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Evaluation of two MM5-PBL parameterizations for solar radiation and temperature estimation in the South-Eastern area of the Iberian Peninsula

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Summary. — We study the relative performance of two different MM5-PBL parameterizations (Blackadar and MRF) simulating hourly values of solar irradiance and temperature in the south-eastern part of the Iberian Peninsula. The evaluation was carried out throughout the different seasons of the year 2005 and for three different sky conditions: clear-sky, broken-clouds and overcast conditions. Two integrations, one per PBL parameterization, were carried out for every sky condition and season of the year and results were compared with observational data. Overall, the MM5 model, both using the Blackadar or MRF PBL parameterization, revealed to be a valid tool to estimate hourly values of solar radiation and temperature over the study area. The influence of the PBL parameterization on the model estimates was found to be more important for the solar radiation than for the temperature and highly dependent on the season and sky conditions. Particularly, a detailed analysis revealed that, during broken-clouds conditions, the ability of the model to reproduce hourly changes in the solar radiation strongly depends upon the selected PBL parameterization. Additionally, it was found that solar radiation RMSE values are about one order of magnitude higher during broken-clouds and overcast conditions compared to clear-sky conditions. For the temperature, the two PBL parameterizations provide very similar estimates. Only under overcast conditions and during the autumn, the MRF provides significantly better estimates.

PACS `92.60.Fm` – Boundary layer structure and processes.
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1. – Introduction

The release of the 4th IPPC assessment report has put in evidence that Europe faces real climate challenges. Particularly, the report warns about that there is a more than 50% chance that European (and global) temperatures will rise during this century by more than 5 °C due to the increases in the greenhouse gases concentration in the atmosphere. As is known, the energy use and transformation is responsible for more than 90% of these greenhouse emissions. In March 2007, the European Commission proposed a package to provide solutions to these challenges. The central pillar of this package is an accelerating shift towards a "*low carbon energy*". Particularly, the Commission proposes to maintain the EU's position as a world leader in renewable energy, by promoting that a binding target of 20% of its overall energy mix be obtained from renewable energy by 2020. This will require a massive growth in all three renewable energy sectors: electricity, bio-fuels, heating and cooling. To meet this 20%, target research will be crucial. A particular area that will need considerable research is the evaluation and forecasting of renewable energy resources. The renewable energies have the advantage of a smaller incidence in the environment in comparison with other energy sources; however, their production is conditioned by variations in the weather and in the climate.

The Spanish National Renewable Energy Plan 2005-2010 (PER) aims to cover the 12% of the primary energy using renewable energies by 2010. In terms of electric generation, this implies to increase the renewable energy dependence from the current 20% to a 30% level. Regarding the solar energy, the PER allows for around new 400 MW of photovoltaic (PV) and around 500 MW of thermoelectric solar power plants. This strong increment of the dependence, along with the inherent variability to the renewable energy resources, highlights problems related to the security and management of the supply. Particularly, the future success of the solar-based electricity generation is associated with the incorporation of the production to the Electric Market. This implies that the solar electric producers should assure a concrete injection of energy in the electric net.

To sum up, to reach the energy policies goals and to obtain a greater role of the electric generation from solar origin it is necessary to allow the integration of the solar energy production inside the structures of the current energy supply system. It is in this context where the detailed and in advance knowledge of the available solar energy resources has a strategic importance [1].

Recently, the use of Numerical Weather Prediction Models (NWPs) to simulate the Earth's climate has substantially grown. The NWPs are expected to have the potential to satisfy the requirements in forecasting solar irradiance for up to 72 hours. Global numerical weather prediction models have usually a coarse resolution and do not allow for a detailed mapping of small-scale features.

The MM5 model, Mesoscale Model of 5th generation (MM5), developed at the Penn State University/National Center for Atmospheric Research (PSU/NCAR) [2], is probably the most intensively used around the world and extensively assessed NWP model. The MM5, particularly, has a wide number of parameterizations which allow adapting the model to the specific climatic conditions of a particular region. Additionally, it presents a non-hydrostatic dynamics that makes it suitable for high spatial resolution simulations ($\sim$ km). Finally, it can be configured to account for the effects of the topography and the aerosols on the solar radiation estimates.

Very few studies have addressed the issue of the evaluation of solar irradiance evaluation and forecast using NWPs as the MM5. There are some evaluation studies in single locations in the USA [3, 4]. Additionally, solar radiation forecasts of the ETA model of the National Environmental Prediction Center (NCEP) of the USA have been evaluated in South America [5]. Sánchez-Sánchez *et al.* [6] carried out some preliminary works on this field. Particularly, they evaluated high resolution (1 km and 4 km) MM5 solar radiation estimates in Jaén (Spain).

It should be noted that the skill of a simulation with a NWP model depends on factors as the model itself [7], soil specifications [8], spatial configuration [9], boundary conditions [10], region and season [11], and, particularly, on the physical options such the parameterizations [12, 13]. The latter, particularly, are a key issue. Despite the high resolution of NWPs, a number of physical processes that occur at sub-grid scale have to be represented in the model by approximate parameterizations. The range of validity of these parameterizations is constrained and they may be valid only in certain regions or seasons, or, even more, for particular variables or timescales. The question to arise is whether or not there is a single set of parameterizations that provides the best estimates for a particular study, *i.e.* for a particular region, variable, temporal and spatial scale, and whether or not the same set remains the optimal throughout the annual cycle and for different meteorological variables.

As mentioned above, the MM5 has a wide number of parameterizations which makes possible adapting the model to the specific climatic conditions of a particular region. The MM5 parameterizations allow for representing the explicit moisture, cumulus, radiation and planetary boundary layer (PBL) processes. Turbulence is critical to the prediction of the temperature and radiation, the two magnitudes of interest in this work. The PBL parameterization determines the fluxes near the earth surface. The strong interaction that takes place between the radiation, the clouds and the soil schemes of the NWPs rules the temperature and solar radiation estimated by the model at the earth surface.

