Anonymous Referee #1
Authors' response

This paper quantifies a present day and future reduction in summertime solar radiation at the surface due to aerosol and aerosol-cloud interactions over Europe using WRF as a regional climate model (RCM). Previous work has used static aerosol concentrations to quantify insolation reductions due to aerosol, while this study uses online dynamic aerosols through the GOCART module in WRF-Chem.

Overall, this paper is missing interpretations of key physical processes, model validation, may have a flawed model design, and does not fall under the purview of GMD. As the paper currently stands, my recommendation is "reject." To enter major-revisions territory, significant changes to the model setup, experimental design, and analysis would be necessary.

We do thank the reviewer for the time devoted to read and thoughtfully comment on our work. Below we provide detailed answers to each comment, hoping to have been clear enough in our explanations. Attending these comments and the ones posted by the other reviewers and the Editor, the new version of the manuscript:

1 – Has been entirely revised by a native speaker in order to improve the redaction.

2 – Has a new title. The change intends to avoid that the reader interprets that we are comparing simulations with dynamic vs. static aerosols. The new title is:

"Sensitivity of surface solar radiation to aerosol-radiation and aerosol-cloud interactions over Europe in WRFv3.6.1 climatic runs with fully interactive aerosols"

In this line, we have made an effort to make the scientific purpose of the manuscript clearer throughout the whole text.

3 – Includes further details and arguments on the experimental set-up and the methodology. Section 2 has been divided into 3 subsections.

4 – The formerly labeled ACI simulations are now named ARCI to emphasize that these include both aerosol-radiation and aerosol-cloud interactions.

5 – Includes a brief validation exercise. We now face the outputs of our simulations with ERA5.

6 – Includes two subsections within the Results section: one for the historical simulations and another for the future projections. Both has been expanded providing physical interpretation of the results.

7 – Includes a deeper discussion of the results attending the reviewers' comments.

8 – Includes a link where all the data and codes to reproduce our study have been made publicly available: http://doi.org/10.23728/b2share.a65d25c2b3ba49e1a46e970783e9476e.

We are confident that these major changes have improved significantly the manuscript and provides a larger support to its key findings.

We must also notice that we used wrong AOD values in the previous version of the paper, as it was noted by the reviewer2. These had been computed from the TAUAER3 and TAUAER4 variables, which do exhibit a weird evolution along the year. After inspection, we figured out that these and the EXTCOF55 variables had been wrongly recorded in the wrfout files (not new, apparently, see e.g.: https://forum.mmm.ucar.edu/phpBB3/viewtopic.php?t=9313&p=17464). So we have now adopted an alternative method to compute AOD following Palacios-Peña et al (2020), where, in fact, the representation of AOD by these model configurations (ARI and ARCI) were deeply evaluated. The new AOD files were estimated using the reconstructed mass-extinction method (Malm et al 1994) from the well-recorded concentrations of the various aerosol species in the wrfout files, namely: black carbon, organic carbon, dust and sea salt. Sulfates were estimated from SO2 and OH recorded concentrations using the same kinetic reaction as the one implemented in the RACM-KPP module. We want to remark that the mistake occurered during the postprocessing of the wrfout files, while WRF-Chem run satisfactorily. These wrfout files were removed after postprocessed, so we have now generated a sample one (using the ARI configuration) and uploaded it for checking together with all the other data files. Importantly, this change in the methodology for estimating AOD values did not alter the the overall results of the paper.

Regarding the interest of our work for the GMD audience, it should be noted that we submit it to the inter-journal Special Issue *Chemistry–Climate Modelling Initiative*. Although the managing Editor should have agreed it is within the scope of the journal and the Special Issue, we would be open to move it from GMD to a counterpart journal.

