by calcu-
136 lating the attenuation in the column above the surface. For the global and
137 direct irradiance, this attenuation absorption is estimated through reflection
138 and transmission factors defined by the multiple-scattering theory using the
139 two-stream approximation (LH74 (Lacis and Hansen, 1974)). The atmo-
140 sphere is assumed to have horizontally homogeneous optical properties and
141 gas concentrations. The reflection and transmission factors of LH74 are used
142 with the optical properties of atmospheric components integrated over the

143 vertical axis. The original LH74 scheme has been modified to introduce the
144 cloud fraction and differentiate the calculation during cloudy and clear-sky
145 days, to compute both the direct and diffuse components of solar irradiance,
146 and to take into account the aerosol contribution.

147

148 The description of the equations used here are similar to those of KS18,
149 and are described in the appendix. The difference between KS18 and the
150 present study lies in the calculation of the direct irradiance : in KS18, the
151 parameterisation of (Psiloglou and Kambezidis, 2007) is used while the cur-
152 rent study uses a formula that we derived and that is more consistent with
153 the global irradiance model developed by LH74.

154 *2.2. Input data*

155 The solar irradiance scheme needs several inputs to be specified, such as
156 the ground albedo and the vertical distribution of:

- 157 • Meteorological variables: temperature, pressure, relative humidity.
- 158 • Aerosol and cloud optical properties (optical depth, liquid water path
159 (LWP), cloud cover fraction, single scattering albedo and asymmetry
160 factor).

161 The simulations of direct, global and diffuse solar irradiances are per-
162 formed and compared to measurements at the French SIRTa observatory,
163 located at Palaiseau, in the southern suburbs of Paris (Haeffelin et al., 2005).
164 The SIRTa observatory hosts the BSRN station of Palaiseau. Two periods
165 are simulated: the period of 'August 2009', from 04/08/2009 to 28/08/2009,
166 as in KS18, and the 'year 2014', from 08/01/2014 to 28/10/2014. The model's
167 chain used is represented in Figure 1:

168 The input meteorological data (temperature, pressure, relative humidity)
169 and ground albedo are obtained from WRF simulations. The cloud optical
170 properties (cloud cover fraction, liquid water content) are derived from WRF
171 outputs or from measurements. The air-quality platform Polyphemus pro-
172 vided the aerosol concentration data for the year 2014, as presented in the
173 following section. The aerosol optical properties are extracted from measure-
174 ments for the period of August 2009. The configuration of the simulation
175 used to generate the data is now briefly summarised, as well as the observa-
176 tional data used as input of the irradiance scheme to improve the cloudy-sky
177 irradiance simulations.

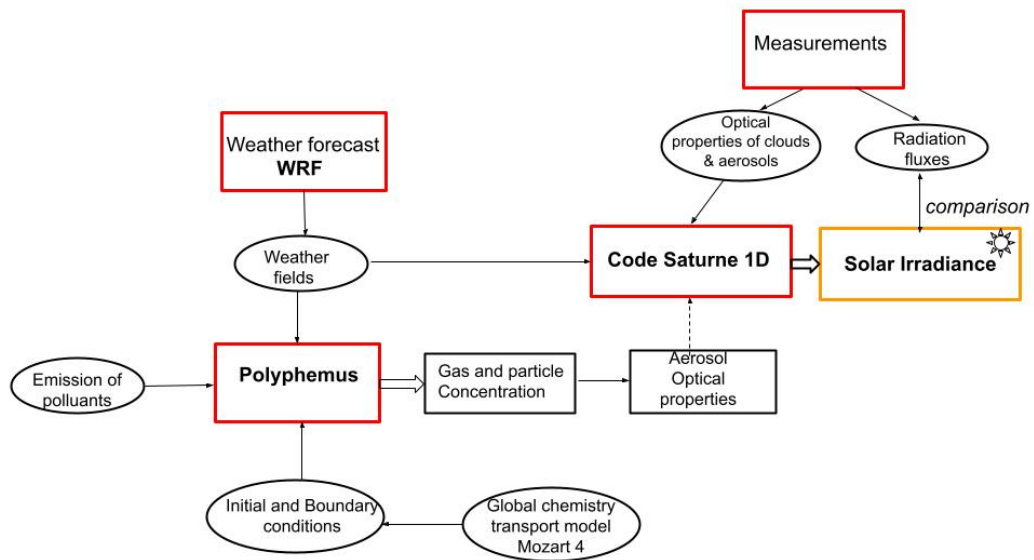


Figure 1: Scheme representing the models chain used for our cases of studies of August 2009 and the year 2014.

178 *2.2.1. Simulated meteorological data*

179 The input meteorological fields are obtained from simulations with the
180 WRF model. WRF is an open-source mesoscale model that solves the com-
181 pressible and non-hydro-static Navier-Stokes equations (Skamarock et al.,
182 2008).

183 For August 2009, as detailed in KS18, the WRF model ran from 10 July to
184 30 August 2009 with hourly outputs. WRF simulations were initialized at
185 0000 UTC every 7 days with a 24 hours spin up. The simulation over the
186 french domain was used for the current study. It has a spatial resolution of
187 $20 \times 20 \text{ km}^2$ (65 x 61 grid points), see Figure 1 of KS18. The vertical reso-
188 lution goes from the surface up to 50 hPa. It is made of 40 terrain-following
189 levels. The WRF "single moment 6 classes" scheme was used for the micro-
190 physics, combined with the Kain-Fritsch cumulus scheme ((Kain and Fritsch,
191 1993)).

192
193 For the year 2014, the set-up of the WRF simulation is detailed in (Sartelet
194 et al., 2018). WRF simulations ran from 02 January to 28 October 2014 with
195 hourly outputs. They were initialized at 0000 UTC every 6, 3 or 2 days de-
196 pending on the period. The simulation over the greater Paris (Île-de-France)
197 domain is used in the current study. Its spatial resolution is $5 \times 5 \text{ km}^2$
198 resolution (41 \times 41 grid points). The vertical resolution goes up to 100hPa
199 and is made of 28 vertical levels refined near the surface. For miscrophysics,
200 Kessler scheme (Kessler, 1995) is used combined with the cumulus Grell-
201 Freitas ensemble scheme (Grell and Devenyi, 2002).

202 *Evaluation of the simulated ground albedo.* The ground albedo is obtained
203 from WRF simulations. For the period 'year 2014', the averaged simulated
204 albedo is equal to 0.2 with a standard deviation of 0.02. The averaged mea-
205 sured albedo is equal to 0.13 with a standard deviation of 0.08. The use of
206 measured albedo instead of simulated values in `code_saturne` doesn't impact
207 solar irradiance calculations. Contrary to simulated values, the measured
208 albedo depends on the zenith angle μ_0 . For values of μ_0 for which irradiance
209 is the strongest during the day, simulated albedo are similar to measurements.

210 *2.2.2. Simulated aerosol concentrations*

211 Aerosol optical data are computed using the air-quality modelling plat-
212 form *Polyphemus* as detailed in KS18. The aerosol concentrations are com-
213 puted with the chemistry-transport model Polair3D of the platform Polyphe-

214 mus, which also determined the size and the composition of particles. The
215 meteorological data needed as input of Polair3D/Polyphemus were obtained
216 by interpolating the WRF simulations detailed in the previous section on the
217 Polair3D/Polyphemus grid. The set-up of the simulations is detailed in KS18
218 for August 2009 and in (Sartelet et al., 2018) for the year 2014. For August
219 2009, the simulations were performed from 15 July to 29 August 2009 over
220 the France domain, with a spatial resolution of $0.2249^\circ \times 0.2249^\circ$ ranging
221 from latitude 41.2°N to 51.32°N and from longitude 5°W to 9.84°E . The
222 vertical was discretized with 8 levels of interfaces: 0, 50, 150, 300, 800, 1500,
223 2500, 4000, 6000 m. For the year 2014, the simulations were performed from
224 08/01/2014 to 30/12/2014 on the Île-de-France domain: spatial resolution
225 of $0.02^\circ \times 0.02^\circ$ ranging from latitude 48°N to 49.5°N and from longitude
226 1.35°E to 3.55°E . The vertical was discretized with 14 levels of interfaces: 0,
227 30, 60, 100, 150, 200, 300, 500, 750, 1000, 1500, 2400, 3500, 6000, 12000 m.

