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***An Iberian Climatology of Solar Radiation obtained from WRF
regional climate simulations for 1950-2010 period***

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Abstract

The mesoscale Weather Research and Forecasting (WRF) Model is used over the Iberian Peninsula to generate 60 years (1950-2010) of climate data, at 5 km resolution, in order to evaluate and characterize the incident shortwave downward radiation at the surface ($SW\downarrow$), in present climate.

The simulated values of $SW\downarrow$ in the period 2000-2009 were compared with data measured in Spanish and Portuguese meteorological stations before and a statistical BIAS correction was applied using data from Clouds and the Earth's Radiant Energy System (CERES), on board four different satellites. The spatial and temporal comparison between WRF results and observations show a good agreement for the analyzed period, although the model overestimates observations. This overestimation has a mean normalized bias of about 7% after BIAS correction (or 17% for original WRF output). Additionally, the present simulation was confronted against another previously validated WRF simulation performed with different resolution and set of parametrizations, showing comparable results. WRF adequately reproduces the observational features of $SW\downarrow$ with correlation coefficients above 0.8 in annual and seasonal basis.

60 years of simulated $SW\downarrow$ over the Iberian Peninsula were produced, which showed annual mean values that range from 130 W/m^2 , in the northern regions, to a maximum of around 230 W/m^2 in the southeast of the Iberian Peninsula (IP). $SW\downarrow$ over IP shows a positive gradient from north to south and from west to east, with local effects influenced by topography and distance to the coast.

The analysis of the simulated cloud fraction indicates that clear sky days are found in more than 30% of the period at the southern area of IP, particularly in the Algarve (Portugal) and Andalusia (Spain), and this value increases significantly in the summer season for values above 80%.

Keywords: WRF model; Downscaling Climatology; Downward Solar radiation; Cloud fractions; Iberian Peninsula.

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1 Introduction

Incoming solar radiation is an important variable from meteorological, economic and social perspectives. In the last IPCC report it is stated that “CO₂ emissions from fossil fuel combustion and industrial processes contributed about 78 % of the total greenhouse gas emission increase from 1970 to 2010, with a similar percentage contribution for the period 2000 – 2010” (IPCC, 2014). To reduce CO₂ emissions it is necessary to decarbonize the electricity generation. Detailed knowledge of the solar resource in the present and in the near future is essential for assessing the viability of projects related to the harnessing of solar energy.

Solar radiation studies carried out in various regions have revealed that, in the past century, the Earth has undergone two opposite periods regarding the variability of solar radiation: Global Dimming (Stanhill and Cohen, 2001), with a reduction in solar radiation at the surface until the mid-1980s and later the global Brightening (Wild et al., 2005), with an increase of global radiation at the surface. Based on observations and ERA-40 reanalysis, Perdigão et al. (2016) confirmed the existence of these two distinct periods in Portugal, known as dimming and brightening, but with an earlier turning year than the one described in the literature, in particular over the south of Portugal. This latter study revealed an increasing trend of surface global radiation located in the south of Portugal, without a pronounced decrease before the 1980s, in the period 1964–1986.

Before reaching the Earth’s surface, incoming solar radiation is scattered, absorbed and reflected in the atmosphere. Clouds play a major role in spatiotemporal solar radiation variability. Hence, it is common that studies on solar radiation at Earth’s surface include also an analysis of cloud cover. Sanchez-Lorenzo et al. (2009) analysed observational cloudiness series for Iberian Peninsula (IP) and found a decreasing trend in the IP between

1960 and mid 2000s. The authors report higher annual values over northern areas (4.5 oktas) and smaller values in southern areas (3.5 oktas), reaching minimum values in July and August (less than 3 oktas). According to the authors, the sunshine duration series show a decrease from 1950 to the mid-1980s that is not associated with total cloud cover. On the other hand, later on, Sanchez-Lorenzo et al. (2013) found, for the 1985-2010 period, a positive trend in the global radiation in line with the sunshine duration trends since the 1980s.

Many commercial systems have been installed in the IP intended for solar energy power generation, particularly in the southern regions. In the study of Ridao et al. (2007), present and future of renewable solar energy was analyzed for Andalusia, with an average solar radiation energy of $4.6 \pm 0.3 \text{ kWh/m}^2 \text{ day}$, which qualifies the southern IP as a strategic region in Europe regarding solar energy technology implementation. In the European Union, solar energy presents itself as the main source of renewable energy investment until 2030 (APREN, 2014). Spain is the fifth country of the European Union in the production of photovoltaic energy, with more than 4GW of installed capacity (IDAE, 2016). In Portugal, the currently installed solar power capacity is more than 450MW (almost 3% of the energy produced) and it is expected to double that capacity by 2030. Alentejo and Algarve are the Portuguese regions with the highest installed solar capacity (APREN, 2014).

Santabàrbara et al. (1996) built annual and seasonal maps of solar radiation in and around Catalonia province (Spain), for the period 1964-1993, from daily in situ global solar irradiation datasets and found maximum values over the inner part of Catalonia and at the south coast. According to Jerez et al. (2013), IP shows a strong potential in terms of complementarity between solar and wind power. The authors combined simulated data obtained from the MM5 numerical model with a new developed algorithm to identify

optimum spatial distributions for solar and wind power plants in order to guarantee a certain energy generation provided by renewable resources. Results show Valencia, Murcia and Andalusia provinces (Spain), as well as Algarve (Portugal), as optimal locations for solar power plants. Šúri et al. (2007) used a solar radiation model (Šúri and Hofierka, 2004) and showed that Portugal and the Mediterranean regions have the greatest potential for solar electricity production with maximum values in summer months. Also, Ruiz-Arias et al. (2012) showed similar conclusions. The authors evaluated the potential of renewable energies in electricity production for the province of Jaén (southern of Spain) and proposed a scenario where PV could produce up to 21% of the electricity demand in that region.

Due to the increasing demand of solar energy systems, an accurate knowledge of the solar resource plays a key role from an economic perspective. There are several methodologies and models to obtain solar irradiation maps and to predict solar radiation. For instance, Ehnberg and Bollen (2005) proposed a model based on cloud observations. Alsamamra et al. (2009) used a statistical methodology for mapping global solar radiation at the surface. Martín et al. (2010), applied several statistical methods based on observational time series to predict half daily values of global solar irradiances. Martín et al. (2010), proposed an empirical model to estimate the solar energy as a function of other climatic variables. Ruiz-Arias et al. (2015) used an interpolation methodology to adjust global horizontal and direct normal irradiances obtained with WRF model with observational ground-based station data.

The application of Regional climate models (RCMs) in the evaluation of solar radiation features (trends, variability and climatology) in the past, present and future may overcome the problem of gaps in observational time series, the poor spatial coverage of ground-based stations and time series size. This approach allows for a detailed spatial

characterization of any regions in order to select the one with best conditions to receive solar power plants, improving in that way the risk analysis of their implementations for political and economic decision-makers.

RCMs are used for downscaling of global climate simulations and have been extensively used in various regions (e.g. Feser et al., 2011; Soares et al., 2012). Reviews on RCMs can be seen in Dudhia (2014), Rummukainen (2010), Laprise (2008) or Giorgi and Mearns (1999). The mesoscale Weather Research and Forecasting (WRF) model (Skamarock et al. 2008) has been increasingly used as RCM. It is an open source tool, with considerable flexibility given the variety of parameterizations available, which makes it a very versatile tool for research in atmospheric physics. This model was used and evaluated over IP for different meteorological variables and by several authors such as Ruiz-Arias et al. (2015), Dasari et al. (2014), Rios-Entenza et al. (2014), Soares et al. (2014), Cardoso et al. (2013), Soares et al. (2012), Mercader et al. (2010), among others. For instance, Santos-Alamillos et al. (2012) proposed and evaluated a method to analyze the spatiotemporal balance between solar and wind resources over the southern part of IP, using the WRF model with a spatial resolution of 9 km. The results show the existence of complementarity between the solar and wind energy, but with a marked seasonality in strength and spatial coverage.