Several studies have dealt with the selection of different parameterization for the MM5 [14, 15]. Most of them are focused on the short-range forecast and coarse resolution and mainly focused on precipitation. There are also parameterization evaluation studies of the MM5 specifically for the Iberian Peninsula [13], but mainly focused on the inter-annual climate variability and the monthly scale. Regarding the PBL, the MM5 have seven different parameterizations, and few works have evaluated the sensitivity of the MM5 estimates to these parameterizations. For instance, Zhang and Zheng [16] conducted a 3-day case study in summertime over central United States to test the effects of five boundary layer parameterizations on MM5 simulations of diurnal cycle of surface wind and temperature. Berg and Zhong [17] investigated the sensitivity of high-resolution MM5 simulations to three PBL parameterizations by using observations from two field campaigns over limited areas of United States. Zhiwei *et al.* [18] evaluated five different PBL parameterizations for the Asian region. Although these works all provide valuable results, none of them dealt with the solar radiation.

The main goal of this work is to evaluate the performance of two different MM5-PBL parameterizations, namely the Blackadar and the MRF, in simulating hourly values of solar irradiance and temperature throughout the year. The study has been carried out for the year 2005, in the area of Huéneja (Granada), in the south-eastern part of the Iberian Peninsula. In this area, several Concentration Solar Power Plants (CSP), more than 300 MW in total, are under construction. Solar radiation and temperature forecasts are a key issue for operating this kind of solar plants [19].

A set of integrations, using the two PBL parameterizations, were carried out and results were evaluated using measured data. Given the importance of the sky conditions and the season of the year, the evaluation is carried out explicitly for different sky conditions along the seasons of the year. The final aim is to determine the best MM5 set-up,

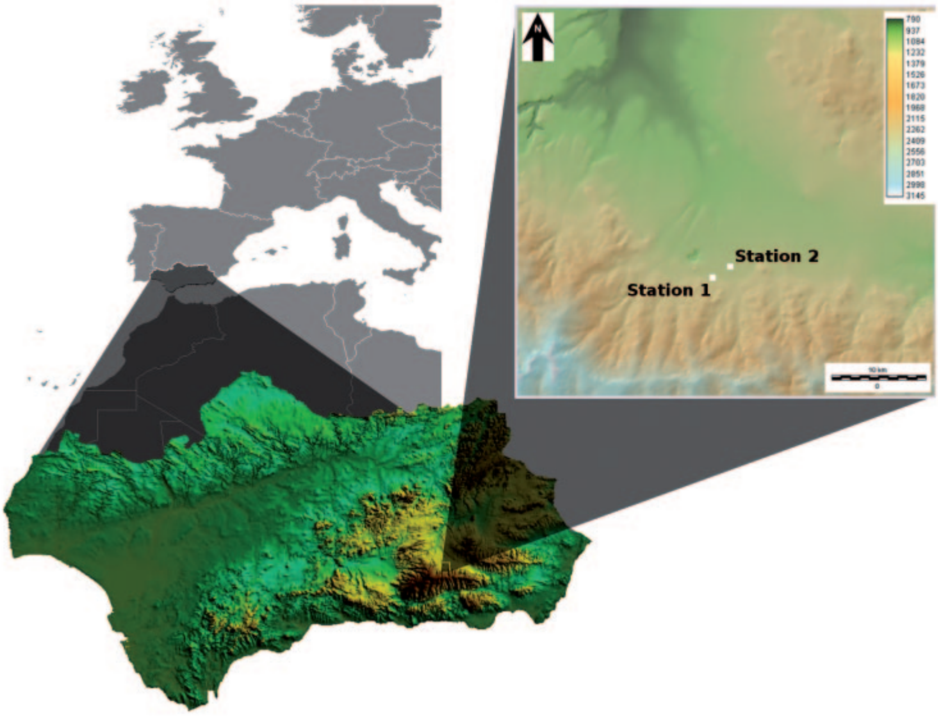

Fig. 1. – Location of the study area in Andalucia, south of Spain.

regarding the PBL parameterization, for solar radiation and temperature estimation and forecasting in the study area.

The work is organized as follows: in sect. **2** the experiment design is presented, including the MM5 set-up, the description of the study area and the observational data. The comparison between the model runs and the observations are carried out in sect. **3**. Finally, a summary of the results and conclusions are provided in sect. **4**.

2. – Experiment design

2˙1. *Study area and observations.* – The region of the study (fig. 1) is located in the eastern part of Andalusia (Southern Iberian Peninsula). As commented above, the area has an enormous interest for solar-radiation–related research, since it has been planned to build several CSP plants totaling more than 300 MW. This will make this region as one of the areas of the world with greatest renewable energy production.

The simulation domain of the MM5 integrations extends over an area of 400 km^2, located in a plateau with a mean elevation of 1100 m and surrounded by several mountain ridges. The climate is that typical of the Mediterranean climate, somehow modified by the relatively high elevation of this region. Particularly, summer is dry and hot, with mainly convective precipitation. Winters are cold and precipitation is mainly snow, while relatively high precipitation is found in autumn and spring. During these seasons, precipitation is mainly caused by large-scale synoptic systems, totalling about 400 mm. Vegetation in all the study area is relatively homogeneous, mainly grass and bush, so the influence of the land cover on the results is believed low.