228 *Evaluation of the simulated AOD.* For August 2009, as detailed in KS18: at
229 500 nm, the measured and simulated mean AODs are respectively 0.18 and
230 0.14 with a mean fractional error (MFE) of 43% and a mean fractional bias
231 (MFBE) of -28%. For the year 2014, at 500 nm, the measured AODs from
232 the SARTA ReOBS (Chiriaco et al., 2018) and simulated mean values are
233 respectively 0.056 and 0.07 with a MFE of 48% and a MFBE of +19 %. To
234 evaluate simulations of particle concentrations, (Boylan and Russell, 2006)
235 defined the following criteria: the MFE should be lower than 50 % and the
236 MFBE should be between -30 % and + 30 %, which are well satisfied here.
237 The AODs simulated by Polyphemus compare well to measurements.

238 *2.2.3. Observational data at SARTA*

239 SARTA is a French observatory dedicated to the observation of the atmo-
240 sphere. It has been collecting data for more than 15 years from active and
241 passive remote sensing instruments and in-situ measurements. It is located in
242 a semi-urban area, 20 km south of Paris, France ($48,71^\circ\text{N}$, 2.2°E). SARTA
243 Re-OBS is a project whose goal is to synthesize, analyze, homogenize, all
244 SARTA observations hourly averaged in a single NetCDF file from 2003 to
245 now (Chiriaco et al., 2018).

246 *Instruments and parameters*

247 The instruments used and the parameters extracted from SARTA Re-Obs
248 are resumed in table 1.

Instrument	Variables	Uncertainty	Native Resolution	Availibility	Reference
Multi-wavelength sun-photometer (CIMEL CE-318)	AOD by Sun and sky scanning	0.01	–	in 2009 and 2014	(Holben et al., 1998)
Pyranometers and Pyrhe-liometers (PYR)	Surface downwelling shortwave irradiance (global, direct and diffuse components); cloud fraction	-5 W m^{-2}	1s	in 2009 and 2014	(Long et al., 2006)
Sky imager	Cloud fraction	$\sim 5\%$; depends on cloudy situation	1min	in 2009 and 2014	(Long and DeLuisi, 1998)
Lidar	Cloud fraction (by integration over time); cloud base height	$\sim 5\%$	1h	in 2009	(Morille et al., 2007)
Meteosat Second Generation satellite	Cloud fraction (using the percentage of cloudy pixels over 15x15 pixels images); COD (in an iterative manner, by simultaneously comparing satellite-observed reflectances at visible and near-infrared wavelengths to lookup tables (LUTs) of simulated reflectances); LWP (from the retrieved COD and droplet effective radius)	–	3 km	in 2009	(Roebeling et al., 2006)
Microwave radiometer HATPRO	LWP	$\pm 20 \text{ g m}^2$	5s	in 2014	(Rose et al., 2005)
Celiometer	Cloud base height 10	15 m	30 s	in 2014	(Haeffelin et al., 2005)
Rain gauge R3070	Precipitation	0.1 mm	5s	in 2009 and 2014	(Haeffelin et al., 2005)

Table 1: Instruments and parameters extracted from SIRTA ReObs.

249 *2.3. Determination of cloud properties*

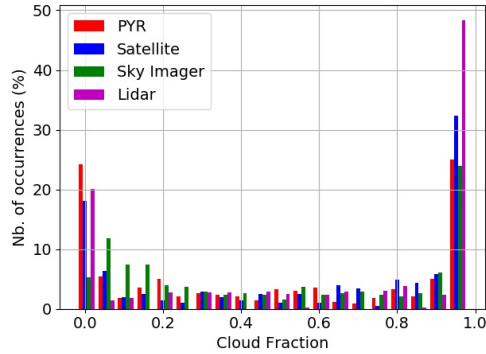
250 In order to represent clouds in the model, the cloud fraction and differ-
251 ent cloud optical parameters (COP) are used: COD, which is presented in
252 the following section, single scattering albedo, asymmetry factor, and cloud
253 droplets effective radii, described in the appendix.

254 *2.3.1. Cloud fraction*

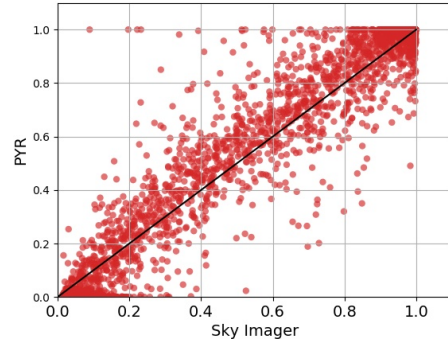
255 *From WRF simulations.* The simulated cloud fraction is known at each ver-
256 tical level of the model. It is difficult to estimate the cloud fraction seen from
257 the ground because the overlapping between cloud layers is not known. Here
258 a maximum overlapping is assumed.

259 *Comparisons of cloud fraction from satellite, PYR, sky imager and lidar in*
260 *August 2009.* The measured cloud fraction is integrated over the vertical.
261 Cloud fractions issued from Meteosat Second Generation satellite data using
262 the percentage of cloudy pixels are of great interest, because of their global
263 coverage. However, data are only available when the satellite is passing above
264 the studied location. Thus, the data extracted from satellite images is the
265 one with the most invalid data ($\sim 28\%$ of invalid values during the day).
266 This percentage of invalid data is $\sim 10\%$ for the cloud fraction measured
267 with a lidar, $\sim 7\%$ for PYR, and 0% for the sky imager. The cloud fraction
268 distribution in August 2009 obtained with these instruments is represented
269 in the histogram of Figure 2a. In the set of values extracted from PYR and
270 from satellite images there are respectively: $\sim 25\%$ and $\sim 32\%$ of cloudy
271 sky ($F_C > 0.95$), $\sim 25\%$ and $\sim 18\%$ of clear-sky situations ($F_C < 0.05$)
272 and $\sim 50\%$ of partially cloudy-sky situations for both data sets. The data
273 extracted from the sky imager does not contain values exactly equal to 0 or
274 1 but it contains , respectively, : $\sim 5\%$ and : $\sim 24\%$ of clear and cloudy
275 sky situations.

276 *Comparisons of cloud fraction from PYR and sky imager in 2014.* For the
277 year 2014, only the cloud fraction from PYR and from sky imager are avail-
278 able: the two set of data are quite similar with a RMSE score of 0.168, they
279 are represented in figure 2b. The distribution of cloud fraction from PYR
280 for the year 2014 is represented in Figure 3a and the box diagram for each
281 season in Figure 3b. It should be noticed that in Autumn (October), 50%
282 of the values of cloud fraction are equal to 1 and the other 50% are between
283 0.1 and 1. For the other seasons the median is around 0.85 in winter, 0.75



(a) Four different data sets are presented: cloud fraction from PYR, satellite images, sky imager and lidar.



(b) Cloud fraction from PYR versus sky imager

Figure 2: Distribution of cloud fraction during August 2009 (a) and the comparison between the two available cloud fractions for year 2014 (b) at SIRTA.

284 in spring 0.82 in summer. Figure 3a represents the distribution of cloud
 285 fraction for each season, normalized by the number of valid values for each
 286 season. Over the whole year, fully cloudy situations (cloud fraction of 1) are
 287 the most frequent. The other values are in the range $[0,0.99]$ with a higher
 288 density around 0. Therefore, there are only a few clear-sky situations and
 289 the distribution of cloud fraction is quite similar throughout the different
 290 seasons.

291 2.3.2. Cloud Optical Depth

292 The COD (τ_C) is an adimensional parameter that characterizes the strength
 293 of attenuation by clouds. When it is equal to 0, there is no extinction of ir-
 294 radiance due to clouds. τ_C depends on the type of cloud and the size of the
 295 water drops or ice crystals. For water clouds, it can be approximated by
 296 (Stephens, 1978):

$$\tau_C = \frac{3 LWP}{2 \rho r_e} \quad (1)$$

297 where LWP is the liquid water path (g m^{-2}), ρ the density of water (g m^{-3})
 298 and r_e the effective diameter in m.