Lara-Fanego et al. (2012a) evaluated the reliability of WRF to predict global and direct irradiance over Andalusia (southern of Spain) and found that the model presents substantial quality. Nevertheless, their analysis showed that WRF tends to overestimate both irradiances with a relative seasonal bias of about 10% for global and twice higher for direct radiation.

The common practice in dynamical regional climate downscaling is to perform long continuous integrations with RCMs, starting from a single set of initial conditions, for a

long period without re-initialization time slices. (e.g. Soares et al., 2012; Marteau et al., 2015). This technique allows the model to develop internal variability but it is computationally expensive. In this work, we used a WRF simulation of six decades with annual re-initializations to avoid such computation costs (Dasari et al., 2014). This approach allows to perform model simulations simultaneously, resulting in a gain of execution time of the complete numerical experiment. This procedure is in agreement with other authors, namely Raju et al. (2015) and Xue et al. (2014). Lo et al. (2008) discuss advantages and disadvantages of this technique. According to these authors, the re-initialization approach is widely accepted in weather forecasting to mitigate the problems of systematic error growth in long integrations but it is rarely used in regional climate simulations. This happens because: (i) it is not easily portable; (ii) long spin-up time of RCMs constrains the re-initialization process and (iii) possible occurrence of discontinuity points between consecutive simulations. However, Lo et al. (2008) compared long-term continuous integration with short-term reinitialized simulations showing that the re-initialization runs outperform the continuous simulation runs.

Many authors pointed out the difficulties RCMs have in the representation of the large-scale features as they are forced at their boundaries (e.g. Jones et al., 1995; Yhang and Hong, 2011). Waldron et al. (1996) and Von Storch (2000) firstly presented the nudging methodology. In the subsequent years nudging techniques were further developed and employed in many studies, but its use is not consensual (Alexandru et al., 2008; Miguez-Macho et al., 2004; Hong and Chang, 2012, Hong and Kanamitsu, 2014), due to disagreements regarding the advantage of reducing freedom from regional model's large scales and other potentially negative lateral consequences.

An important issue in NWP analysis is the evaluation of the model results. Usually, this evaluation is performed through the comparison between observational ground-based

data with the nearest grid point of the model outputs. BIAS correction (eg, Ruiz-Arias et al., 2015; Acharya et al., 2013; Haddeland et al., 2012; Piani et al., 2010), in a post-processing stage, is often performed. Ehret et al., (2012) present the state-of-the art of bias correction methods as well the assumptions and implications.

The main objectives of this paper are: firstly, to evaluate the quality of the 5 km resolution WRF simulations with annual re-initializations, to predict incident shortwave solar radiation at the surface ($SW\downarrow$) through the comparison with observations and other WRF simulations (continuous and previously validated); secondly, to characterize the solar radiation at the surface with BIAS correction and the cloud fraction, in the 1950-2010 period over the IP, in order to assess the regions with major solar resource potential. The paper is structured as follows: section two describes the methodology used in this study, as well as the data, model setup and study area. The performance of the simulations and BIAS correction methodology is discussed in section 3. A detailed climatology of $SW\downarrow$ and cloud cover over IP is presented and discussed in section 4. Finally, conclusions are presented in section 5.

2 Datasets and Methods

2.1. Model and numerical experiments

WRF mesoscale model V3.3.1. (Skamarock et al., 2008) was configured with two domains, using two-way nesting, with horizontal resolutions of 75 *km* and 25 *km*, and 30 vertical pressure levels. From the 25 *km* resolution simulation output, a dynamical downscaling to a 5 *km* resolution domain was carried out (Figure1), using one way nesting, with hourly output. The results of the 5 *km* resolution simulation (WRF5 hereinafter) are used in the characterization of the IP climatology.

Figure 1. 75km, 25km and 5km WRF simulation domains (left) and orography (in meters) used by WRF simulations (right).

In order to reduce the time required to simulate 60 years, the procedure adopted in this work consists in splitting the climate runs into several yearly simulations that are performed simultaneously. WRF5 was integrated continuously for 13 months starting from 00 UTC 1 May of each year for six decades (1950-2010). The first month of each simulation was used as model spin up time and was neglected in the analysis. The NCEP/NCAR (National Centers for Environmental Prediction/National Center for

Atmospheric Research) reanalysis data at 2.5° latitude/longitude resolution (Kalnay et al., 1996), updated every 6 hours, was used as initial and forcing boundary condition. The model setup for these simulations are described in detail in Dasari et al. (2014), where the results were validated for extreme events of heat and cold waves and showing a good agreement with E-OBS V7.0 dataset (Haylock et al., 2008).

Since the WRF5 simulation followed a less common simulation strategy based on multiple one year time-slices, its performance is also investigated through comparison with results obtained from a continuously integrated WRF simulation (WRF9). WRF9 simulation was previously validated for temperature and precipitation over Portugal (Soares et al., 2012), precipitation over Iberia (Cardoso et al., 2013) and offshore wind (Soares et al., 2014), with the results showing a good agreement with observations. In WRF9, the model simulation ran continuously from 00 UTC 1 January 1989 to the end of 2012 where the first month is used as model spin up. The WRF9 simulation was performed using two one-way nested grids (27 and 9 km horizontal resolution) and the results from the finer domain are used for comparison. The outermost domain was designed in a way to reduce spurious boundary effects in the inner region and both grids were centered in the Iberian Peninsula. Additionally, grid nudging (Staufner and Seaman 1990) was applied to the outermost grid, every 6h at all levels above the planetary boundary layer. This WRF simulation was forced by ERA-Interim reanalysis (Berrisford et al., 2009). CAM3 was selected to parameterize radiation processes at sub-grid scales for both shortwave and longwave radiation (Collins et al., 2004). This scheme takes into account the interactions of the radiation with clouds and with several aerosol types and trace gases. A detailed description of WRF9 simulations can be found in Soares et al. (2012). Similarities and differences in physical parameterizations, for WRF5 and WRF9, can be seen in Table1.

Table1. Configurations of the physical parametrizations used in each model.

Model	NCEP/NCAR ARW WRF	
Acronym	WRF5	WRF9
Resolution	5km	9km
Vertical Level	30 σ	49 σ
Microphysics	WSM3 – class simple ice scheme (Hong et al., 2004)	WSM6 – Class single moment (Hong and Lim, 2006)
SW	CAM3 (Colins et al., 2004)	Mellor-Yamada-Janjic (Janjic, 2001)
LW		
PBL	YSU (Hong et al., 2006)	Janjic (1990; 1994,2000)
Convection scheme	Grell-Devenyi ensemble (Grell, G.A. and D. Devenyi, 2002)	Betts-Miller-Janjic (Betts, 1986; Betts and Miller, 1986; Janjic, 1990; 1994,2000)

2.2 Observational data

In order to assess the ability of WRF model to simulate the $SW\downarrow$, these results were compared with daily observations obtained from 65 stations of IPMA (Portuguese Weather service) and AEMET (Spanish Weather service).

Global solar irradiance was measured using Kipp & Zonen pyranometers, model CM-11, with a spectral sensitivity in the wavelength range 305-2800 nm and with an uncertainty of $\pm 2\%$ (according to the manufacturer). These instruments are classified, in accordance with International Standard ISO 9060/1990, as secondary standards. This classification was adopted by the World Meteorological Organization (WMO, 2008).

In the Spanish network, all radiometers are calibrated every two years. For more information see Ruiz-Arias et al. (2015) or García et al. (2014). Relatively to IPMA, calibration was performed only at the factory (Kipp & Zonen), and some of the pyranometers in the network were replaced in the period used. The quality control is based mainly on the spatial distribution of records over all observational stations.

The comparison between simulations and observations was made using the nearest neighbour technique, i.e., the closest grid point model values were compared with the correspondent measured ones. The analysis was made for the time periods when observations and simulations were simultaneously available (2000-2009).

Figure 2. Geographical location of the 65 observational stations used to evaluate the WRF simulations and length of the time series. The scale indicates the percentage of days available at each station for the period 2000-2009.