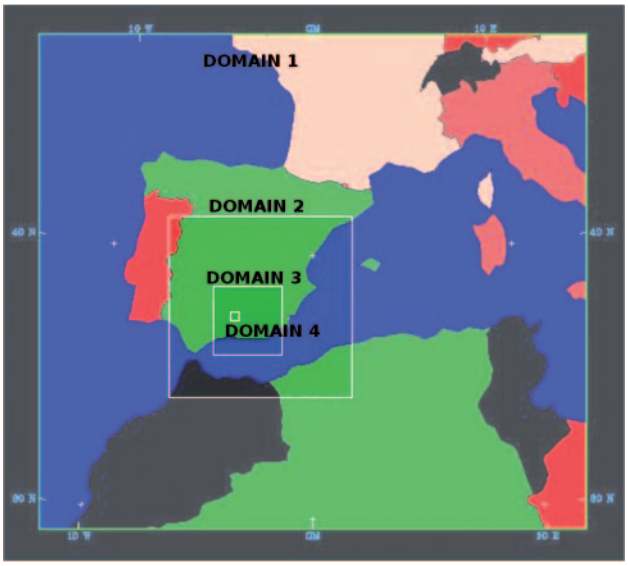

Fig. 2. – Domains used in the simulations. The coarser domain (D1) has a horizontal resolution of 108 km, D2 has 36 km, D3 12 km. Finally, the inner domain (D4) is set to a 4 km grid spacing.

Data collected during the year 2005 at two meteorological stations were employed for evaluating the MM5 estimates. The two stations are located roughly in the middle of the study area (fig. 1), at 1120 m and 1090 m elevation, with a separation distance of about 1.5 km. Temperature was gathered using Onset TMC6-HB probes, while LICOR LI-200SZ pyranometers were used for measuring the incoming solar radiation. The radiometers are calibrated periodically using a Kipp-Zonnen pyranometer. The data of this network have been used in other studies [20]. All data were recorded on a 2.5 minute basis and hourly integrations were then computed.

Since in the MM5 integration every grid point is representative of an area of 4×4 square kilometres, the MM5 results were tested not against data collected at a single station but rather against a synthetic data base obtained by averaging the values obtained at the two stations. This evaluation procedure, along with the relatively homogeneous land cover and topographic conditions of the study area, ensures a meaningful evaluation of the MM5 estimates.

2˙2. *MM5 set-up*. – The aim of this work is to evaluate the ability of different PBL MM5 parameterizations in reproducing the temperature and solar radiation in the study area at hourly scale. In this section, both the spatial and physical MM5 set-ups selected are presented.

The spatial configuration of the MM5 used in this work consisted in four nested domains (fig. 2) and twenty four unevenly spaced sigma levels. The coarser domain (D1) has a horizontal resolution of 108 km, the next one (D2) has 36 km, the third (D3) 12 km. Finally, the inner domain (D4) is set to 4 km grid-spacing. Estimates corresponding to the grid point of this inner domain that enclosed the two stations are used in the evaluation procedure. Two-way nesting was used to feed the information between domains. Atmospheric initial and boundary conditions were extracted from

Table I. – *List of the main MM5V3.6 physical schemes and parameterizations. The parameterizations used in the present work are identified in boldface. Note the two highlighted PBL parameterizations.*

Explicit moisture	Cumulus	PBL	Radiation
1. Dry	1. None	0. None	0. None
2. Stable precip.	2. Anthes-Kuo	1. Bulk PBL	1. Simple cooling
3. Warm rain	3. Grell	**2. Blackadar**	**2. Cloud**
4. Simple ice	4. Arakawa-Shubert	3. Burk-Thompson	3. CCM2
5. Mixed-phase	5. Fritsch-Chappell	4. Eta	4. RRTM
6. Goddard	**6. Kain-Fritsch**	**5. MRF**	
	7. Bett-Miller	6. Gayno-Seaman	
	8. Kain-Fritsch	7. Pleim-Chang	

the analysis produced by the European Centre for Medium-Range Weather Forecasting (ECMWF), available every 6 hours. A spin-up of one day is applied at the beginning of all the integrations.

The MM5 modelling system allows the choice of a wide range of options for the different physical parameterizations, particularly, for explicit moisture, cumulus convection, radiation, soil and planetary boundary layer (PBL). Table I shows the main options available in the MM5 v.3.7.2 version, used in this work. All these schemes play an important role in the estimation of the solar radiation and temperature by the MM5 modelling system.

Based on the existing literature, the variables and time scales of interest and given the region of study, a first choice of the explicit moisture, the cumulus and radiation schemes was carried out (highlighted in bold face in table I). Regarding the PBL parameterization, two options were evaluated: Blackadar and MRF. The rationales behind these choices are explained in the next paragraphs.

Regarding the explicit moisture parameterization, two different parameterizations are commonly used for middle-latitude studies: the Simple-Ice [21] and the Mixed-Phase [22]. The two parameterizations are similar, being the main difference that the Mixed-Phase includes supercooled water and slow melting of snow. In this evaluation work, following Fernández *et al.* [13], we have used the Mixed-Phase one.

Regarding the cumulus convection, again two schemes are usually employed in the latitudes of the study area: the Grell [2] and Kain-Fritsch [23]. The main differences between these schemes are that the Kain-Fritsch depends on a temperature perturbation proportional to the grid-scale vertical velocity and the convective available potential energy (CAPE), while the Grell depends on the rate of change of destabilization due to advection. Both parameterizations have showed a good performance in several situations and regions [24]. In this work, following Fernández *et al.* [13], we have used the Kain-Fritsch scheme. Since convective clouds could be resolved by the explicit moisture scheme at grid scales less than 10 km, the cumulus parameterization has been only used for domains one and two.

Two different radiation parameterizations are commonly used: the Cloud (or Dhudia scheme) [21] and the Rapid Radiative Transfer Model (RRTM) [25]. The irradiance parameterization of the Cloud scheme is based on the Lacis and Hansen [26] model, that

Table II. – *Simulation time periods with the MM5 for each sky condition and season. All the dates correspond to the year 2005.*

	Winter	Spring	Summer	Autumn
Clear sky	31–3 February(*)	9–12 April	28–30 August	4–6 October
Broken clouds	8–10 February	10–12 June	15–17 July	10–11 October
Overcast	5–7 February			8–9 October

(*) This period corresponds to 31 January to 3 February.

considers that solar radiation varies with cloud amount and composition, humidity and the zenith angle of the Sun. The RRTM is an accurate long-wave scheme that represents a detailed absorption spectrum taking into account water vapour, carbon dioxide, methane, nitrous oxide and ozone. As short-wave scheme, the RRTM uses the Cloud scheme. Since the main focus of this work is the solar resource, the Cloud scheme was used.