299

300 *From WRF simulations.* When WRF simulations are used to estimate τ_C ,
 301 it is calculated using equation (1) with LWP calculated with WRF and a

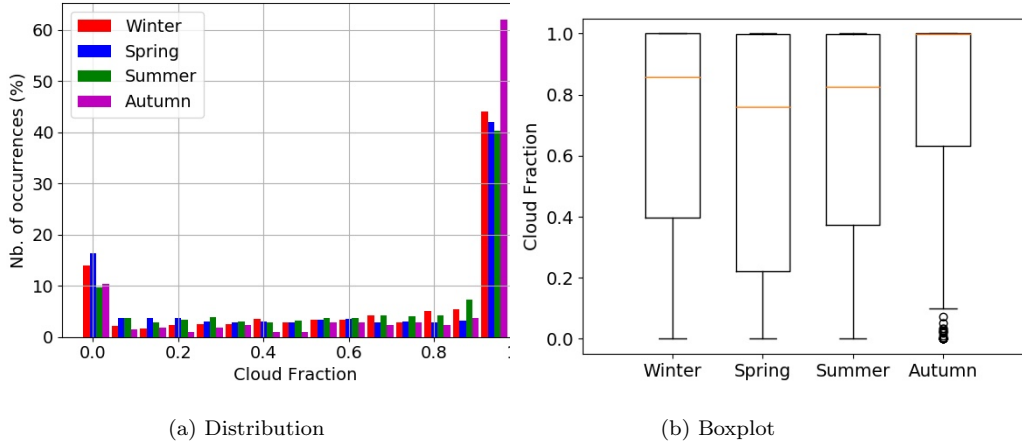


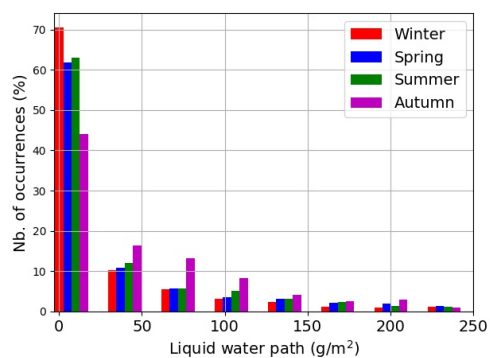
Figure 3: The cloud fraction (PYR) at SIRTa during the four seasons of 2014.

302 constant value of r_e ($14 \mu\text{m}$ (Stubenrauch, 2013)).

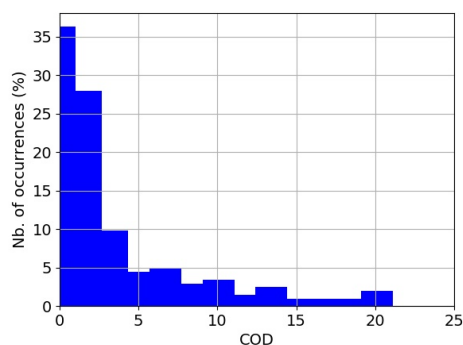
303 *Satellite measurements of COD.* They are available in the SIRTa ReObs
 304 data base for year 2009. The COD distribution is represented in the his-
 305 togram of Figure 4b. The values range between 0 and 109 with a majority
 306 in the range $[0,4]$. Therefore, most of the clouds present at SIRTa are low
 307 density clouds (Stephens et al., 1984).

308 *Microwave radiometer measurements of LWP.* They are available for the
 309 year 2014 and their distribution is represented in Figure 4a. It can be seen
 310 that the LWP distribution is similar for the different seasons with most of
 311 the values lower than 25 g m^{-2} . The differences observed for autumn can be
 312 explained at least in part by the fact that autumn includes only October in
 313 this study. The variations of the LWP span a wider range of values when
 314 the cloud fraction is higher than 0.5 (Figure 5 shows the LWP versus cloud
 315 fraction in March and June, the evolution during these two months is well
 316 representative of the year). These high variations might be caused by the
 317 simultaneous occurrence of multiple cloud layers. Furthermore, the LWP
 318 increases with the cloud fraction.

319 *Improvement of the estimation of COD from LWP.* Because no estimation
 320 of COD and cloud droplet radii was available in 2014, the COD is calculated
 321 from the LWP data obtained from microwave radiometric measurements.

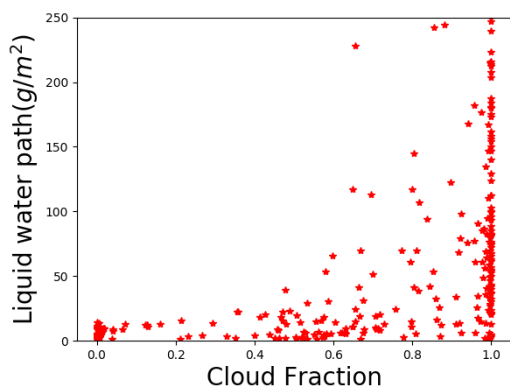


(a) Distribution of liquid water path from SARTA microwave radiometric measurements according to the four seasons in 2014 (in g m^{-2})

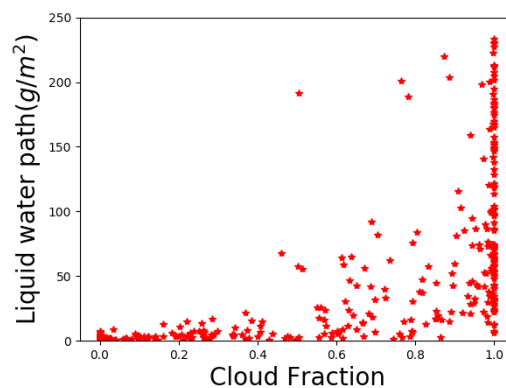


(b) Distribution of COD from SARTA satellite measurements.

Figure 4: Distribution of COP in August 2009 and year 2014.



(a) March 2014



(b) June 2014

Figure 5: Distribution of LWP versus cloud fraction from PYR

322 To determine the relation between COD and LWP at SIRTA, satellite data
323 from 2005 to 2010 are used. These data include values of COD and of LWP
324 (which is derived from COD and from an estimation of the effective radius r_e
325 following (Roebeling et al., 2006)). A first approach consisted in computing
326 an averaged value of the effective radius over the whole period 2005-2010 (12
327 μm), and then to derive the COD for 2014 from the LWP measurements with
328 equation 1 using this mean effective radius. As the effective radius varies in
329 time, a second approach is to determine a statistical relation between COD
330 and LWP using the satellite data from the period 2005-2010.

331 The relation between COD and LWP is fitted using two different equa-
332 tions, depending on the value of LWP:

- 333 1. A linear fit for values of the LWP lower than 14 g m^{-2} : $\tau_c = 0.181LWP -$
334 0.001 when $LWP \leq 14 \text{ g m}^{-2}$
- 335 2. A logarithmic fit for values of LWP higher than 14 g m^{-2} : $\log_{10}(\tau_c) =$
336 $1.7095 \ln(\log_{10}(LWP)) + 0.2633$. This equation was inspired from the
337 fitted equation of (Stephens et al., 1984) for conservative scattering
338 because purely scattering is a good approximation for clouds for solar
339 irradiance.

340 The scattering plot of COD versus LWP and the fitted models are rep-
341 resented in Figure 6a. The RMSE between the estimated COD and the
342 measured one is calculated to compare the different models over the period
343 2005-2010. A RMSE of 8.18 is obtained with equation 1 and 7.6 with the
344 relation established in this paper, which is the best approximation of COD
345 for our specific case. The distribution of LWP for the period 2005-2010
346 shows that the majority of points are in a range of LWP going from 5 to 100
347 g m^{-2} (Figure 6b). The fitted model is then pushed by those values of LWP,
348 it coincides well for our case: in 2014, the majority of LWP falls into the
349 same range (Figure 4a).

350 *2.4. Separation between clear-sky and cloudy-sky days*

351 Due to the difficulties linked to the modelling of clouds, the model is
352 evaluated separately for clear-sky days and cloudy-sky days. At the SIRTA,
353 the separation between clear-sky days and cloudy-sky days is done using
354 the measured cloud fraction from a radiometric station (for August 2009) or
355 PYR (for year 2014). A day is classified as clear sky, when the average of the
356 hourly cloud fraction shortwave is lower than 5% between 9 UTC and 15 UTC
357 (Sartelet et al., 2018). The other days are considered as cloudy-sky days and

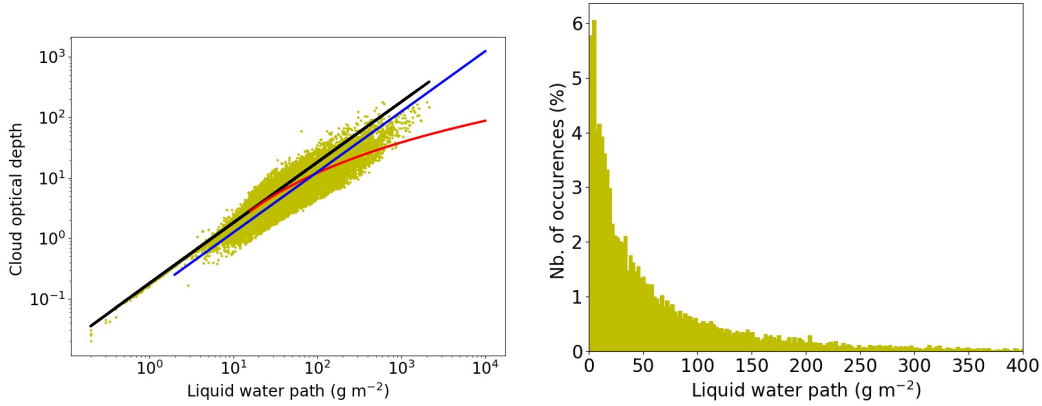


Figure 6: COD versus LWP from 2005 to 2010 at SIRTA (*), the approximation of COD using the fitted model (linear model — + logarithmic model — and equation 1 with $r_e=12\mu\text{m}$ —).