Figure 2 presents the location of the $SW_{\downarrow}$ groundbased stations and the percentage of days with data within the mentioned period. Since the observations have different time periods, for seasonal analysis, it was decided not to compute monthly means for the stations with less than 20 days for each month in the respective observation period, yielding a total of fifteen stations. In turn, a given yearly value is considered valid if at least $2/3$ of valid monthly values are available in that year. IP average errors were computed considering all fifteen stations. Winter (DJF), Spring (MAM), Summer (JJA) and Autumn (SON) were defined according to standard procedures in meteorology.

2.3. Cloud Fraction estimation

Clouds have a strong impact in the Earth's radiation budget by modifying the shortwave (SW) and longwave (LW) radiative fluxes. From RCMs it is possible to obtain radiation fluxes considering the presence (all sky) or absence (clear sky) of clouds. In this work, clear sky and all-sky shortwave downward radiation are used in order to estimate the cloud fraction simulated by the WRF model. In this sense, a shortwave radiative cloud fraction (SWRCLF) was defined as the ratio of the global solar radiation downward to clear-sky radiation as suggested by Deardorf (1978), Crawford and Duchon (1999), Choi et al. (2008) and Gubler et al., (2012):

$$SWRCLF = 1 - \frac{SW_{all_sky}}{SW_{clear_sky}}$$

SW_{all_sky} is the all-sky shortwave downward radiation at the surface, and SW_{clear_sky} is the clear sky shortwave downward radiation that reaches the Earth's surface. The ratio $SW_{all_sky}/SW_{clear_sky}$ expresses the reduction of solar radiation mainly due to clouds, with values near one representing clear-sky conditions and near zero a total cloud cover. It should be noticed that the SWRCLF is not exactly a cloud fraction, in particular it never attains the value 1. Despite being different from the cloud cover estimated by the meteorological observers, this definition linked to the light attenuation by clouds, may be used as a proxy to cloud fraction, with the advantage of that it is directly applicable in the field of solar energy, as it is an indicator of the cloud effect on its availability at the surface. In this work, the term *clear sky days* means days without clouds or partially cloudy and refer to SWRCLF values lower than or equal to 0.10 (less than 1 okta ~ 0.13).

2.4 Statistical error measures and methods

The results of global radiation for each station were compared with the ground-based measurements in order to assess the quality of the simulations. The mean bias (BIAS), mean absolute error (MAE), mean absolute percentage error (MAPE), root mean square error (RMSE) and correlation coefficient (r) were calculated and are defined as:

$$BIAS = \frac{1}{N} \sum_{i=1}^N (m_i - o_i)$$

$$MAE = \frac{1}{N} \sum_{i=1}^N |m_i - o_i|$$

$$MAPE = \frac{MAE}{\frac{1}{N} \sum_{i=1}^N o_i}$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (m_i - o_i)^2 \right]^{\frac{1}{2}}$$

$$r = \frac{\sum_{i=1}^N (o_i - \bar{o}) - (m_i - \bar{m})}{[\sum_{i=1}^N (o_i - \bar{o})^2 \sum_{i=1}^N (m_i - \bar{m})^2]^{\frac{1}{2}}}$$

where N is the number of data and m and o are respectively the model simulation and observed values. We defined normalized bias (NBIAS), and normalized root mean square error (NRMSE) as respectively BIAS and RMSE divided by the $SW\downarrow$ mean.

2.5 Statistical BIAS correction methodology

In this study a BIAS correction was applied, based on the methodology proposed by Piani et al. (2010) where a detailed description may be found. The implementation described in Hagemann et al. (2011) was followed. The methodology is based on the adjustment of a transfer function that “transforms” the original simulated dataset in a corrected set with the same probability distribution function (PDF) as the observed set. In order to adjust the transfer function, the simulated and observed time series, of the same length and for the same period, are sorted in ascending order and plotted one versus another. The transfer function, with a few set of parameters is then the result of a fitting procedure. In general, different kinds of functions can be tested, but Hagemann et al. (2011) found that in the majority of the cases a two-parameter linear fit is sufficient.

In this study, data from the Clouds and the Earth’s Radiant Energy System (CERES) were used as the observations, in order to correct the WRF5 model outputs. The CERES experiment is one of the scientific satellite instruments developed for NASA's Earth Observing System (EOS). The first CERES instrument was launched in December of 1997 aboard NASA's Tropical Rainfall Measurement Mission (TRMM) satellite. CERES instruments are now installed also on three separate satellite missions, including the EOS Terra and Aqua observatories more recently on the Suomi National Polar-orbiting Partnership (S-NPP) observatory. CERES is a set of three co-aligned broadband radiometer detectors whose spectral ranges are 8 to 12 μ m for infrared, 0.3 to 5 μ m for shortwave and 0.3 to 100 μ m for global radiation. CERES products include both solar-reflected and Earth-emitted radiation from the top of the atmosphere to the Earth's surface. The Energy Balanced and Filled (EBAF) surface products (Kato et al., 2013) are used in this study corresponding to the Surface Downwelling Shortwave Radiation and Surface

Downwelling Clear-Sky Shortwave Radiation, for the period March 2000 until December 2009. CERES data were obtained from NASA website (ceres.larc.nasa.gov) and are available on a monthly basis with a $1^{\circ} \times 1^{\circ}$ horizontal resolution. Detailed information about CERES origins, instrument calibrations, source of errors among other technical features, can be found in Wielicki et al. (1996).

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3. Regional Climate model simulations: Assessment and BIAS correction

3.1 Comparison of daily and seasonal simulated $SW\downarrow$ against observations

Figure 3a shows the daily BIAS values of $SW\downarrow$ and it is found that for the majority of the stations the model overestimates the $SW\downarrow$ with values of approximately 30 W/m^2 . The highest BIAS values are mostly located in the north/northeastern part of IP (Asturias, Basque Country and Catalonia) with values between $30 - 50\text{ W/m}^2$. In the central part of IP, WRF5 overestimates the $SW\downarrow$ by 30 W/m^2 . At southwest and southeast, WRF5 tends to underestimate observations exhibiting values in the range of -20 W/m^2 to 0 W/m^2 .

The mean BIAS in WRF5 is consistent with the one obtained for Spain by Ruiz-Arias et al. (2016). These authors found a mean BIAS of approximately 29 W/m^2 over the period 2003-2012, with highest values along the Cantabrian coast and mountains as in the case of present WRF5 analysis.

Figure 3. Daily BIAS (a) and correlation coefficient (b) for the WRF5. BIAS in W/m^2 . (In the computation of the correlation, the annual cycle was not suppressed).

WRF5 daily simulation shows highest RMSE at the northern regions of IP (not shown here), especially over the Basque country (above $80 W/m^2$) and smallest values in central and south regions over IP ($65 W/m^2$).

Daily correlation coefficients between ground-based observations and WRF5 (figure 3b) show that WRF5 performs better in the central part of IP, with high correlation coefficients, above 0.80. North/northwestern regions of IP present the smallest r values (above 0.6). It is important to notice that the correlation coefficient is insensitive to biases and thus it only explains the spatial similarities/differences between simulations and

observations for the various stations over the figure. Table 2 summarizes the errors found for daily values.

Table 2. Performance of WRF model for both resolutions in a daily and seasonal basis (spatially averaged values over the IP).

	Resolution	DAILY	DJF	MAM	JJA	SON
<i>BIAS</i> (W/m^2)	WRF5	29.9	25.1	43.6	37.1	22.1
	WRF9	31.8	17.1	47.6	45.4	21.1
<i>MAE</i> (W/m^2)	WRF5	51.7	25.9	46.8	52.4	28.1
	WRF9	39.2	18.0	47.6	46.1	21.7
<i>RMSE</i> (W/m^2)	WRF5	71.6	29.7	53.9	61.7	33.0
	WRF9	55.5	21.6	51.6	52.5	25.5
<i>r</i>	WRF5	0.8	0.9	0.8	0.6	0.9
	WRF9	0.9	0.9	0.9	0.8	0.9

As detailed in section 2.2, the seasonal analysis was done considering only fifteen ground-stations. The seasonal BIAS shows similar spatial patterns to the results obtained for the daily BIAS analysis. WRF5 is able to simulate the seasonal evolution of $SW\downarrow$ (see figure 4), although an overall overestimation can be seen in the majority of the ground-based stations for all seasons, with only two exceptions: Sines (south-west coast of Portugal) and Ibiza (Spanish Mediterranean island).