For all the integrations, the ground temperature is given by a five-layer soil model [27] with a soil moisture prescribed according to soil characteristics and season.

The MM5 has seven different parameterizations for the PBL. In this work, we have only considered two of them: the Blackadar [28] and MRF [29] schemes. They are the best-performing PBL parameterizations according to many previous studies [16, 17, 30]. The Blackadar scheme deals with the stable and unstable regimes differently. In the nocturnal regime, a first-order closure approach based on K-theory is used to determine the turbulent fluxes. In that case, mixing is assumed to occur only between adjacent model layers. In contrast, the free-convective regime employs a nonlocal approach where buoyant plumes from the surface layer mix directly with all other layers within the PBL. The MRF scheme is also a first-order, nonlocal scheme based on the results of the large-eddy simulations. It uses nonlocal K-theory during unstable conditions in which the counter gradient transports of temperature and moisture are added to the local gradient transports. The eddy diffusivities are obtained from a prescribed profile shape. During stable stratification the local K-approach is utilized for all prognostic variables, in a way similar to that used in Blackadar scheme but with a different stability categorization.

2˙3. *MM5 integrations.* – Since this work is mainly focused on the evaluation of the MM5 solar radiation estimates, and given the enormous influence of the sky conditions on the solar radiation, different experiments were considered to account for different sky conditions. Particularly, three sky conditions were considered: clear-sky, broken-clouds and overcast conditions. A clearness index, based on the measured radiation values, was used to evaluate these sky conditions. Particularly, the clearness index, k_t, is defined as the ratio of the hemispherical horizontal total global solar irradiance, I_G (measured with an unshaded pyranometer), to the horizontal total extraterrestrial irradiance:

$$k_t = \frac{I_G}{I_0 \cos Z}\,, \tag{1}$$

where I_0 is the normal extraterrestrial irradiance and Z is the solar zenith angle. A clearness index greater than 0.7 was used for clear-sky days, between 0.7 and 0.4 for broken-clouds and less than 0.4 for overcast conditions.

Table III. – *Evaluation results of the MM5 solar irradiance estimates, under clear-sky conditions, for the two PBL parameterizations indicated in table I. Irradiance values are given in* Wm^{-2}.

PBL Param.	Winter (31-3 Feb.)		Spring (9-12 Apr.)		Summer (28-30 Aug.)		Autumn (4-6 Oct.)	
	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE
Blackadar	−14.7	39.0	8.2	131.9	−13.8	32.3	17.1	59.6
MRF	−12.9	38.5	4.2	117.2	−12.8	31.8	17.5	60.0

Based on this classification, a set of at least two consecutive days (table II) of clear-sky, broken-clouds and overcast conditions were selected for each season of the year 2005. Note that the overcast conditions were only evaluated for winter and autumn (no set of consecutive overcast days was found for summer and spring). Two integrations were carried out for each of the set of days in table II: one using the Blackadar PBL parameterization and one using the MRF one. For the rest of the parameterizations, the selected schemes were those highlighted in bold in table I. Hourly solar radiation at the Earth's surface and temperature at 2 meters estimates, resulting from the integrations, were evaluated in terms of the Mean Bias Error (MBE) and the Root-Mean-Square Error (RMSE). The MBE quantified the overall bias and detects if the model is producing overestimation or underestimation, while the RMSE accounts for the spread of the error distribution. All error estimates are computed using hourly values along the whole simulated period. In the case of solar radiation, only diurnal values (values different from zero) were considered.

3. – Results

In this section, an analysis of MM5 solar radiation and temperature estimates, using two PBL parameterizations, is presented.

3˙1. *Clear-sky conditions.* – Table III shows the results of the evaluation of solar radiation MM5 estimates, under clear-sky conditions and for the different seasons of the year, for the two PBL parameterizations. Overall, the MM5 shows considerable skills in estimating the solar radiation under clear-sky conditions along the whole year. RMSE values remain relatively low, ranging from around $30\,\mathrm{W/m^2}$ in summer to around $130\,\mathrm{W/m^2}$ in spring, when the highest RMSE values are found. Additionally, from the analysis of the MBE values, one can derive the existence of a general tendency to overestimate the solar radiation in winter and summer and to underestimate the radiation in autumn and spring. Differences between the performances of the two PBL parameterizations are relatively low, except during spring. For this season, the Blackadar parameterization shows higher RMSE and MBE than MRF one. Note that in autumn the Blackadar shows slightly better estimates than the MRF.

Figure 3 shows the estimated, both using the Blackadar and the MRF parameterizations, and measured values of the solar radiation for spring. These seasons present the greatest differences between MM5 estimates. The MM5 clearly overestimates the solar radiation around solar noon, with error values of around $100\,\mathrm{W/m^2}$. During winter, autumn and summer (not shown) this overestimation is lower (around $50\,\mathrm{W/m^2}$). Note

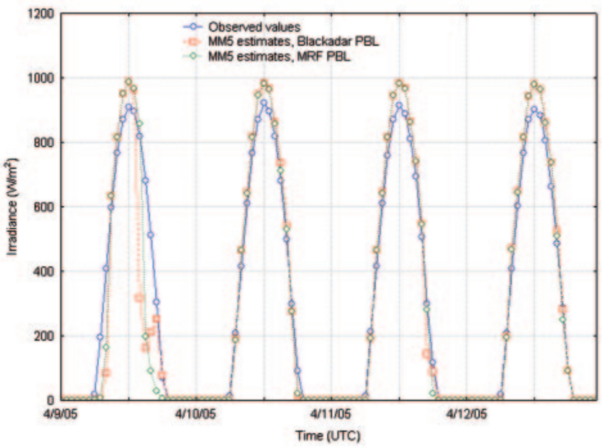

Fig. 3. – Solar irradiance predicted by MM5, using the Blackadar and MRF PBL parameterizations, and measured solar irradiance, as a function of time for 9-12 Apr. 2005.

that MM5 estimates errors are relatively high around solar noon, while the rest of the day remain lower. The better performance of the MRF PBL parameterization (table III) is associated with better estimates during the second part of the first day; the rest of the simulation estimates are similar. Results can be explained in the light of the MM5 solar radiation scheme and the conditions of the study area. The solar irradiance parameterization used in this work, the Cloud or Dhudia scheme, is based on the Lacis and Hansen [26] model. Particularly, this parameterization considers solar radiation changes with cloud amount and composition, humidity and the zenith angle of the Sun. Additionally, to account for aerosol and other scattering effect, a clear-sky scattering factor of 0.1 is assumed by the model. Finally, this solar radiation scheme neglects stratospheric ozone absorption.