358 they include overcast skies (cloud fraction higher than 0.95). For every day,
 359 only the hours for which all measurements are available are considered. For
 360 the case of August 2009, 5 clear-sky days are identified: 6, 12, 15, 16, 23 of
 361 August, it is the equivalent of 60 hours, and 20 cloudy-sky days (195 hours).
 362 Table 2 shows the number of hours of clear-skies and cloudy-skies for each
 363 month of the year 2014. Because only 6 days (75 hours) can be classified as
 364 clear sky, the statistical scores are less significant than for cloudy-sky days.

365 3. Model evaluation

366 For model evaluation, the computed global and direct irradiances are compared
 367 to those measured at the SIRTA site using PYR (see section 2.2.3).
 368 The definition of the different statistical indicators used to evaluate our model
 369 can be found in appendix C. The different simulations discussed in this paper
 370 are reported in Table 3. In the reference simulations used in this section
 371 and noted sim09.0 for August 2009 and sim14.0 for the year 2014, the WRF
 372 meteorological simulations are used to estimate the COD and the cloud fraction.
 373

374 3.1. Irradiance on clear-sky days

375 The model is first evaluated for clear-sky days, which are less numerous
 376 than cloudy-sky days, but also easier to model. For August 2009, the daily

Month of year 2014	Nb. of clear-sky hours	Nb. of cloudy-sky hours
January	0	147
February	0	204
March	23	284
April	14	287
May	15	229
June	16	332
July	16	307
August	0	398
September	0	316
October	0	275

Table 2: Number of clear-sky and cloudy-sky hours for each month of 2014 following the availability of cloud fraction from PYR and LWP from radiometric measurements.

Period	Case	F _c	COD
August 2009	Sim09.0	WRF	WRF
	Sim09.1	WRF	Satellite
	Sim09.2	1	Satellite
	Sim09.3	PYR	Satellite
	Sim09.4	Sky imager	Satellite
	Sim09.5	Lidar	Satellite
	Sim09.6	Satellite	Satellite
	Sim09.7	PYR	WRF
Year 2014	Sim14.0	WRF	WRF
	Sim14.1	WRF	Fitted model
	Sim14.2	1	Fitted model
	Sim14.3	PYR	Fitted model
	Sim14.4	Sky imager	Fitted model
	Sim14.5	PYR	Equation 1
	Sim14.6	PYR	WRF

Table 3: Cloud parameters defining the different cases studied. F_C : cloud fraction; COD: cloud optical depth.

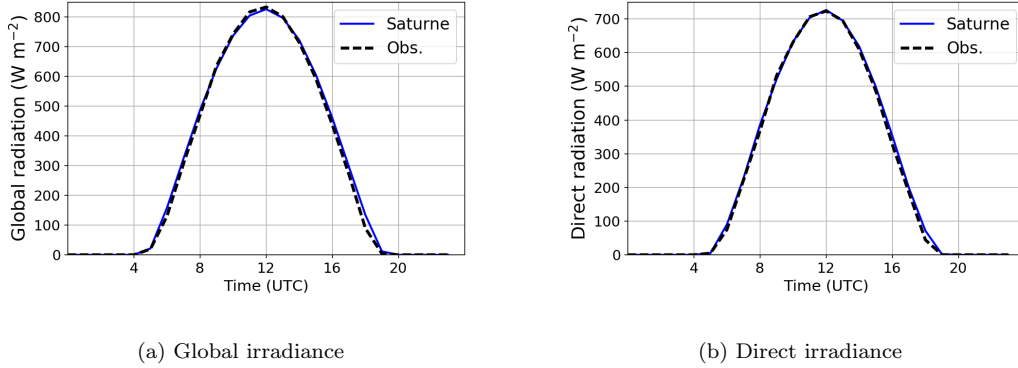


Figure 7: Diurnal cycle of solar irradiances at SIRTa on clear-sky days in August 2009 (in W m^{-2})

377 global and direct solar irradiances on clear-sky days at SIRTa in August 2009
 378 (Sim09.0) are shown respectively in Figures 7a and 7b. The daily cycle and
 379 amplitude are well modelled for both global and direct irradiances. Statistics
 380 show a RMSE around 22 W m^{-2} for global irradiance with a MBE of 5 W m^{-2}
 381 and a RMSE around 19 W m^{-2} for direct irradiance with a MBE of 5 W m^{-2} .

382 For the year 2014, the model performs well for global fluxes, although it
 383 slightly underestimates the measurements. The RMSE ranges between 12
 384 and 29 W m^{-2} depending on the month, with an average of 19 W m^{-2} and
 385 a MBE of 5 W m^{-2} on average. For direct fluxes, the model underestimates
 386 the measurements with an averaged MBE of -7 W m^{-2} and the RMSE ranges
 387 between 15 and 28 W m^{-2} depending on the month, with an average of 21
 388 W m^{-2} . The estimation of the direct component is less good in 2014 than in
 389 August 2009, because aerosol optical depths were estimated from the mea-
 390 surements for August 2009 and from the modelling for the year 2014.

391 These scores can be compared to the RMSE scores obtained at the BSRN
 392 station of Palaiseau using the McClear model, an irradiance model devel-
 393 oped for clear-sky conditions (Lefèvre et al., 2013) or to the HelioClim-3v3
 394 database (Blanc et al., 2011; Espinar et al., 2012), which is derived from
 395 images of the Meteosat series of satellites. For the period 2005-2007, the
 396 McClear model leads to a RMSE of 25 W m^{-2} for global irradiance and of 37
 397 W m^{-2} for direct normal irradiance (Lefèvre et al., 2013); for the HelioClim-
 398 3v3 database, the RMSE is equal to 62 W m^{-2} for global irradiance and to
 399 79 W m^{-2} for direct normal irradiance (Espinar et al., 2012).

400 Although the number of cases, the period and the time averaging period of

401 our simulation and measurement are not the same as those of Mc Clear/Helioclim-
402 3v3, the scores obtained with `code_saturne` demonstrate the quality of the
403 model.

404 *3.2. Irradiance on cloudy-sky days*

405 The comparison between observations and simulations during cloudy-sky
406 days in August 2009 is provided in Table 4. As in KS18, Sim09.0 strongly
407 overestimate observations with a RMSE of 149 W m^{-2} and 220 W m^{-2} for
408 global and direct irradiance respectively. The overestimation is larger for
409 the direct than for the global irradiances (MBE= $+108 \text{ W m}^{-2}$ and NMB of
410 $+99\%$ versus $+65 \text{ W m}^{-2}$ and $+31\%$).

411 As for August 2009, the modelled global and direct irradiances are strongly
412 overestimated during the year 2014 (Table 4; Sim14.0). For global irradiance,
413 the RMSE averaged over the whole year 2014 is 146 W m^{-2} with an aver-
414 aged MBE of 26 W m^{-2} and a NMB that reaches its maximum of $+49\%$ in
415 January and its minimum of -7% in June. For direct irradiance, the averaged
416 RMSE is equal to 157 W m^{-2} with a MBE of 23 W m^{-2} and a NMB ranging
417 from $+134\%$ (in January) to $+11\%$ (in July). For both periods, these large
418 errors may come from a bad estimation of cloud fraction and COD. However,
419 statistical scores are slightly better for 2014 than for August 2009, probably
420 because of the lower resolution of WRF simulations in 2009.

421 **4. Improvement of irradiance modelling on cloudy-sky days**

422 In the aim of improving irradiance modelling on cloudy-sky days, different
423 simulations are conducted using observed data for the cloud optical depth
424 and/or the cloud fraction. The simulations are summarized in Table 3.