Figure 4. Seasonal BIAS and correlation coefficient for $SW\downarrow$ compared with ground-based observational data. BIAS in W/m^2 .

WRF5 performance is better in winter and autumn in comparison with spring and summer (see Table 2). The smallest mean BIAS error is found in autumn (22 W/m^2) and the highest value for spring (44 W/m^2), which may be related to the larger variability of cloud conditions over the area in springtime (Salgueiro et al., 2014). According to Ramos et al. (2014), the cyclonic weather type over IP has a maximum in spring, imposing a considerably large cloud radiative effect as documented in Salgueiro et al., 2016. RMSE are relatively high in spring and summer, with values above 50 W/m^2 (Table 2), and the smallest errors are found in the southwestern region and southeastern coast of Iberian Peninsula (not show here), in line with the spatial distribution obtained for BIAS analysis (Figure 3a).

WRF5 seasonal errors are also consistent with the monthly errors found by Ruiz-Arias et al. (2016). The worst statistical results obtained in the mountainous regions of Cantabria and the Pyrenees suggest that the model, at this resolution, has limited skill in representing orographic clouds. However, this topic needs further investigation. Ruiz-Arias et al. (2016), suggest that the BIAS found in WRF could be a result of an underestimation of the actual cloud amount, and possibly, a misrepresentation of the radiative impact of low cumulus clouds.

Seasonal correlation coefficient varies between 0.6 in summer and ~ 0.9 in autumn, with large spatial dispersion in spring and especially in summer. The poor performance of the model in summer was also found by Dasari et al. (2014) for temperature, and it may be explained by an incorrect quantification of the aerosol effects, since the model uses a monthly mean distribution of aerosols (Collins et al., 2004) and not actual values. Cardoso et al. (2013) also found small correlation coefficients in summer precipitation as a result of a combination of strong surface heating, instability and the connected convection over some parts of IP. According to Alapaty et al. (2012), NWP models do not consider

cumulus cloud feedbacks in radiation at a subgrid-scale, and these effects can cause a bias in shortwave and longwave radiation. This may also explain the relatively high RMSE found in our analysis.

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3.2 Comparison with other validated WRF simulation

The WRF5 performance is additionally investigated by comparison with results obtained from the previously validated WRF9 experiment, where continuous model integration was performed.

Table 2 and figure 5 show the results of the comparison with the observation, for both models.

Figure 5. Correlation coefficients and statistical errors (NBIAS, NMAE and NRMSE) over IP, in the 2000-2009 period for WRF5 and WRF9.

In general, WRF5 and WRF9 overestimate the observed $SW\downarrow$, either on a daily or on a seasonal basis. Daily NBIAS of $SW\downarrow$ in WRF5 is slightly smaller than in WRF9, whereas with respect to the MAPE, NRMSE and correlation coefficients, WRF9 shows a slightly better performance than WRF5. Daily NBIAS values show, for both configurations, errors below 17%. NRMSE for WRF5 are larger than for WRF9, with values of $\sim 40\%$ and $\sim 30\%$, respectively. The correlation coefficients between daily simulated and observed $SW\downarrow$, for both experiences during the whole period compared (2000-09) are greater than 0.8, revealing a good model behaviour

Seasonal NBIAS of $SW\downarrow$ show that the WRF5 forecast has a slightly better performance than WRF9, with values varying between $\sim 13\%$ and $\sim 28\%$. With respect to the NRMSE, WRF5 (WRF9) forecast shows values in the range of $\sim 22\%$ ($\sim 19\%$) in summer and $\sim 33\%$ ($\sim 24\%$) in winter (see Figure 5). MAPE shows that WRF5 slightly outperforms WRF9 in spring with an error of $\sim 22\%$, and in the summer season with an error of $\sim 16\%$. Seasonal correlation coefficients produce very similar results with high correlations, for both experiences, especially in autumn ($r \geq 0.9$). It can be observed in Figure 5, that for both experiences, the errors show a clear seasonal dependence.

Our errors present the same magnitude as those of other studies such as Lorenz et al. (2009) over the south of Spain, with NRMSE between irradiance forecasts and observations in the range of 20% to 35%.

The use of different parameterizations in numerical models inevitably leads to different results (Cossu and Hocke, 2014; Mercader et al., 2010) but, according to this analysis, statistical errors obtained in WRF5 and WRF9 are in agreement for $SW\downarrow$ and presents comparable errors.

The comparisons of the simulations obtained in both experiments with the observations show that the quality of the prediction of solar radiation by the WRF5 simulation, which

uses the less conventional technique of annual re-initializations, is not lower than the previously validated WRF9 simulation.

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3.3 Statistical BIAS correction and comparison against observations

The BIAS between models and observations may be reduced by applying a BIAS correction. This methodology was applied to $SW\downarrow$ radiation by Ruiz-Arias et al. (2015). Following the methodology described in Hagemann et al. (2011), summarized in section 2.5, the shortwave all sky and clear sky shortwave radiative fluxes at the surface were corrected using the CERES dataset. To obtain the transfer function, WRF and CERES data were spatially averaged over IP for the common period. The transfer function, shown in figure 6, was obtained using monthly average values.

Figure 6. Transfer functions obtained from WRF data and CERES data on a monthly basis for $SW\downarrow$ (a) and clear Sky $SW\downarrow$ (b). The functions were obtained from monthly spatial mean values over IP for 2000-2009 period.

Figure 6b also reveals that the model produces higher clear sky shortwave radiation than estimated by CERES. The SWRCLF was determined from the BIAS corrected WRF5 clear sky radiation parameter.

The transfer function obtained was applied to all modelled values, at all grid points and time steps. The corrected values were then compared with ground-based observations for

the same period. Note that these time series are independent from the CERES data used to compute the transfer function. Figure 7 shows the correlation and the NBIAS between WRF5 and ground-based observed $SW\downarrow$ fluxes, for the 2000-2009 period, after BIAS correction.

Figure 7 (a) NBIAS (in percentage) and (b) correlation coefficient (c) NRMSE and (d) MAPE for $SW\downarrow$ over 2000-2009 period between model and observations for several Iberian ground-based stations.

The analysis of figure 7 shows a strong correlation between WRF5 $SW\downarrow$ and observations, with a mean correlation of the order of ~ 0.97 , improving the scores obtained before the BIAS correction (see section 3.1). The differences between model and observations were significantly reduced after the correction. The mean NBIAS fell from

17% to 7% ($\sim 11\text{W/m}^2$). The corrected NBIAS are close to those shown in Ruiz-Arias et al. (2015). NRMSE (figure 7c) and MAPE (figure 7d) dropped respectively from 39% to 18% and from 28% to 14%.

In general, WRF5 simulations show a very similar performance when compared with observational ground-based data, WRF9 and CERES data, which increases the confidence in the climatology that will be addressed in the next section.

4. SW↓ climatology over the Iberian Peninsula for 1950-2010 period

Figure 8 illustrates the climatological 60 year mean SW↓ over IP, at a 5 km horizontal resolution, obtained from the WRF5 simulations after applying the post-processing BIAS correction methodology.

Figure 8 Sixty-year annual mean for the 1950-2010 period of, (a) SW↓ and (b) standard deviation. Values are in W/m^2 .

During this period, the mean SW↓ ranged from a minimum of $\sim 140 W/m^2$ in the north of IP to a maximum value above $\sim 230 W/m^2$ at the south corresponding to a spatial average value of $\sim 190 W/m^2$. The spatial distribution clearly shows a gradient increasing from north to south and from west to east modelled by the effects of the coast and topography. Ruiz-Arias et al. (2015) also found this gradient, with lower irradiation values northward.

In Spain, Andalusia and Murcia are the regions with the highest SW↓. The greatest mean value of SW↓ ($\sim 230 W/m^2$) was found in Granada and Almeria. The lowest mean values are associated with the west and north Atlantic coastal zone and range between $\sim 140 W/m^2$ and $\sim 180 W/m^2$. The smallest values are found in Coruna (Galicia –

Spain). For Portugal, the central and southern parts (Alentejo and Algarve) are those with the highest mean $SW\downarrow$ values (above $\sim 200 W/m^2$). This pattern is, in general, consistent with the study conducted by Sanchez-Lorenzo et al. (2009) for Spain, over the 1985-2010 period, which used observational sunshine duration data.