Zamora *et al.* [3] evaluated MM5 predicted fluxes against observations in several locations of the USA. They found that the Dudhia parameterization overestimated the solar radiation during summer. They also showed that the accuracy of the model forecast was strongly dependent on the aerosol optical depth (AOD), with errors that might reach $100\,\mathrm{W/m^2}$ when the AOD exceeds the climatological 0.1 value. Nevertheless, they concluded that the Dudhia solar parameterization provides accurate solar irradiance estimates as long as AOD remains near 0.1. In another work, Zamora *et al.* [4] analyzed the MM5 solar radiation forecasts in three elevated surface ozone events in the USA, finding that ozone absorption accounts for around $30\,\mathrm{W/m^2}$ of error in the MM5 estimates during summer clear sky. Our study region can be regarded as a very low pulluted atmosphere area. Particularly, population of the area is scarce and the agricultural activities are limited. Additionally, a great part of the area is within a natural park. Therefore, it is expectable that the AOD values during evaluation days were not higher than 0.1. This means that the Cloud parameterization should provide reasonable results; provided the ozone absorption is accounted for. Therefore, it could be concluded that most part of the MM5 estimates errors may be related with the unaccounted ozone absorption effect.

Table IV shows the results of the evaluation of two PBL parameterizations for the temperature. Overall, there is a clear tendency to underestimate its observed value.

Table IV. – *As in table III but for temperature estimates. Temperature values are given in* °C.

PBL Param.	Winter (31-3 Feb.)		Spring (9-12 Apr.)		Summer (28-30 Aug.)		Autumn (4-6 Oct.)	
	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE
Blackadar	2.0	2.8	3.2	3.7	1.9	2.8	2.4	3.2
MRF	1.8	2.7	2.9	3.5	1.5	2.5	2.1	3.0

This cold bias holds for the four seasons, but the absolute magnitude of this underestimation is greater in spring and autumn. Particularly, MBE ranges from around 1.5 °C in winter to more than 3 °C in spring, and RMSE ranges from almost 3 °C in winter and summer to almost 4 °C in spring. The performance of the two PBL parameterizations is similar. Particularly, differences in terms of the RMSE are lower than the observational uncertainty.

Figure 4 shows the estimated, both using the Blackadar and MRF PBL parameterizations, and measured values of the temperature for the summer integration (the integration with the greatest difference between the MM5 estimates). Note that the model is able to properly reproduce the cycle of the temperatures, which keeps also for the rest of the seasons (not shown). Night time temperatures are accurately simulated, including minimum temperatures. Nevertheless, high errors are observed for maximum temperatures, when underestimations can reach values up to 5 °C. As a result, it could be concluded that most part of the MBE and RMSE values are associated with the underestimation of the temperature around the maximum values. The better performance of the MRF parameterization is associated with a better estimation of the maximum temperatures. Results are in accordance with other similar studies. Particularly, Akylas *et al.* [31] analyzed the MM5 temperature forecast for Greece, finding similar temperature estimates errors. Also Zhang and Zheng [16], in an evaluation study of the performance of different

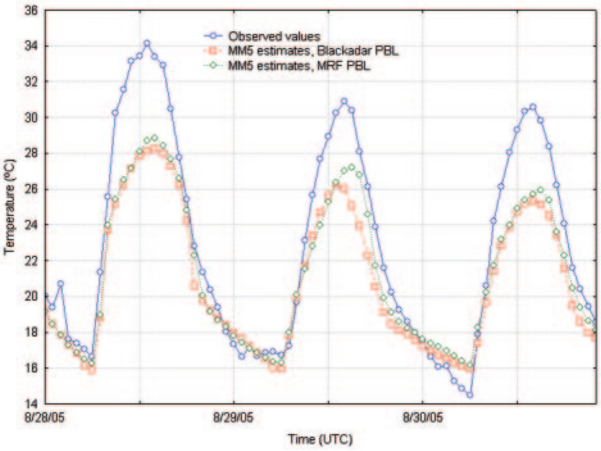

Fig. 4. – Temperature predicted by MM5, using the Blackadar and MRF PBL parameterizations, and measured temperature, as a function of time for 28-30 Aug. 2005.

Table V. – *As in table III but for broken-clouds conditions.*

PBL Param.	Winter (8-10 Feb.)		Spring (10-12 Jun.)		Summer (15-17 Jul.)		Autumn (10-11 Oct.)	
	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE
Blackadar	−75.0	210.2	−28.0	295.4	−194.3	307.0	−11.7	262.6
MRF	−125.0	239.0	−12.7	279.6	−123.2	326.2	57.0	288.2

PBL parameterizations, found a similar underestimation of the maximum temperatures during summer in the central US regions.