425 *4.1. Cloud Fraction*

426 The different measurements of cloud fraction (section 2.2.3) and the sim-
427 ple value of 1, sometimes used in modelling (Nielsen et al., 2014), are used as
428 input to the code. They are compared to the cloud fraction extracted from
429 the WRF simulations. In the cases presented here, the COD is taken from
430 satellite measurements for August 2009 and from the fitted model for the
431 year 2014 using radiometric measurements of LWP.

432 *4.1.1. Cloud fraction equals to 1*

433 The modification of cloud fraction (Sim09.2) has an important impact
434 on the estimation of irradiance for August 2009 and especially for the direct
435 irradiance. Taking the cloud fraction equal to 1 leads to an under-estimation
436 of the measurements: the RMSE is equal to 204 W m^{-2} , the MBE to -101
437 W m^{-2} and the NMB to -67% (against 203 W m^{-2} , $+94 \text{ W m}^{-2}$ and
438 $+78\%$ respectively for direct irradiance using WRF for the cloud fraction -
439 Sim 09.1- Table 4). A similar behavior is seen for the year 2014 (Sim14.2).
440 The RMSEs, MBEs and NMBes are reported for every month in Figures 8,9
441 and 10 and the averages over the year for RMSEs and MBEs are in Table 4.
442 Direct fluxes are highly under-estimated for every month (the NMB varies
443 from -99% (January) to -60% (May), with an averaged MBE of -63 W m^{-2})
444 and values of RMSE range from 33 to 184 W m^{-2} with an average of 131
445 W m^{-2} .

446 For the two simulated periods, the MBEs are high and negative. Due to a
447 significant number of partially cloudy days at SIRTAs, taking a cloud fraction
448 of 1 for the whole period leads to a large under-prediction of the direct
449 irradiance. However, it leads to satisfactory results for global irradiance
450 (RMSE= 65 W m^{-2} , MBE= $+12 \text{ W m}^{-2}$, NMB of $+45 \%$ in January and $+8$
451 $\%$ in May and August), partially justifying its utility in NWP models.

452 *4.1.2. Cloud Fraction extracted from measurements*

453 The computation of irradiances, using measurements for the cloud frac-
454 tion, improved especially for the direct irradiance. Clouds mainly transform
455 direct irradiance in diffuse irradiance and consequently their impact is lower
456 for global irradiance than for direct irradiance. Statistical scores for August
457 2009 are reported in Table 4. For the direct irradiance, the best RMSE is
458 obtained using the cloud fraction from PYR (Sim09.3: RMSE of 87 W m^{-2}
459 and NMB of -17% against 203 W m^{-2} and $+79\%$ when the cloud fraction
460 is from WRF simulation - Sim09.1). The estimation of direct irradiance us-
461 ing the cloud fraction from sky imager also leads to similar results, with a
462 RMSE of 99 W m^{-2} and a NMB of -27% . However, the direct irradiance is
463 highly under-estimated when the cloud fraction is extracted from the lidar
464 (Sim09.5) and satellite images (Sim09.6), with a MBE score equals, respec-
465 tively, to -53 W m^{-2} and -40 W m^{-2} , NMB equals, respectively to -50% and
466 -33% and RMSE equals, respectively, to 135 W m^{-2} and 112 W m^{-2} .

467 For the year 2014, the statistical scores using the cloud fraction from
468 PYR and sky imager are represented in Figures 8, 9 and 10. With a cloud

469 fraction from PYR (Sim14.3), the RMSEs for global irradiance range between
470 37 and 69 W m^{-2} , depending on the month, with an average of 59 W m^{-2}
471 and an average MBE of +17 W m^{-2} . The NMB scores range between +4%
472 and +47%. Global fluxes are always over-estimated. For direct irradiance,
473 the model underestimates the measurements with an averaged MBE of -18
474 W m^{-2} , a NMB between -22% and -45% and the RMSE ranges between
475 16 and 88 W m^{-2} depending on the month, with an average of 50 W m^{-2} .
476 Simulations with the cloud fraction extracted from the sky imager (Sim14.4)
477 lead to similar statistics for global radiation and slightly poorer for direct
478 irradiance: the RMSEs range from 17 to 81 W m^{-2} with an average of 60
479 W m^{-2} , an averaged MBE of -18 W m^{-2} and a NMB between -1.5% and -39%.
480 These statistics are much better than those obtained in the simulations with
481 a cloud fraction from WRF (Sim14.1), which lead to an averaged RMSE for
482 global irradiance of 93 W m^{-2} and of 130 W m^{-2} for direct irradiance. For
483 all conducted tests, acceptable results are obtained for global fluxes but the
484 change of cloud fraction values highly impacts the direct irradiance. However,
485 the direct component is important for different application of solar energy
486 systems, such as concentrating and flat-plate solar systems (Padovan et al.,
487 2014). Hence, a good representation of cloud fraction is crucial. In our case,
488 the best results are obtained with a cloud fraction extracted from PYR or a
489 sky imager.

490 *4.2. Cloud optical depth*

491 In this section, different estimations of the COD are used for August 2009
492 and year 2014 and are compared to the COD calculated by WRF. The cloud
493 fraction is extracted from PYR.

494 *4.2.1. Satellite measurements*

495 For August 2009, simulations using the COD measured by satellite (Sim09.3)
496 lead to satisfactory results for both global and direct irradiances. Statistics
497 are reported in Table 4. The RMSE is around 87 W m^{-2} for both global and
498 direct irradiance and the MBE scores are respectively equal to -13 W m^{-2}
499 and -22 W m^{-2} . It shows that simulated fluxes under-estimate measure-
500 ments. Compared to a COD taken from WRF (Sim09.7), it represents a
501 huge improvement.

502 *4.3. Estimation from LWP*

503 For the year 2014, the COD can be computed from microwave radiometric
504 measurements of LWP using 2 models (fitted model (Sim14.3) or equation

	Direct		Global	
Case	RMSE (W m^{-2})	MBE (W m^{-2})	RMSE (W m^{-2})	MBE (W m^{-2})
Sim09.0	220	+108	149	+65
Sim09.1	203	+94	131	+48
Sim09.2	204	-101	103	-32
Sim09.3	87	-22	87	-13
Sim09.4	99	-33	87	-14
Sim09.5	135	-53	94	-23
Sim09.6	112	-40	88	-18
Sim09.7	198	+82	156	+82
Sim14.0	157	+23	146	+26
Sim14.1	130	-6	93	+33
Sim14.2	131	-63	65	+12
Sim14.3	50	-18	59	+17
Sim14.4	60	-18	60	+19
Sim14.5	49	-16	66	+17
Sim14.6	125	+22	131	+25

Table 4: Comparison of simulated and measured direct and global solar irradiances at SIRTA during cloudy days for the different cases studied. The RMSEs and MBEs are expressed in W m^{-2} .

505 1 (Sim14.5)), as described in section 2.3.2. RMSEs, MBEs and NMBes are
506 respectively reported in Figures 8, 9 and 10. The RMSEs are higher in
507 summer than in winter, because irradiance fluxes are higher. In fact, as it
508 can be seen in Figure 10, relative errors are more important in the winter than
509 in summer (for Sim 14.3: for global irradiance, NMB= +47 % in January
510 and NMB= +4 % in June and for direct irradiance, NMB=-45 % in January
511 and NMB= -22% in June).

512 The direct irradiance estimated using the COD of the fitted model is
513 mainly described by the linear equation (defined for values of LWP lower
514 than 14 g m^{-2}). This is due to the fact that values of LWP greater than 14
515 g m^{-2} lead to COD greater than 2.5, and clouds with COD greater than 2.5
516 are thick enough to lead to very small direct irradiance. The scores are very
517 similar but slightly better when the COD is estimated using equation 1 with
518 a fixed effective radius than using the fitted model.

519
520 In opposite to the direct irradiance, which becomes almost zero if clouds
521 have a LWP higher than 14 g m^{-2} , the global irradiance decreases as the COD
522 increases, but it does not cancel out because of diffuse irradiance. Therefore,
523 the global irradiance is impacted by the whole range of values of COD. Similar
524 statistical scores are obtained with the fitted model and using Equation 1
525 but slightly better scores are obtained with the fitted model (Sim 14.3). For
526 Sim14.3, the lowest RMSE scores, for global irradiance, is equal to 37 W m^{-2}
527 and is obtained in January, and the highest is around 69 W m^{-2} , it is obtained
528 in May. The averaged RMSE is 59 W m^{-2} . For direct irradiance, RMSEs are
529 in the range $[16, 88] \text{ W m}^{-2}$, with an average of 50 W m^{-2} . Therefore, for
530 this case, `code_saturne` overestimates global irradiance and underestimates
531 direct irradiance for every month of the year 2014.