The SW variability (annual standard deviation) is relatively high in the northern part of IP, particularly in Galicia (Spain), with an average value of $\sim 105 W/m^2$. For Portugal, Minho and Douro Litoral (at north) are the regions where the $SW\downarrow$ variability is larger, with averages above $100 W/m^2$. The spatial distribution of $SW\downarrow$ during the four seasons is depicted in Figure 11 and reveals values that range from a minimum of $50 W/m^2$, in winter, to a maximum around $325 W/m^2$, in the summer season. Maximum $SW\downarrow$ values are found over the south of Portugal and Spain. The lowest $SW\downarrow$ values, independently of the season, are found over north/northeast regions of IP. High variability (standard deviation) is found in spring and summer seasons (figures 9), especially along the Atlantic coastal regions, with values above $80 W/m^2$. This same high variability was found by Ruiz-Arias et al. (2015), with the Cantabrian coast presenting lower values of radiation in comparison with the rest of Spain.

Figure 9. Spatial seasonal average in the period 1950-2010 for $SW_{\downarrow}$, Winter (DJF), Spring (MAM), Summer (JJA), Autumn (SON), and standard deviation in Winter (STD_DJF), Spring (STD_MAM), Summer (STD_JJA) and Autumn (STD_SON). Values are in W/m^2 .

Annual cycles of $SW\downarrow$ and $SWRCLF$, obtained from monthly means over land, are plotted in figure 10. These plots show, as expected, an annual pattern for $SW\downarrow$ with maximum values in summer, presenting a peak of 340 W/m^2 (median value) in July and an inverse pattern for $SWRCLF$, with a minimum peak in June and July (0.04). It should be noted that $SWRCLF$ is computed using $SW\downarrow$, which reinforces their interdependence.

Figure 10. Annual cycle of monthly mean area averaged $SW\downarrow$ (a) and $SWRCLF$ (b) over IP for the 1950-2010 period. The horizontal solid line within the box represents the median. The bottom and top of the boxes indicate the first and third quartiles, respectively. The circles and crosses represent outliers. The lower and upper ends of the whiskers are the minimum and maximum values of the datasets, respectively. $SWRCLF$ varies between 0 (without clouds) and 1 (overcast).

The shape of the boxplots show that the data distributions are generally symmetrical (see box and respective median). The interquartile ranges are relatively small in July and August for $SW\downarrow$ and $SWRCLF$, which suggest a low inter-annual variability (long periods with no clouds) during summer. $SW\downarrow$ variability is higher in March and September. For $SWRCLF$, larger spreads are obtained in the months of autumn and winter (figure 10b). In those months, upper quartiles have values above 0.2 as expected and in accordance with the results obtained by Sanchez-Lorenzo (2009), for total cloud cover in Spain. The boxplots of Figure 10 allow for the identification of potential outliers. The

existence of outliers may be partially explained by the interannual variability in the frontal system tracks affecting the region (Ramos et al., 2014; Trigo et al., 2002) and by the irregular occurrence of Saharan dust events (Obregón et al., 2015; Wagner et al., 2009; Alados-Arboledas et al., 2003). These events are not taken into account by the numerical model since the concentration and properties of the aerosols are fixed in the WRF simulations (Collins et al., 2004).

Figure 11 shows maps of the percentage of clear sky days for the whole period and over two selected months: August and December. The maps show a high percentage of days without clouds, especially over central, south (Andalusia and Algarve) and northeast (Catalonia) parts of IP. Over these regions, more than 30% of the days may be considered as clear sky (less than 1 okta - SWRCLF less or equal to 0.1 for a conservative perspective, since the synoptic scale of WMO considers clear sky days until 2 oktas for the recording of the total cloud cover).

Figure 11 Percentage of clear sky days of (a): daily, (b) August and (c) December. Values are in percentage.

In December, for over 2/3 of the Iberian Peninsula (north coastal regions of Portugal until Tagus River, Galicia and Basque Country), the percentage of clear sky days is less than 10% of the days in all period. However, areas along Spanish Mediterranean coast (Southeastern part of Andalusia, Murcia, Valencian community and Catalonia) present more than 30% of clear sky days, even in December. On the other hand, in August, the

percentage of clear sky days is above 70% in more than half of the Iberian Peninsula (central and south). This result is consistent with Ridao et al. (2007), which found that Andalusia (south of Spain) is the region with the greatest potential of all European regions for the implementation of solar energy systems.

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5 Conclusions

A high resolution climatology of $SW\downarrow$ solar radiation over IP, obtained from simulations performed using the WRF model at 5 km resolution (WRF5) is presented in this work. The comparison between WRF5 and observations for the downward shortwave radiation at the surface shows a good performance, although with a slight overestimation of radiation. The results indicate that the model simulations were significantly improved after applying a BIAS correction using CERES data. The daily BIAS over central IP was approximately 28 W/m^2 (~17%) before BIAS correction and 7% after. In the northern coastal regions, namely in Galicia, Asturias, Cantabria and Basque Country, daily BIAS are above 40 W/m^2 (before BIAS correction). Similar results were obtained for the seasonal analysis. Correlation coefficients obtained from the comparisons between the observations and the model results are high, above 0.8 for 70% of the ground-based stations. Seasonal correlation coefficients show a lower correlation in summer and higher values in autumn with values between 0.4 (summer) and 0.9 (autumn).

The WRF5 strategy, based on multiple one year time-slices, was found to be a valid alternative to the more computationally time demanding strategy based on continuous model integration, as its results exhibit a similar behaviour and comparable errors to those obtained in a previously validated WRF run simulation at 9km (WRF9). NRMSE for $SW\downarrow$ ranges from 22 W/m^2 to 39 W/m^2 , for WRF5 and 18 W/m^2 to 30 W/m^2 , for WRF9 configuration. Regardless of the season, WRF9 always presents smaller NRMSE than WRF5.

The errors found in the present work, although mitigated by the application of a BIAS correction, may be related with a misrepresentation of clouds at higher spatial resolution (see Lara-Fanego et al., 2012b), and first of all, by an incorrect quantification of the

aerosol effects, since the run uses a monthly mean distribution of aerosols (Collins et al., 2004) and not actual values. In fact, the main limitation of this work is the failure to take into account the evolution of aerosol distribution over the Iberian Peninsula, which is known to have been very important during the last century (see for example Mateos et al., 2014; Antón et al., 2017). This misrepresentation of the aerosols may introduce large temporal and spatial deviations and prevents the utilization of the simulated series for trend analysis, as the uncertainties related to the non aerosol inclusion are larger than those resulting from solar radiation changes. Future works should take into account the spatial and temporal evolution of aerosol loads.

The IP climatology of $SW\downarrow$ produced for the 1950-2010 period confirms the existence of two gradients (latitudinal and longitudinal). Regions with higher $SW\downarrow$ values are situated in the southeastern regions of IP (Andalusia and Murcia). The lowest values of mean $SW\downarrow$ were found in the northwestern region of Galicia. The variability of $SW\downarrow$ also increases from south to north and from east to west directions with higher values over Galicia.

The cloud cover was also evaluated following the definition proposed by Crawford and Duchon (1999) namely the shortwave radiative cloud fraction (SWRCLF). Results show that the southern half of the Iberian Peninsula has a larger part of its territory with more than 30% of clear sky days during the period under study, and these values are substantially higher in summer months (above 80% for almost all territory).

The $SW\downarrow$ radiation climatology obtained from the WRF 5km simulations is a solid base in the planning of renewable power plants on solar resources, providing estimates in areas where there are no measurements. It should however be taken into account that aerosols can attenuate on average 10 to 20% of the horizontal irradiance and even more when

desert dust aerosols are present. Thus the simulation results presented should be used with some caution since a monthly mean distribution of aerosols was considered.