The relatively high errors in the MM5 maximum temperatures estimates could be explained based on a miss specification of the MM5 energy balance. Note that the diurnal cycle of land air surface temperature comes from the energy balance between the incoming solar radiation and the upward fluxes of sensible and latent heat and long-wave radiation. During clear-sky days, at the beginning of the day, solar radiation exceeds the upward fluxes and the surface warms and stores energy. Heat storage continues and temperature rises until afternoon, when increasing upward fluxes become larger than declining solar radiation. In dry regions, as those of this study, small latent heat fluxes reduce the damping effect of the net upward fluxes, and the surface air temperature is more sensitive to solar forcing than in regions where the surface is wet. It may be concluded that the relatively high MM5 underestimation of the maximum temperatures can be attributed to an excess of soil moisture in the model. This excess enhances the evapo-transpiration and, therefore, reduces the near-surface temperature. This also would explain the relatively fair estimations of the minimum temperatures. The MRF parameterization seems to provide lower surface latent fluxes, providing better maximum temperature estimates.

3˙2. *Broken clouds conditions*. – Table V shows the evaluation results of the two PBL parameterizations for the solar radiation during broken-clouds conditions. They are characterized by steep changes in the sky cloudiness along relatively short time scales. This gives rise to sharp changes in the measured solar irradiance at the Earth's surface. Therefore, from the point of view of the MM5 simulation, this situation is the more stringent.

Overall errors are, as expected, considerable higher than in the case of clear-sky conditions for all the seasons. Particularly, the RMSE values are one order of magnitude higher, ranging from around 200 $\mathrm{W/m^2}$ in winter to over 300 $\mathrm{W/m^2}$ in summer. Regarding MBE, values are also considerable higher than in the clear-sky case, but differences are lower and highly dependent on the concrete season. MM5 overestimates the solar radiation in all the seasons except in autumn, meaning an overall lack of ability of the model to simulate the presence of clouds.

Differences in the performance of the two PBL parameterizations are higher than in the clear-sky case. During winter and autumn, the Blackadar parameterization provides better estimates than the MRF, with considerable differences in terms of the MBE. During spring, nevertheless, the MRF scheme provides better estimates. Particularly, for this season, MBE values are about one half using the MRF than using the Blackadar parameterization. Finally, during summer, the Blackadar scheme provides slightly better results in terms of RMSE values. It can be then be concluded that the selection of the

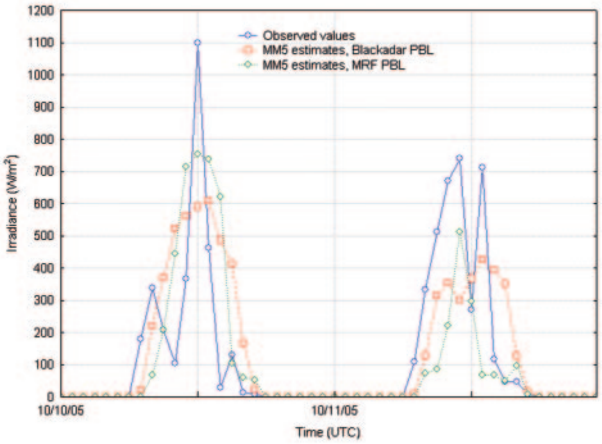

Fig. 5. – Solar irradiance predicted by MM5, using the Blackadar and MRF PBL parameterizations, and measured solar irradiance, as a function of time for 10-11 Oct. 2005.

best parameterization is, for this particular case of broken clouds, highly dependent on the season of the year.

Figure 5 shows the estimated, both using the Blackadar and MRF parameterizations, and measured values of the solar radiation for autumn integration (when differences between integrations are higher). Note that MM5 is not able to estimate the radiation during the first two days of simulation with reasonable accuracy.

Overall, the existence of cloudy conditions is well detected during these two days of simulation. Nevertheless, the model is not able to precisely reproduce, based solely on the information given by the ECMWF analysis, steep changes in the solar radiation due to moving groups of clouds. Note the existence of several peaks of measured solar irradiance associated with the presence of broken clouds. This causes strong differences between simulated and measured values associated with these peak values. The better performance of the Blackadar parameterization seems to be associated with a better estimation of the radiation during the second day of integration. Similar conclusion can be obtained when analyzing the rest of the season simulations.

To sum up, during broken-clouds conditions, the MM5 is, overall, able to notice the presence of clouds. Nevertheless, it is hardly able to resolve the continuous changes associated with the movement of the clouds. As a consequence, the solar irradiance at hourly scale is hardly resolved by the model during these conditions, although it is able to simulate the overall reduction in the radiation values. An important issue regarding this conclusion is the importance of the spatial resolution (4 km in the present work) of the integration. This question will be addressed in a future work.

Table VI presents the evaluation of the temperature estimates. Differences with the clear-sky case are highly dependent on the analyzed season. Particularly, for winter, both the MBE and RMSE errors are considerable lower than in the clear-sky case. On the other hand, during summer, errors are considerable higher than during clear-sky days and reach the maximum of all the analyzed cases in this work. Finally, during spring and autumn, errors are slightly lower. Based on the MBE values, there is a clear underestimation of the temperature during spring and summer and an overestimation

TABLE VI. – *As in table IV but for the broken-clouds conditions.*

PBL Param.	Winter (8-10 Feb.)		Spring (10-12 Jun.)		Summer (15-17 Jul.)		Autumn (10-11 Oct.)	
	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE
Blackadar	0.2	1.1	1.8	2.8	3.8	5.0	−2.2	2.8
MRF	−0.1	1.0	1.7	2.6	3.5	4.9	−1.9	2.7

during autumn. On the other hand, during winter MBE values are close to zero. The two PBL parameterizations perform similarly, with differences lower than 10%, both in terms of MBE and RMSE values. Again, differences between the two estimates errors are of the order of the observational uncertainty.

Figure 6 shows the estimated, using the two PBL parameterizations, and measured values of the temperature for the autumn integration. Note that the MM5 overestimates the temperature. This overestimation is particularly high during the late afternoon and night, reaching about 5 °C. On the other hand, maximum temperatures are reasonable well reproduced during the broken-clouds conditions. The better performance of the MRF parameterization is associated with a better estimation of the minimum temperatures. Particularly, differences in the estimates using the MRF and the Blackadar scheme even reach more than 2 °C during the second day of the integration. The considerable differences between the MM5 estimation and the ground truth during the afternoon of the first day seem to be associated with a misrepresentation of the clouds conditions by the MM5.