532 The results are satisfactory and a big improvement compared to the case
533 when COD is taken from WRF measurements (Sim14.6: the averaged RMSE
534 for global irradiance is about 131 W m^{-2} and for direct irradiance, the RMSE
535 is about 125 W m^{-2}).

536 This study shows the importance of COD in the estimation of irradiance
537 fluxes during cloudy sky days. It can be well estimated from LWP data (in
538 this case extracted from radiometric measurements) or empirical relations to
539 improve the estimation of irradiance during cloudy-sky days. It also shows
540 the stronger importance of COD compared to the cloud fraction for the
541 estimation of global irradiance.

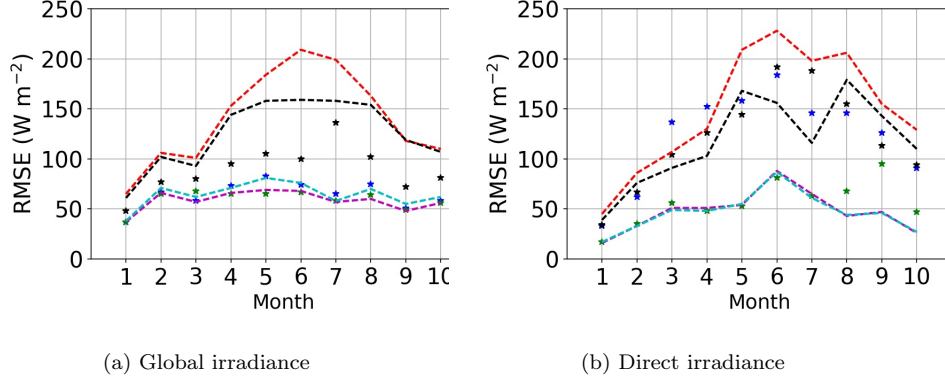


Figure 8: RMSEs (in W m^{-2}) between simulated and measured global (a) and direct (b) solar irradiances at SIRTAs during cloudy-sky days in 2014. WRF evaluation: - - - Sim14.0. Sensitivity to cloud fraction/COD: * Sim14.1; * Sim14.2; * Sim14.4; - - - Sim14.3; - - - Sim14.5; - - - Sim14.6.

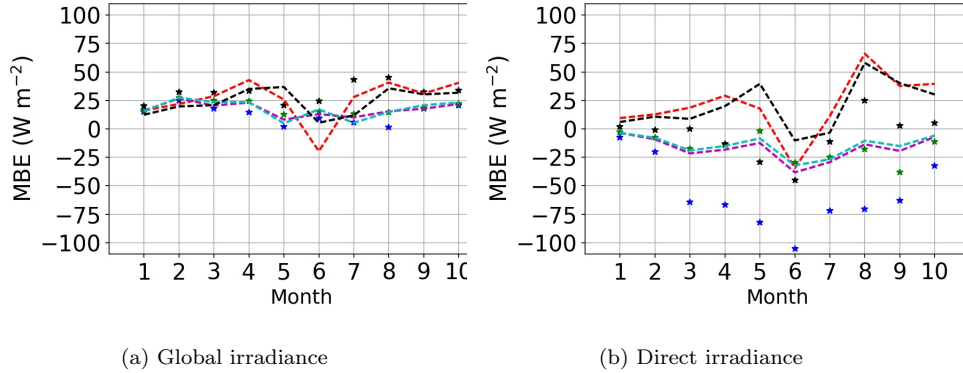


Figure 9: MBEs (in W m^{-2}) between simulated and measured global (a) and direct (b) solar irradiances at SIRTAs during cloudy-sky days in 2014. WRF evaluation: - - - Sim14.0. Sensitivity to cloud fraction/COD: * Sim14.1; * Sim14.2; * Sim14.4; - - - Sim14.3; - - - Sim14.5; - - - Sim14.6.

542 5. Discussion

543 The calculation of irradiance fluxes by `code_saturne` is done hourly. For
 544 the majority of simulated hours, `code_saturne` approximates well the obser-
 545 vations. However, it is not always the case. Thus, an analysis of the results
 546 is conducted in order to understand why the quality of the estimation of the

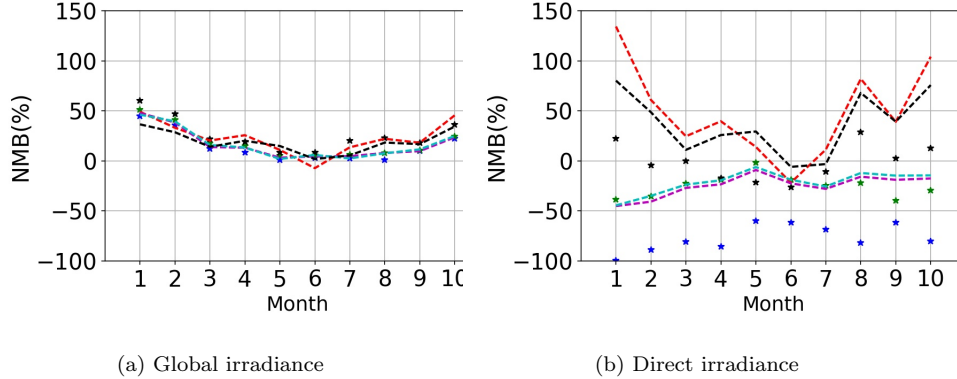


Figure 10: NMB scores (in %) between simulated and measured global (a) and direct (b) solar irradiances at SIRTA during cloudy-sky days in 2014. WRF evaluation: - - - Sim14.0. Sensitivity to cloud fraction/COD: * Sim14.1; * Sim14.2; * Sim14.4; - - - Sim14.3; - - - Sim14.5; - - - Sim14.6.

547 irradiance varies. The analysis is done for August 2009 (Sim 09.3) and for the
 548 year 2014 (Sim14.3). One first explanation of the gap between observation
 549 and simulation is that `code_saturne` calculates the irradiance fluxes at each
 550 full hour without integration while the observational data are averaged. In
 551 fact, for each variable taken from the SIRTA ReObs file, the hourly mean
 552 values are calculated from the native resolution data (5 s to 1 min) by aver-
 553 aging all the data available within ± 30 min around the full hour (Chiriaco
 554 et al., 2018).

555 For August 2009, the cases when the absolute difference on global or
 556 direct irradiance is higher than 200 W m^{-2} are analysed: 20 hours in 2009
 557 were detected. Among these cases of large differences between simulated and
 558 observed direct irradiance, 63% correspond to partially cloudy days and 32%
 559 to fully cloudy days. There was no precipitation for any case. In most of
 560 the cases, 58%, were obtained when a low cloud was present. 32% of cases
 561 were obtained during a transition period of COD: the hour after a minima
 562 or maxima of COD.

563 The analysis is now conducted for the entire simulation of year 2014.
 564 The standard deviation of the measured global irradiance, LWP and cloud
 565 fraction are extracted from the SIRTA ReObs file. Table 5 shows the MAE of
 566 global and direct irradiances for different conditions on the measured global
 567 irradiance, LWP and cloud fraction. A better estimation of global irradiance

	MAE(G)	MAE(D)
$\sigma(G_{obs}) > 100$	68	73
$\sigma(G_{obs}) < 100$	25	13
$\sigma(LWP) > 30$	39	16
$\sigma(LWP) < 30$	29	24
$\sigma(F_C) > 0.2$	62	64
$\sigma(F_C) < 0.2$	30	19

Table 5: MAE of global (G) /direct (D) irradiance fluxes (in W m^{-2}) for different ranges of standard variation of measured global irradiance G_{obs} (in W m^{-2})/liquid water path LWP in (g m^{-2}) / cloud fraction F_C in 2014.

	$G_{CS} - G_{obs} < 0$	$G_{CS} - G_{obs} > 0$
$\bar{\sigma}(G_{obs})$	88	32
$\bar{\sigma}(LWP)$	78	41
$\bar{\sigma}(F_C)$	0.086	0.06

Table 6: Averaged standard variation of measured global irradiance G_{obs} (in W m^{-2})/liquid water path LWP (in g m^{-2}) / cloud fraction F_C when measured global irradiance is underestimated or overestimated by `code_saturne` in 2014.