The presented climatology points out Andalusia (Spain), Murcia (Spain), Alentejo (Portugal) and Algarve (Portugal) as the regions with the greatest $SW\downarrow$ potential to implement solar energy systems, allowing to identify, at a fine scale, the areas that have higher solar potential.

Based on these results, it can be stated that WRF simulations over Iberian Peninsula represent relatively well the downward solar radiation at the surface after a simple BIAS correction and can be used to study the future distribution of solar radiation over the region, according to different climate change scenarios.

Conflict of Interests

The authors declare there is no conflict of interests with regard to this manuscript.

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References

- Acharya, N., Chattopadhyay, S., Mohanty, U. C., Dash, S. K., Sahoo, L. N., 2013. On the bias correction of general circulation model output for Indian summer monsoon. *Meteorological Applications* 20 (3), 349-356, doi: 10.1002/met.1294
- Alados-Arboledas, L., Lyamani, H., Olmo, F. J., 2003. Aerosol size properties at Armilla, Granada (Spain), *Q.J.R. Meteorol. Soc.* 129, 1395-1413, doi: 10.1256/qj.01.207.
- Alapaty, K., Herwehe, J. A., Otte, T. L., Nolte, G., Bullock, O. R., Mallard, M. S., Kain, J. S., Dudhia, J., 2012. Introducing subgrid-scale cloud feedbacks to radiation for regional meteorological and climate modelling. *Geophys. Res. Lett.* 39, L24809. doi:10.1029/2012GL054031.
- Alsamamra, H., Ruiz-Arias, J. A., Pozo-Vázquez, D., Tovar-Pescador, J., 2009. A comparative study of ordinary and residual kriging techniques for mapping global solar radiation over southern Spain. *Agricultural and Forest meteorology* 149 (8), 1343-1357, <https://doi.org/10.1016/j.agrformet.2009.03.005>
- Alexandru, A., de Elia, R., Laprise, R., Separovic, L., Biner, S., 2008. Sensitivity study of regional climate model simulations to largescale nudging parameters. *Mon Wea Rev* 137, 1666–1686, doi:10.1175/2008MWR2620.1
- Antón, M., R. Román, A. Sanchez-Lorenzo, J. Calbó, J.M. Vaquero, 2017. Variability analysis of the reconstructed daily global solar radiation under all-sky and cloud-free conditions in Madrid during the period 1887-1950. *Atmospheric Research* 191, 94-100, <http://dx.doi.org/10.1016/j.atmosres.2017.03.013>.
- Berrisford, P., Dee, D., Fielding, K., Fuentes, M., Kallberg, P., Kobayashi, S., Uppala, S., 2009. The ERA-Interim Archive. ERA Report Series. 1. Technical Report. European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading, pp16.

- Betts A.K., 1986. A new convective adjustment scheme. Part I: Observational and theoretical basis. *Quart. J. Roy. Meteor. Soc.* 112, 677–691.
- Betts, A.K., Miller, M.J., 1986. A new convective adjustment scheme. Part II: Single column tests using GATE wave, BOMEX, and arctic air-mass data sets. *Quart. J. Roy. Meteor. Soc.* 112, 693–709.
- Cardoso, R. M., Soares, P. M. M., Miranda, P. M. A., Belo-Pereira, M., 2013. WRF high resolution simulation of Iberian mean and extreme precipitation climate. *International Journal of Climatology* 33 (11), 2591-2608, DOI: 10.1002/joc.3616.
- Choi, M., Jacobs, J. M., Kustas, W. P., 2008. Assessment of clear and cloudy sky parameterizations for daily downwelling longwave radiation over different land surfaces in Florida. USA. *Geophys. Res. Lett.* 35, L20402, doi:10.1029/2008GL035731
- Collins, W. D., Rasch, P. J., Boville, B. A., Hack, J. J., McCaa, J. R., Williamson, D. L., and Zhang, M., 2004. Description of the NCAR community atmosphere model (CAM 3.0). NCAR Tech. Note NCAR/TN-464+ STR, 226.
- Cossu, F., Hocke, K., 2014. Influence of microphysical schemes on atmospheric water in the Weather Research and Forecasting model. *Geoscientific Model Development* 7(1), 147-160.
- Crawford, T. M., Duchon, C. E., 1999. An improved parameterization for estimating effective atmospheric emissivity for use in calculating daytime downwelling longwave radiation. *J. Appl. Meteorol.* 38, 474–480.
- Dasari, H. P., Salgado, R., Perdigao, J., Challa, V. S., 2014. A Regional Climate Simulation Study Using WRF-ARW Model over Europe and Evaluation for Extreme Temperature Weather Events. *International Journal of Atmospheric Sciences*, Article ID: 704079, 22 p.

- Deardorff, J. W., 1978. Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation. *Journal of Geophysical Research: Oceans* 83 (C4), 1889-1903.
- Dudhia, J. 2014. A history of mesoscale model development. *Asia-Pacific Journal of Atmospheric Sciences* 50 (1), 121-131, DOI:10.1007/s13143-014-0031-8.
- Ehnberg, J. S., Bollen, M. H., 2005. Simulation of global solar radiation based on cloud observations. *Solar Energy* 78 (2), 157-162, DOI: 10.1016/j.solener.2004.08.016
- Ehret, U., Zehe, E., Wulfmeyer, V., Warrach-Sagi, K., Liebert, J., 2012. Should we apply bias correction to global and regional climate model data?. *Hydrology and Earth System Sciences* 16 (9), 3391-3404, doi: 10.5194/hess-16-3391-2012
- Feser, F., Rockel, B., Von Storch, H., Winterfeldt, J., Zahn, M., 2011. Regional climate models add value to global model data: a review and selected examples. *Bulletin of the American Meteorological Society* 92 (9), 1181, <https://doi.org/10.1175/2011BAMS3061.1>
- García, R. D., Cuevas, E., García, O. E., Cachorro, V. E., Pallé, P., Bustos, J. J., Romero-Campos, P. M., de Frutos, A. M., 2014. Reconstruction of global solar radiation time series from 1933 to 2013 at the Izaña Atmospheric Observatory. *Atmos. Meas. Tech.* 7, 3139-3150, doi:10.5194/amt-7-3139-2014
- Giorgi, F., Mearns, L. O., 1999. Introduction to special section: Regional Climate Modeling Revisited, *J. Geophys. Res.* 104 (D6), 6335–6352, doi:10.1029/98JD02072.
- Grell, G.A., Devenyi, D., 2002. A generalized approach to parameterizing convection combining ensemble and data assimilation techniques. *Geoph. Res. Let.* 29 (14), doi: 10.1029/2002GL015311

- Gubler, S., Gruber, S., Purves, R. S., 2012. Uncertainties of parameterized surface downward clear-sky shortwave and all-sky longwave radiation. *Atmospheric Chemistry and Physics* 12 (11), 5077-5098.
- Haddeland, I., Heinke, J., Voß, F., Eisner, S., Chen, C., Hagemann, S., Ludwig, F., 2012. Effects of climate model radiation, humidity and wind estimates on hydrological simulations. *Hydrology and Earth System Sciences* 16 (2), 305-318, doi:10.5194/hess-16-305-2012
- Hagemann, S., Chen, C., Haerter, J. O., Heinke, J., Gerten, D., Piani, C., 2011. Impact of a statistical bias correction on the projected hydrological changes obtained from three GCMs and two hydrology models. *Journal of Hydrometeorology* 12 (4), 556-578, <http://dx.doi.org/10.1175/2011JHM1336.1>
- Haylock, M.R., Hofstra, N., Tank A.M.G. K., Klok E.J., Jones P.D., New, M., 2008. A European daily high-resolution gridded dataset of surface temperature and precipitation. *J. Geophys. Res. Atmospheres* 113, D20119, doi:10.1029/2008JD10201.
- Hong, S-Y., J. Dudhia, and S.H. Chen, 2004. A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. *Mon. Weather Rev.* 132, 103 – 120.
- Hong S-Y., Lim J-OJ, 2006. The WRF single-moment 6-class microphysics scheme (WSM6). *J. Korean Meteorol. Soc.* 42, 129–151.
- Hong, S-Y. Noh, Dudhia, J., 2006. A new vertical diffusion package with an explicit treatment of entrainment processes. *Mon. Wea. Rev.* 134, 2318–2341, doi:10.1175/MWR3199.1.
- Hong, S-Y., Chang, E-C., 2012. *Asia-Pacific J. Atmos. Sci.* 48, 345-355 doi:10.1007/s13143-012-0033-3