Regarding the winter (figure not shown), temperature estimation proved to be the most accurate among all the evaluated MM5 estimations. Particularly, the model is able to properly reproduce the maximum and minimum temperatures, with MBE close to zero and RMSE values considerable lower than in the case of clear sky. During spring, MM5

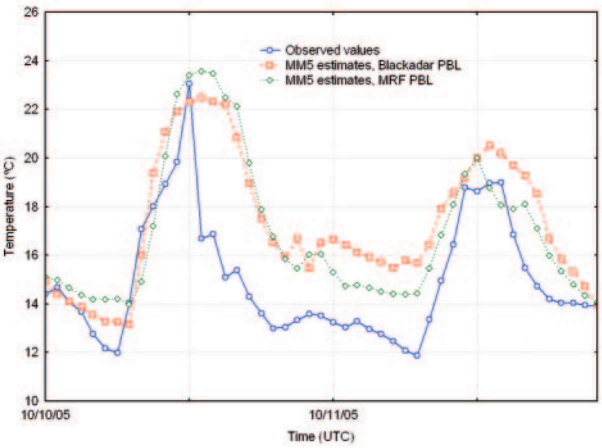

Fig. 6. – Temperature predicted by MM5, using the Blackadar and MRF PBL parameterizations, and measured temperature, as a function of time for 10-11 Oct. 2005.

TABLE VII. – *As in table III but for overcast conditions.*

PBL Param.	Winter (8-10 Feb.)		Autumn (8-9 Oct.)	
	MBE	RMSE	MBE	RMSE
Blackadar	−95.3	156.8	35.5	108.0
MRF	−119.9	182.2	12.3	97.3

fairly reproduces minimum temperatures but clearly underestimates maximum values. Finally, the high error associated with the summer integration could be related to the fact that the MM5 did not simulate the existence of clouds but, rather, simulated values resembling that of clear-sky conditions. As a consequence, the cold bias presented in the model is enhanced when real conditions were cloudy skies.

3·3. *Overcast conditions.* – Table VII shows the evaluation results for the overcast conditions. Only two periods were analyzed, from 5 to 7 of February, and from 9 to 10 of October, representatives, respectively, of the winter and autumn seasons. There was not a set of at least two consecutive overcast days during spring and summer and, therefore, these seasons were not analyzed.

Overall, solar radiation estimates show higher errors values than those of clear-sky conditions, but considerable lower than for broken-clouds conditions. Particularly, during autumn, RMSE errors are twice higher than for clear-sky conditions, but just one third higher than during broken clouds. MBE values are considerable higher and negative during winter, indicating a lack of ability of the MM5 to reproduce the presence of clouds. Differences in the ability of the two PBL parameterizations to simulate the solar radiation are considerable. Particularly, during winter, the Blackadar scheme performs better, with differences of around 15% in terms of RMSE and 20% in terms of MBE. On the other hand, the MRF scheme performs better during autumn, when MBE values are remarkably different (MBE is 35.5 W/m^2 using the Blackadar PBL and just 12.3 W/m^2 using the MRF).

Figure 7 shows the estimated, using both the Blackadar and MRF shemes, and measured values of the solar radiation during winter. Note that the model is able to reasonably simulate the overcast conditions using both PBL schemes during the first day of the integration. On the other hand, during the second day, only the simulation using the Blackadar PBL parameterization is able to reproduce the overcast conditions. Finally, during the third day of simulation the model fails to simulate the sky conditions both using the MRF or the Blackadar parameterization, and estimated values resemble those obtained during clear-sky conditions. Overall, results during overcast conditions are similar to those obtained during broken-clouds conditions.

Table VIII presents the evaluation results for the temperature under overcast conditions. Both the MBE and RMSE values are considerably lower than for the clear-sky case and as lower as for broken-clouds days. Based on the MBE values, there is a clear overestimation of the temperature during autumn, while during winter MBE is close to zero. The performance of the two PBL parameterizations is similar in winter, while in autumn some differences are found. Particularly, during autumn the MRF parameterization provides slightly better estimates in terms of the MBE. This late parameterization, therefore, can be used for these cloudiness conditions.

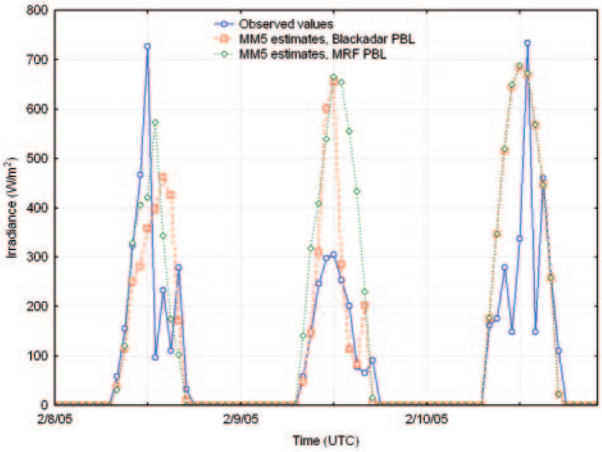

Fig. 7. – Solar irradiance predicted by MM5, using the Blackadar and MRF PBL parameterizations, and measured solar irradiance, as a function of time for 8-10 Oct. 2005.

Figure 8 shows the estimated, using the two PBL parameterizations, and measured values of the temperature during autumn. Note that the model is able to properly reproduce the cycle of temperatures. The negative MBE is associated with a notably high overestimation of the temperature during the night hours. Particularly, minimum temperatures are overestimated by more than 4 °C. On the other hand, temperatures around solar noon are fairly well reproduced, with very low error in the maximum temperature estimates. The better performance of the MRF parameterization seems to be associated with the last part of the integration, when the Blackadar parameterization provides considerably lower temperatures than the observed.