Condition	$F_c > 0.95$	$0.50 < F_c < 0.75$	$0.25 < F_c < 0.50$
MAE (G)	83	62	43
\bar{G}_{obs}	178	452	458
$\text{MAE(G)}/\bar{G}_{obs}$	0.46	0.14	0.09
MAE (D)	12	81	75
\bar{D}_{obs}	13	239	305
$\text{MAE(D)}/\bar{D}_{obs}$	0.92	0.34	0.25

Table 7: Mean absolute error (MAE) of global (G) and direct (D) irradiances and the ratio MAE over the averaged measured fluxes for different conditions on the cloud fraction (F_C) in 2014 (in W m^{-2}).

568 is obtained for lower fluctuations of measured global irradiance, LWP and
569 cloud fraction. A similar tendency is obtained for direct irradiance except
570 when the standard deviation of LWP is higher than 30 g m^{-2} . It is normal
571 considered that direct irradiance is attenuated for values of LWP higher than
572 14 g m^{-2} . Therefore, the quality of the estimation is linked to the quick
573 changes within an hour in the measurements.

574 Table 6 shows the standard variation of measured global irradiance fluxes/
575 LWP and cloud fraction when measured global irradiance is over-estimated
576 and under-estimated. When `code_saturne` under-estimates observations, the
577 averaged standard deviation of observed global irradiance, LWP and cloud
578 fraction are higher than when `code_saturne` overestimates observations. It
579 can be related to the fact that averaging of measurements pushes them to-
580 wards higher values.

581
582 The mean absolute error (MAE) is calculated for the global and direct
583 irradiances for different ranges of cloud fraction in 2014 (table 7). The MAE
584 increases with the cloud fraction. The ratio MAE-mean measured irradiance
585 is higher for the direct irradiance. For overcast situations, diffuse irradiance
586 is dominant. The few high values of simulated direct irradiance during over-
587 cast sky are obtained when the COD is low, they might be due to a poorly
588 coordination between measured LWP and cloud fraction or to a low density
589 cloud blocking the sun.

590
591 The type of clouds does not contribute significantly to the difference.
592 Cirrus clouds optical depth is usually described by another formula than
593 used here (for ice clouds, the definition of cloud optical proprieties can be
594 found in (Fu, 1996; Baum et al., 2014)). A study was done on hours during
595 which cirrus clouds were the only type of cloud present. It was shown that
596 they are well represented in `code_saturne` and hourly differences of irradiance
597 fluxes are not linked to their presence.

598 **6. Conclusion**

599 The 1D irradiance model of the atmospheric module of `code_saturne`
600 was used to calculate irradiance fluxes at SIRTa in Palaiseau, Ile-de-France.
601 This study aimed at improving the estimation of irradiance during cloudy-
602 sky days. Therefore, the model was evaluated hourly and with the presence

603 of clouds during two periods: August 2009 and year 2014. Cloud proper-
604 ties, such as the cloud fraction and COD, are used as input. Because the
605 mesoscale meteorological model have difficulties to estimate them, measure-
606 ments done at the SIRTA site were used. The cloud fraction was extracted
607 from satellite images, lidar, shortwave measurements (PYR) and sky imager.
608 The liquid water path (LWP)/COD were extracted from radiometric and
609 satellite measurements. The main conclusions are:

- 610 • A good representation of the COD is crucial for modelling solar irra-
611 diance during cloudy-sky days. The cloud fraction may improve solar
612 irradiance modelling if the estimation of COD is correct, especially for
613 direct irradiance.
- 614 • Assuming the sky completely cloudy but with an accurate represen-
615 tation of COD leads to simulated global irradiance that may be more
616 accurate than using an estimation of cloud fraction from numerical
617 models. However, it is not the case for the direct irradiance.
- 618 • The simulated irradiance obtained using a cloud fraction extracted from
619 PYR or from sky imager is more accurate than those obtained using
620 lidar or satellite measurements.
- 621 • A fitted model was developed to estimate COD from LWP measure-
622 ments. Satellite and radiometric measurements of LWP lead to satisfac-
623 tory simulations of irradiances, although satellite data are not always
624 available. This shows that the link that exists between COD and LWP
625 is well established, and that LWP may be used as a proxy of COD in
626 irradiance modelling.

627 Moreover, hourly values of solar fluxes were examined to determine the
628 reasons for the few discrepancies between measurements and simulated irra-
629 diances. The main source of errors that were detected are:

- 630 • `code_saturne` calculates fluxes every hour, while observational data are
631 averaged within 30 mins around the full hour.
- 632 • The hourly bias is higher when the fluctuations within the hour of
633 global irradiance/LWP/cloud fraction measurements are high.

- 634 • There was no particular type of clouds that impacted the results. How-
635 ever in August 2009, during more than 50% of the cases leading to a
636 large discrepancy between measurements and observations, a low cloud
637 was present.
- 638 • The MAE on irradiance fluxes increases with the cloud fraction and its
639 impact is more important for the direct component.

640 Overall, we showed that `code_saturne` performs well at SIRTAs during clear-
641 sky and cloudy-sky days, when measurements of cloud fraction and LWP
642 are used. All components of irradiance are well modeled and especially the
643 direct fluxes (with RMSEs around 21 W m⁻² during clear-sky days and 50
644 W m⁻² during cloudy sky-days) which is mandatory for some applications
645 such as concentrating and flat-plate solar systems.

646
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651 **Appendix A. Calculation of cloud optical properties**

652 The cloud fraction, COD and LWP were extracted from SIRTAs Re-Obs
653 data file or WRF simulation. The cloud droplet radii, single scattering albedo
654 (SSA) and asymmetry factor had to be calculated in the code.

655 *Cloud droplet radii.* It is calculated following equation 1.

656 *Cloud single scattering albedo (SSA) and the cloud asymmetry factor .* The
657 calculations are made separately in the UV-vis band and in the SIR band.
658 They are approximated following the formulations of (Nielsen et al., 2014).
659 They depend only on the equivalent cloud droplets radius r_e , and are defined
660 for different spectral bands: 250-440; 440-690nm in the UV-visible domain
661 and 690-1190; 1190-2380nm in near IR domain. The integration over the
662 wavelength is made by weighting each formulation with the irradiance energy
663 contained in each band. The single scattering albedo (SSA) in the UV-visible
664 and SIR bands (ω_0^{UV-Vis} and ω_0^{SIR}) are calculated with the following formulas:

$$\omega_0^{UV-Vis} = \omega_{0-1} \times 0.24 + \omega_{0-2} \times 0.76 \quad (\text{A.1})$$

$$\omega_{0-1} = 1 - 3.3 \times 10^{-8} re \quad (\text{A.2})$$

665

$$\omega_{0-2} = 1 - 10^{-7} re \quad (\text{A.3})$$

666 In the SIR band,

$$\omega_0^{SIR} = \omega_{0-3} \times 0.60 + \omega_{0-4} \times 0.40 \quad (\text{A.4})$$

$$\omega_{0-3} = 0.99 - 1.49 \times 10^{-5} re \quad (\text{A.5})$$

667

$$\omega_{0-4} = 0.9985 - 9.210^{-4} re \quad (\text{A.6})$$

668 In the UV-Vis band, the cloud asymmetry, g_0^{UV-Vis} , is calculated with
669 the following formula:

$$g_0^{UV-Vis} = \omega_{0-1} \times 0.24 \times g_1 + \omega_{0-2} \times 0.76 \times g_2 \quad (\text{A.7})$$

$$g_{0-1} = 0.868 + 1.4 \times 10^{-4} re - 6.1 \times 10^{-3} e^{-0.25re} \quad (\text{A.8})$$

670

$$g_{0-2} = 0.868 + 2.5 \times 10^{-4} re - 6.3 \times 10^{-3} e^{-0.25re} \quad (\text{A.9})$$

671 In the SIR band, the cloud asymmetry, g_0^{SIR} , is calculated with the following
672 formula:

$$g^{SIR} = \omega_{0-3} \times 0.60 \times g_3 + \omega_{0-4} \times 0.40 \times g_4 \quad (\text{A.10})$$

$$g_{0-3} = 0.867 + 3.1 \times 10^{-4} re - 7.8 \times 10^{-3} e^{-0.195re} \quad (\text{A.11})$$

673

$$g_{0-4} = 0.864 + 5.4 \times 10^{-4} re - 0.133e^{-0.194re} \quad (\text{A.12})$$