Major Comments

1. I do not believe that with the current model namelist settings there is a realistic representation of aerosol-cloud-interactions (ACI). It is my understanding that WRF-Chem requires aqueous-phase chemistry combined with a modal/sectional aerosol scheme (MOSAIC or MADE/SORGAM) to model ACI. This experiment uses GOCART for aerosol, which is single moment in mass, whereas double moment in mass + number is required for ACI studies. I point the authors to the WRF-Chem User's Guide, which has a section on setting up the model for ACI.

I am familiar with the Thompson & Eidhammer (2014) aerosol-aware microphysics (MP), which backs out aerosol number information from the mass-only GOCART values via a lognormal aerosol distribution assumption. After digging around in the source code, I believe the module_mixactivate.F might do something similar for the Lin-GOCART setup. However, the specifics and whether or not and how the model is doing this transformation (or defaulting to a prescribed constant number when a sectional aerosol model isn't found) needs to be confirmed by the authors. This mass to number conversion does not make a scheme double moment because number is not a prognostic variable: it's inferred. This single moment approach is not enough to study ACI in a dynamical framework.

This is a well-argued concern. However, we confirm that although the microphysics implemented in the simulations rely on the Lin scheme, this single moment scheme turns into a double moment scheme in the simulations denoted as ACI. See details on how ARCI are implemented in the simulations in the response to the next comment. We have also added these details in the manuscript.

2. It's not considered ACI by the community to run a non-chemistry WRF simulation with a prescribed constant CCN number (single moment cloud) to a simulation with dynamic aerosol (double moment cloud). The change in moments and the change in CCN are intertwined and you cannot deconvolve these changes from each other. It is more realistic to run two WRF-Chem simulations with scale emissions and to run everything in double-moment.

As aforementioned, the Lin scheme is a single moment scheme based on Lin et al. (1983), including some modifications, such as saturation adjustment (Tao et al. 1989) and ice sedimentation, which is related to the sedimentation of small ice crystals (Mitchell et al. 2008). It includes six classes of hydrometeors: water vapour, cloud water, rain, cloud ice, snow, and graupel. This scheme was one of the first to parameterize snow, graupel, and mixed-phase processes (such as the Bergeron process and hail growth by riming), and it has been widely used in numerical weather studies.

The one-moment microphysical scheme is, effectively, unsuitable for assessing the aerosol-cloud interactions as it only predicts the mass of cloud droplets and does not represent the number or concentration of cloud droplets (Li et al. 2008). The prediction of two moments provides a more robust treatment of the particle size distributions, which is key for computing the microphysical process rates and cloud/precipitation evolution. Therefore, prediction of additional moments allows greater flexibility in representing size distributions and hence microphysical process rates.

In this sense, although the Lin microphysics is presented as a single moment scheme, the WRF-Chem model allows to transform the single- into a double-moment scheme. A prognostic treatment of cloud droplet number was added (Ghan et al. 1997), which treats water vapor and cloud water, rain, cloud ice, snow, and graupel. The autoconversion of cloud droplets to rain droplets depends on droplet number (Liu et al. 2005). Droplet-number nucleation and (complete) evaporation rates correspond to the aerosol activation and resuspension rates. Ice nuclei based on predicted particulates are not treated. However, ice clouds were included via the prescribed ice nuclei distribution following the Lin scheme. Finally, the interactions of clouds and incoming solar radiation were implemented by linking simulated cloud droplet number with the Goddard shortwave radiation scheme, representing the first indirect effect, and with Lin microphysics, representing the second indirect effect (Skamarock et al. 2008). Thus, droplet number will affect both the calculated droplet mean radius and cloud optical depth.

References:

Ghan, S. J., Leung, L. R., Easter, R. C., & Abdul Razzak, H. (1997). Prediction of cloud droplet number in a general circulation model. *Journal of Geophysical Research: Atmospheres*, *102*(D18), 21777-21794.

Li, G., Wang, Y., & Zhang, R. (2008). Implementation of a two moment bulk microphysics scheme to the WRF model to investigate aerosol cloud interaction. *Journal of Geophysical Research: Atmospheres*, *113*(D15).