4. – Concluding remarks

A set of integrations were carried out in order to evaluate the performance of two different MM5-PBL parameterizations (Blackadar and MRF) in simulating hourly values of solar irradiance and temperature. The study was conducted in the southeastern area of the Iberian Peninsula and the evaluation was carried out for the different seasons of the year 2005. Additionally, three different sky conditions were considered: clear-sky, broken-clouds and overcast conditions. Two integrations, one per PBL parameterization, were performed for each sky condition and results were compared with observational data.

TABLE VIII. – *As in table IV but for overcast conditions.*

PBL Param.	Winter (8-10 Feb.)		Autumn (8-9 Oct.)	
	MBE	RMSE	MBE	RMSE
Blackadar	0.1	1.4	−1.7	2.1
MRF	−0.1	1.4	−1.1	1.6

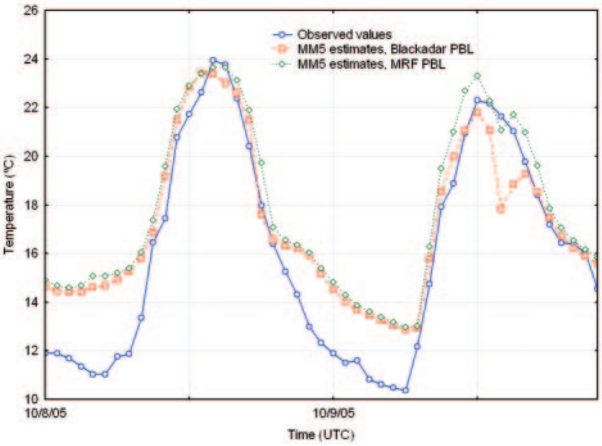

Fig. 8. – Temperature predicted by MM5, using the Blackadar and MRF PBL parameterizations, and measured temperature, as a function of time for 8-9 Oct. 2005.

Under clear-sky conditions, the model (using either of the two PBL parameterizations) showed considerable skills in estimating the solar radiation along the whole year. Particularly, RMSE values ranged from 30 W/m^2 in summer to around 130 W/m^2 in spring. Nevertheless, a tendency to overestimate the solar radiation in winter and summer and to underestimate the radiation in autumn and spring was observed. Differences between the performances of the two PBL parameterizations are relatively low, except during spring. For this season, the Blackadar parameterization shows a higher RMSE and MBE than MRF one.

Performance of the model substantially decreases for broken-clouds conditions. For such conditions, the model is able to reasonably notice the presence of clouds, but it does not satisfactorily resolve the continuous changes in the cloud cover associated with the movement of the clouds. As a consequence, estimates errors are considerably higher than for the case of clear-sky conditions for all the seasons, with RMSE ranging from 200 W/m^2 in winter to over 300 W/m^2 in summer. Differences between the performances of the two PBL parameterizations are higher than in the clear-sky case. During winter and autumn, the Blackadar parameterization provides better estimates than the MRF, but during spring, the MRF scheme provides better estimates (MBE values are about one half using the MRF than using the Blackadar parameterization). It can then be concluded that the choice of the best parameterization is, for this particular case of broken clouds, highly dependent on the season of the year. Finally, a detailed analysis revealed that, during broken-clouds conditions, the ability of the model to reproduce hourly changes in the solar radiation strongly depends on the selected PBL parameterization.

Under overcast conditions, MM5 solar radiation estimates show higher errors values than in the case of clear-sky conditions, but lower than for the broken-clouds conditions. Differences in the ability of the two PBL parameterizations in simulating the solar radiation are considerable. Particularly, during winter, the Blackadar scheme performs better, with differences of around 15% in terms of RMSE and 20% in terms of MBE. On the other hand, the MRF scheme performs better during autumn, when MBE values are remarkably different (MBE is 35.5 W/m^2 using the Blackadar PBL and just 12.3 W/m^2 using the MRF).

Regarding the temperature, and under clear-sky conditions, the model (using both PBLs) shows a cold bias, with MBE ranging from 1.5 °C in winter to more than 3 °C in spring. RMSE values range from almost 3 °C in winter and summer to almost 4 °C in spring. The performances of the two PBL parameterizations are similar, with differences of the order of observational uncertainty.

During broken-clouds conditions, the MBE and RMSE errors are considerably lower than in the clear-sky case except during summer. The two PBL parameterizations perform similarly, with differences lower than 10%, both in terms of MBE and RMSE values, the MRF parameterization providing better estimates. Finally, both MBE and RMSE values during overcast conditions are considerably lower than for the clear-sky case and of similar magnitude than for broken-clouds days. Based on the MBE values, there is a clear overestimation of the temperature during autumn while in winter MBE is close to zero. The performance of the two PBL parameterizations is similar during winter, while in autumn the MRF provides slightly better estimates in terms of the MBE and RMSE.

Some conclusions can be derived from the former summary.

1) Overall, the MM5 model, both using the Blackadar or MRF PBL parameterizations, revealed to be a valid tool to estimate hourly values of solar radiation and temperature over the study area.

2) The influence of the PBL parameterization on the model estimates is more important for the solar radiation than for the temperature.

3) Regarding solar radiation estimates, the performance of the two PBL parameterizations shows significant differences for clear-sky conditions only during summer, when the Blackadar provides better estimates. For broken-clouds conditions, the Blackadar performs better during winter and autumn, and the MRF during spring and summer. Finally, for overcast conditions, the Blackadar performs better during winter and the MRF during autumn.

4) Regarding temperature estimates, the two PBL parameterizations provide very similar estimates. Only under overcast conditions and during autumn, the MRF provides significantly better estimates.

5) For the solar radiation, it was found that model's performance is highly dependent on the sky conditions and that can be substantially improved upon the selection of the PBL parameterization. Particularly, solar radiation RMSE values are about one order of magnitude higher during broken-clouds and overcast conditions compared to clear-sky conditions.

* * *

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