- Hong, S-Y. & Kanamitsu, M., 2014. Asia-Pacific J, Atmos, Sci, 50: 83, doi:10.1007/s13143-014-0029-2
- IPCC, 2014: Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R.Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J.Savolainen, S. Schlömer, C. Von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Janjic ZI., 1990. The step-mountain coordinate: physical package. Mon. Weather Rev. 118, 1429–1443.
- Janjic ZI., 1994. The step-mountain eta coordinate model: further developments of the convection, viscous sublayer and turbulence closure schemes. Mon. Weather Rev. 122, 927–945.
- Janjic ZI., 2000. Comments on “development and evaluation of a convection scheme for use in climate models”. J. Atmos. Sci. 57, 3686.
- Janjic ZI, 2001. Nonsingular implementation of the Mellor–Yamada level 2.5 scheme in the NCEP meso model. NCEP office note 437, 61 pp
- Jerez, S., Trigo, R. M., Sarsa, A., Lorente-Plazas, R., Pozo-Vázquez, D., Montávez, J. P., 2013. Spatio-temporal complementarity between solar and wind power in the Iberian Peninsula. Energy Procedia 40, 48-57.
- Jones R.G., Murphy, J.M., Noguer, M., 1995. Simulation of climate change over Europe using a nested regional-climate model. I: Assessment of control climate, including sensitivity to location of lateral boundaries. Quart. J. Roy. Meteor. Soc. 121, 1413–1449.

- Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., and Zhu, Y., 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* **77** (3), 437-471.
- Kato, S., Loeb, N. G., Rose, F. G., Doelling, D. R., D., Rutan, A., Caldwell, T. E., Yu, L., Weller, R. A., 2013. Surface irradiances consistent with CERES-derived top-of-atmosphere shortwave and longwave irradiances. *J. Climate* **26**, 2719–2740.
- Lara-Fanego, V., Ruiz-Arias, J. A., Pozo-Vázquez, D., Santos-Alamillos, F. J., Tovar-Pescador, J., 2012a. Evaluation of the WRF model solar irradiance forecasts in Andalusia (southern Spain). *Solar Energy* **86** (8), 2200-2217, doi:10.1016/j.solener.2011.02.014
- Lara-Fanego, V., Ruiz-Arias, J.A., Pozo-Vázquez., A. D., Gueymard, C. A., Tovar-Pescador, J., 2012b. Evaluation of DNI forecast based on the WRF mesoscale atmospheric model for CPV applications. In *AIP Conference Proceedings-American Institute of Physics*, vol. 1477, no. 1, p. 317, <http://dx.doi.org/10.1063/1.4753895>
- Laprise, René, 2008. Regional climate modelling. *Journal of Computational Physics* **227** (7), 3641-3666.
- Lo, J. C. F., Yang, Z. L., Pielke Sr., R. A., 2008. Assessment of three dynamical climate downscaling methods using the Weather Research and Forecasting (WRF) model. *J. Geophys. Res.* **113**, D09112, doi:10.1029/2007JD009216.
- Lorenz, E., Remund, J., Müller, S. C., Traunmüller, W., Steinmaurer, G., Pozo, D., Kurz, C., 2009. Benchmarking of different approaches to forecast solar irradiance. In *24th European photovoltaic solar energy conference, Hamburg, Germany* (Vol. 21, p. 25).
- Marteau, R., Richard, Y., Pohl, B., Smith, C. C., Castel, T., 2015. High-resolution rainfall variability simulated by the WRF RCM: application to eastern France. *ClimateDynamics* **44** (3-4), 1093-1107.

- Martín, L., Zarzalejo, L. F., Polo, J., Navarro, A., Marchante, R., Cony, M., 2010. Prediction of global solar irradiance based on time series analysis: Application to solar thermal power plants energy production planning. *Solar Energy* 84 (10), 1772-1781, doi: 10.1016/j.solener.2010.07.002
- Mateos, D., Antón, M., Toledano, C., Cachorro, V. E., Alados-Arboledas, L., Sorribas, M., Costa, M. J., Baldasano, J. M., 2014. Aerosol radiative effects in the ultraviolet, visible, and near-infrared spectral ranges using long-term aerosol data series over the Iberian Peninsula. *Atmos. Chem. Phys.* 14, 13497-13514, <https://doi.org/10.5194/acp-14-13497-2014>, 2014.
- Mercader, J., Codina, B., Sairouni, A., Cunillera, J., 2010. Results of the Meteorological Model WRF-ARW over Catalonia using different parameterizations of convection and cloud microphysics. *Tethys* 7, 75-86, <http://dx.doi.org/10.3369/tethys.2010.7.07>
- Miguez-Macho G., Stenchikov, GL, Robock, A., 2004. Spectral nudging to eliminate the effects of domain position and geometry in regional climate model simulations. *J. Geophys. Res.* 109, D13104, doi:10.1029/2003JD004495
- Obregón, M.A., Pereira, S., Salguero, V., Costa, M. J., Silva, A. M., Serrano, A., Bortoli, D., 2015. Aerosol radiative effects during two desert dust events in August 2012 over the Southwestern Iberian Peninsula. *Atmospheric Research* 153, 404–415.
- Perdigão, J. C., Salgado, R., Costa, M. J., Dasari, H. P., Sanchez-Lorenzo, A., 2016. Variability and trends of downward surface global solar radiation over the Iberian Peninsula based on ERA-40 reanalysis. *Int. J. Climatol.*, 36, 3917–3933. doi:10.1002/joc.4603
- Piani, C., Weeden, G. P., Best, M., Gomes, S. M., Viterbo, P., Hagemann, S., Haerter, J. O., 2010. Statistical bias correction of global simulated daily precipitation and

- temperature for the application of hydrological models. *Journal of Hydrology* 395, 199-215, doi:10.1016/j.jhydrol.2010.10.024
- Raju, A., Parekh, A., Chowdary, J. S., Gnanaseelan, C., 2015. Assessment of the Indian summer monsoon in the WRF regional climate model. *Climate Dynamics* 44 (11-12), 3077-3100, Doi 10.1007/s00382-014-2295-1
- Ramos, A. M., Cortesi, N., Trigo, R. M., 2014. Circulation weather types and spatial variability of the daily precipitation in the Iberian Peninsula. *Frontiers in Earth Science* 2, 1-17, doi: 10.3389/feart. 00025.
- Ridao, A. R., Garca, E. H., Escobar, B. M., Toro, M. Z., 2007. Solar energy in Andalusia (Spain): present state and prospects for the future. *Renewable and Sustainable Energy Reviews* 11 (1), 148-161.
- Rios-Entenza, A., Soares, P. M., Trigo, R. M., Cardoso, R. M., Miguez-Macho, G. 2014. Moisture recycling in the Iberian Peninsula from a regional climate simulation: Spatiotemporal analysis and impact on the precipitation regime. *Journal of Geophysical Research. Atmospheres* 119 (10), 5895-5912, doi: 10.1002/2013JD021274
- Ruiz-Arias, J. A., Terrados, J., Pérez-Higueras, P., Pozo-Vázquez, D., Almonacid, G. 2012. Assessment of the renewable energies potential for intensive electricity production in the province of Jaén, southern Spain. *Renewable and Sustainable Energy Reviews* 16 (5), 2994-3001, doi: 10.1016/j.rser.2012.02.006
- Ruiz-Arias, J. A., Quesada-Ruiz, S., Fernández, E. F., Gueymard, C. A., 2015. Optimal combination of gridded and ground-observed solar radiation data for regional solar resource assessment. *Solar Energy* 112, 411-424, <http://dx.doi.org/10.1016/j.solener.2014.12.011>