674 **Appendix B. The irradiance model - integral method**

675 *Global Irradiance.*

676 **UV-Vis band** The most significant source of heating in the strato-
677 sphere comes from the absorption of solar irradiance by ozone. Rayleigh dif-
678 fusion through multiple-scattering is taken into account with a simple albedo
679 and the global irradiance G_{UV-VIS} , is expressed as follows:

$$G_{UV-VIS} = F_C G_{1,UV-VIS} + (1 - F_C) G_{2,UV-VIS} \quad (\text{B.1})$$

680 where F_C is the cloud fraction, $G_{1,UV-VIS}$ and $G_{2,UV-VIS}$ the global irra-
681 diance for cloudy-sky and clear-sky with aerosols respectively. They are
682 expressed as:

$$G_{1,UV-VIS} = \mu_0 F_0 (0.647 - \bar{R}_r(\mu_0) - A_{UV-VIS}^G) \frac{T_{c,UV-VIS}^G}{1 - R_{c,UV-VIS}^G R_g} T_{mg} \quad (\text{B.2})$$

683

$$G_{2,UV-VIS} = \mu_0 F_0 (0.647 - \bar{R}_r(\mu_0) - A_{UV-VIS}^G) \frac{T_{a,UV-VIS}^G}{1 - R_{a,UV-VIS}^G R_g} T_{mg} \quad (\text{B.3})$$

- 684 • μ_0 the cosine of the zenith angle
- 685 • F_0 the irradiance flux incident at the top of the Earth atmosphere. It is
686 calculated using the formula of (Paltridge and Platt, 1976) : $F_0 = 1365$
687 W m^{-2}
- 688 • \bar{R}_r the albedo due to Rayleigh scattering (as in LH74)
- 689 • R_g the ground albedo (calculated by WRF)
- 690 • A_{UV-VIS}^G is the irradiance absorption function in the UV-VIS band by
691 O_3 (as in LH74)
- 692 • $T_{c,UV-VIS}^G$ and $R_{c,UV-VIS}^G$ the transmission and reflective functions for
693 clouds
- 694 • $T_{a,UV-VIS}^G$ and $R_{a,UV-VIS}^G$ the transmission and reflective functions for
695 clear-sky for aerosols
- 696 • T_{mg} is the general transmittance function for seven main atmospheric
697 gases (H_2O , O_3 , CO_2 , CO , N_2O , CH_4 and O_2). It is expressed follow-
698 ing (Psiloglou et al., 1997), it depends on 'm', the air mass, given by
699 (Kasten and Young, 1989).

700 **SIR band** The most important source of heating in the low atmosphere
 701 is due to water vapor absorption. As reported by LH74, parametrizing water
 702 vapor absorption is more complicated than for ozone absorption. In the SIR
 703 band spectrum, G_{SIR} , is expressed as follows:

$$G_{SIR} = F_C G_{1,SIR} + (1 - F_C) G_{2,SIR} \quad (\text{B.4})$$

704 where F_C is the cloud fraction; the global irradiance for cloudy-sky $G_{1,SIR}$
 705 and clear-sky with aerosols $G_{2,SIR}$ are expressed as:

$$G_{1,SIR} = \mu_0 F_0 (0.353 - A_{SIR}^G) \frac{T_{c,SIR}^G}{1 - R_{c,SIR}^G R_g} T_{mg} \quad (\text{B.5})$$

706

$$G_{2,SIR} = \mu_0 F_0 (0.353 - A_{SIR}^G) \frac{T_{a,SIR}^G}{1 - R_{a,SIR}^G R_g} T_{mg} \quad (\text{B.6})$$

- 707 • A_{SIR}^G represents the absorption by water vapor (as in LH74)
- 708 • $T_{c,SIR}^G$ and $R_{c,SIR}^G$ the transmission and reflective functions for clouds
- 709 • $T_{a,SIR}^G$ and $R_{a,SIR}^G$ the transmission and reflective functions for clear-sky
 710 for aerosols

711 **The transmission and reflective functions** The transmission and
 712 reflective functions for cloudy-sky, T_c^G and R_c^G and for clear-sky T_a^G and R_a^G
 713 are described by the following formulas of (Meador and Weaver, 1980):

$$T^G = \frac{2k}{(k + \gamma_1)e^{k\tau'} + (k - \gamma_1)e^{-k\tau'}} \quad (\text{B.7})$$

$$R^G = \frac{\gamma_2[e^{k\tau'} - e^{-k\tau'}]}{(k + \gamma_1)e^{k\tau'} + (k - \gamma_1)e^{-k\tau'}} \quad (\text{B.8})$$

714 where

$$k = (\gamma_1^2 - \gamma_2^2)^{1/2} \quad (\text{B.9})$$

715

$$\gamma_1 = \frac{\sqrt{3}}{2} [2 - \omega'_0(1 + g')] \quad (\text{B.10})$$

716

$$\gamma_2 = \frac{\sqrt{3}\omega'_0}{2} (1 - g') \quad (\text{B.11})$$

717 where τ' , g' and ω'_0 are the scaled optical depths, single scattering albedo and
 718 asymmetry factor. They are introduced by (Joseph et al., 1976) in order to
 719 take into account the highly forward scattering for water clouds and aerosols
 720 (Stephens et al., 1984). This correction is often called δ two-stream(Liou,
 721 2002):

$$\tau' = \tau(1 - \omega_0 * g^2) \quad (\text{B.12})$$

$$\omega'_0 = \frac{\omega_0(1 - g^2)}{1 - g^2\omega_0} \quad (\text{B.13})$$

$$g' = \frac{(g - g^2)}{(1 - g^2)} \quad (\text{B.14})$$

724 The coefficients τ , g and ω_0 change depending if we are on clear-sky or
 725 on cloudy-sky conditions:

726 For clear-sky:

727 • $\tau = \tau_a$

728 • $\omega_0 = \omega_a$

729 • $g = g_a$

730 For cloudy-sky:

731 • $\tau = \tau_a + \tau_C$

732 • $\omega_0 = (\omega_a\tau_a + \omega_C\tau_C)/\tau$

733 • $g = (g_a\omega_a\tau_a + g_C\omega_C\tau_C)/\tau\omega_0$

734 *Direct Irradiance.* In order to calculate the direct irradiance, a model in-
 735 spired by LH74 was developed. It is similar to the one developed for global
 736 irradiance and it is based on the same principles.

UV-vis band

$$I_{1,UV-VIS} = \mu_0 F_0 (0.647 - \bar{R}_r - A_{UV-VIS}^G) T_{mg} T_C^D \quad (\text{B.15})$$

$$I_{2,UV-VIS} = \mu_0 F_0 (0.647 - \bar{R}_r - A_{UV-VIS}^G) T_{mg} T_{a,UV-VIS}^D \quad (\text{B.16})$$

SIR band

$$I_{1,SIR} = \mu_0 F_0 (0.353 - A_{SIR}^G) T_{mg} T_C^D \quad (B.17)$$

$$I_{2,SIR} = \mu_0 F_0 (0.353 - A_{SIR}^G) T_{mg} T_{a,SIR}^D \quad (B.18)$$

where $\mu_0, F_0, \bar{R}_r, A^G$ have been defined in the previous paragraphs. T^D is given by:

$$T^D = e^{-m\tau} \quad (B.19)$$

Appendix C. Statistical indicators

Different statistical indicators are calculated in this study, they are defined in the following section. o_i and c_i are the observed and the simulated concentrations at time and location i , respectively. n is the number of data. The **Root Mean Square Error (RMSE)**

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (c_i - o_i)^2} \quad (C.1)$$

The **Mean Fractional Bias Error (MFBE)**

$$MFBE = \frac{1}{n} \sum_{i=1}^n \frac{c_i - o_i}{(c_i + o_i)/2} \quad (C.2)$$

The **Mean Bias Error (MBE)**

$$MBE = \frac{1}{n} \sum_{i=1}^n (c_i - o_i) \quad (C.3)$$

The **Mean Fractional Error (MFE)**

$$MFE = \frac{1}{n} \sum_{i=1}^n \frac{|c_i - o_i|}{(c_i + o_i)/2} \quad (C.4)$$

The **Mean Absolute Error (MAE)**

$$MAE = \frac{1}{n} \sum_{i=1}^n |c_i - o_i| \quad (C.5)$$

The **Normalized Mean Bias (NMB)**

$$NMB = \frac{\sum_{i=1}^n (c_i - o_i)}{\sum_{i=1}^n o_i} \quad (C.6)$$

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Highlights

Improvement of solar irradiance modelling during cloudy-sky days using measurements

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- Parameterised global irradiance modelling is improved by using measurements of cloud optical depth (COD) only
- Liquid water path is a good-enough proxy to determine COD
- Measurements of cloud fraction are useful if COD is well estimated
- A good representation of cloud fraction is crucial for the estimation of direct irradiance