- Ruiz-Arias, J. A., Arbizu-Barrena, C., Santos-Alamillos, F. J., Tovar-Pescador, J., Pozo-Vázquez, D., 2016. Assessing the Surface Solar Radiation Budget in the WRF Model: A Spatiotemporal Analysis of the Bias and Its Causes. *Monthly Weather Review* 144(2), 703-711, <http://dx.doi.org/10.1175/MWR-D-15-0262.1>
- Rummukainen, M., 2010. State of the art with Regional Climate Models. *Wiley Interdisciplinary Reviews: Climate Change* 1 (1), 82-96.
- Salgueiro, V., Costa, M. J., Silva, A. M., Bortoli, D., 2014. Variability of the Daily-Mean Shortwave Cloud Radiative Forcing at the Surface at a Midlatitude Site in Southwestern Europe. *J. Climate* 27, 7769–7780, <http://dx.doi.org/10.1175/JCLI-D-13-00696.1>
- Salgueiro, V., Costa, M. J., Silva, A. M., Bortoli, D., 2016. Effects of clouds on the surface shortwave radiation at a rural inland mid-latitude site. *Atmospheric Research*, in press.
- Santabàrbara, J. M., Calbó, J., Baldasano, J. M., Esteve, J., Mitjà, A., 1996. Month-to-month variation of global solar radiation in Catalonia (SPAIN). *Int. J. Climatol.*, 16, 711–721, doi:10.1002/(SICI)1097-0088(199606)16:6<711::AID -JOC42>3.0.CO;2-M
- Sanchez-Lorenzo, A., Calbó, J., Brunetti, M., Deser, C., 2009. Dimming/brightening over the Iberian Peninsula: Trends in sunshine duration and cloud cover and their relations with atmospheric circulation. *Journal of Geophysical Research* 114, D00D09, doi:10.1029/2008JD011394.
- Sanchez-Lorenzo, A., Wild, M., Trentmann, J., 2013. Validation and stability assessment of the monthly mean CM SAF surface solar radiation dataset over Europe against a homogenized surface dataset (1983–2005). *Remote Sens. Environ.* 134, 355–366.

- Santos-Alamillos, F. J., Pozo-Vázquez, D., Ruiz-Arias, J. A., Lara-Fanego, V., Tovar-Pescador, J., 2012. Analysis of spatiotemporal balancing between wind and solar energy resources in the southern Iberian Peninsula. *Journal of Applied Meteorology and Climatology* 51(11), 2005-2024, doi: 10.1175/JAMC-D-11-0189.1
- Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Duda, M. G., Huang X.-Y., Wang, W., Powers, J. G., 2008. A Description of the Advanced Research WRF Version 3. NCAR Technical Note, NCAR/TN-475+STR. Mesoscale and Microscale Meteorology Division, National Center for Atmospheric Research, Boulder, CO, USA,
- Soares, P. M., Cardoso, R. M., Miranda, P. M., de Medeiros, J., Belo-Pereira, M., Espirito-Santo, F., 2012. WRF high resolution dynamical downscaling of ERA-Interim for Portugal. *Climate Dynamics* 39 (9-10), 2497-2522, doi 10.1007/s00382-012-1315-2
- Soares, P. M., Cardoso, R. M., Semedo, Á., Chinita, M. J., Ranjha, R., 2014. Climatology of the Iberia coastal low-level wind jet: weather research forecasting model high-resolution results. *Tellus A* 66, <http://dx.doi.org/10.3402/tellusa.v66.223777>
- Stanhill G, Cohen, G. 2001. Global dimming: a review of the evidence for a widespread and significant reduction in global reduction with discussion of its probable causes on possible agriculture consequences. *Agric. For. Meteorol.* 107, 255–278, doi: 10.1016/S0168-1923(00)00241-0.
- Stauffer, D. R., Seaman, N. L., 1990. Use of four-dimensional data assimilation in a limited-area mesoscale model. Part I: Experiments with synoptic-scale data. *Monthly Weather Review* 118 (6), 1250-1277, [http://dx.doi.org/10.1175/1520-0493\(1990\)118<1250:UOFDDA>2.0.CO;2](http://dx.doi.org/10.1175/1520-0493(1990)118<1250:UOFDDA>2.0.CO;2)

- Šúri, M., Hofierka, J., 2004. A New GIS-based Solar Radiation Model and Its Application to Photovoltaic Assessments. *Transactions in GIS* 8, 175–190, doi:10.1111/j.1467-9671.2004.00174.x
- Šúri, M., Huld, T. A., Dunlop, E. D., Ossenbrink, H., A., 2007. Potential of solar electricity generation in the European Union member states and candidate countries. *Solar energy* 81 (10), 1295-1305, doi:10.1016/j.solener.2006.12.007
- Trigo, R. M., Osborn, T. J., Corte-Real, J. M., 2002. The North Atlantic Oscillation influence on Europe: climate impacts and associated physical mechanisms. *Climate Research* 20 (1), 9-17.
- Von Storch, H., Langenberg, H., Feser, F., 2000. A spectral nudging technique for dynamical downscaling purposes. *Mon. Wea. Rev.* 128, 3664–3673.
- Wagner, F., Bortoli, D., Pereira, S., Costa, M. J., SILVA, A., Weinzierl, B., Tegen, I., 2009. Properties of dust aerosol particles transported to Portugal from the Sahara desert. *Tellus B* 61 (1), 297-306, doi: 10.1111/j.1600-0889.2008.00393.x
- Waldron, K.M, Peagle, J., Horel, J.D., 1996. Sensitivity of a spectrally filtered and nudged limited area model to outer model options. *Mon. Wea. Rev.* 124, 529–547.
- Wielicki, B. A., Barkstrom, B. R., Harrison, E. F., Lee III, R. B., Louis Smith, G., Cooper, J. E., 1996. Clouds and the Earth's Radiant Energy System (CERES): An earth observing system experiment. *Bulletin of the American Meteorological Society* 77 (5), 853-868, [http://dx.doi.org/10.1175/1520-0477\(1996\)077<0853:CATERE>2.0.CO;2](http://dx.doi.org/10.1175/1520-0477(1996)077<0853:CATERE>2.0.CO;2)
- Wild, M., Gilgen, H., Roesch, A., Ohmura, A., Long, C. N., Dutton, E. G., Tsvetkov, A., 2005. From dimming to brightening: Decadal changes in solar radiation at Earth's surface. *Science* 308 (5723), 847-850.
- WMO., 2008. Guide to Meteorological Instruments and Methods of Observation. WMO-No. 8, Seventh edition.

- Xue, Y., Janjic, Z., Dudhia, J., Vasic, R., De Sales, F., 2014. A review on regional dynamical downscaling in intraseasonal to seasonal simulation/prediction and major factors that affect downscaling ability. *Atmospheric Research* 147, 68-85, <http://dx.doi.org/10.1016/j.atmosres.2014.05.001>
- Yhang, YB., Hong, SY., 2011. A study on large-scale nudging effects in regional climate model simulation. *Asia-Pacific J. Atmos. Sci.* 47 (235), doi:10.1007/s13143-011-0012-0
- APREN: <http://www.apren.pt/pt/projectos/nacionais/estudo-apren-deloitte/>
- APREN: http://www.apren.pt/fotos/editor2/impacto_fer_relatorio_final_20140930.pdf
- IDAE: <http://informeestadistico.idae.es/t10.htm>
- DGAE: <http://www.dgeg.pt/>

Highlights

- ↪ Manuscript presents an evaluation of shortwave Solar Radiation ($SW\downarrow$) at the surface in the Iberian Peninsula (IP) from 1950 to 2010 using the Weather Research and Forecasting (WRF) NWP model, at high resolution – 5km;
- ↪ Simulations obtained with annual re-initializations (time-slices) were compared with observations and with another WRF configuration operating with a continuous run;
- ↪ WRF strategy, based on multiple one year time-slices, was found to be a valid alternative to the more computationally time demanding strategy based on continuous model integration
- ↪ WRF simulations over IP represent relatively well the $SW\downarrow$ (after post-processing methodology) and can be used to study the future distribution of Solar Radiation over the region as a qualitative approach;
- ↪ A climatology of $SW\downarrow$ and cloud fraction (after a post-processing methodology), over Iberian Peninsula is done and results show that the southern half of the IP has a larger part of the territory with clear sky days;