Lin, Y. L., Farley, R. D., & Orville, H. D. (1983). Bulk parameterization of the snow field in a cloud model. Journal of Climate and Applied Meteorology, 22(6), 1065-1092.

Liu, Y., Daum, P. H., & McGraw, R. L. (2005). Size truncation effect, threshold behavior, and a new type of autoconversion parameterization. *Geophysical research letters*, *32*(11).

Mitchell, D. L., Rasch, P., Ivanova, D., McFarquhar, G., & Nousiainen, T. (2008). Impact of small ice crystal assumptions on ice sedimentation rates in cirrus clouds and GCM simulations. *Geophysical research letters*, *35*(9).

Skamarock, W.C.; Klemp, J.B.; Dudhia, J.; Gill, D.O.; Barker, D.M.; Wang, W.; Powers, J.G. A Description of the Advanced Research WRF Version 3; Technical Report NCAR Tech. Note TN-475+STR; NCAR: Boulder, CO, USA, 2008.

Tao, W. K., Simpson, J., & McCumber, M. (1989). An ice-water saturation adjustment. *Monthly Weather Review, 117*(1), 231-235.

3. There is a difference in which autoconversion scheme is called between progn=0 and progn=1 in the Lin-MP (single moment vs double moment cloud). Some of the ACI attributed here is from the difference in the representation of autoconversion and not actually from ACI. This scheme change can be significant – see Liu et al. 2005 in GRL.

The reviewer is totally right. The autoconversion scheme activated with progn=1 (ARCI simulations), so that cloud droplets can turn into rain droplets, is different to the autoconversion scheme called with progn=0 (ARI simulations). Henceforth, this change in the flags of WRF-Chem configuration can lead to ARCI-ARI differences that cannot necessarily be attributed to aerosol-cloud interactions from a physical point of view, but also to different processes and schemes that play a role when progn flag is changed from 0 to 1. In this same sense, the activation of the aerosol-cloud interactions requires further changes in the model configuration (as compared to the configuration used for the simulations labeled as ARI) beyond the autoconversion scheme (e.g. activation of aqueous chemistry or wet scavenging processes), that could also have an added impact to the effect that can be strictly attributed to the aerosol-cloud interactions. However, the encoding of the WRF-Chem model imposes that ARI experiments should be performed with progn=0 in order not to allow an on-line calculation of cloud condensation nuclei, while ARCI experiments should be run with progn=1 if the on-line estimations of aerosols wants to be used not only for the radiative balance, but also for CCN (which change between progn=0 and progn=1 simulations). This is true not only with the Lin scheme used here, but also with the Morrison microphysics parametrization (the other scheme available including a double-moment mycrophysics). Therefore, ARCI-ARI differences can not be strictly attributed to the aerosol-cloud interactions from a purely physical point of view, but to the activation of the aerosol-cloud interactions from a modeling point of view (that involves several modifications, including the autoconversion process as stated by the reviewer). All these unavoidable changes are intrinsic to the definition of the flags leading to the representation of aerosol-cloud interactions in WRF-Chem executions. We have now emphasized in the manuscript this aspect of the model configuration and its potential repercussion when interpreting the signals (see Discussion).

4. This manuscript makes no attempt to attribute the results to physical processes for ACI. Why are we seeing these results? What microphysical or environmental processes are actually causing the change in cloudiness? It's not enough to simply state that the change occurs. Most of the results section of the manuscript is describing what is on the plots and not interpreting the physics.

We now make more emphasis in attributing the signals to the direct, semi-direct and indirect aerosols effects, and provide physical interpretation of the results.

5. The WRF simulations are compared to the coarse GCM for validation. Why not compare them (at least in the present-day scenario) to reanalysis that is run at higher resolution? There is no validation of the model against observations. At least reanalysis incorporates observations and is a start for validation.

The manuscript now includes a brief comparison of the present-day simulations with ERA5.

6. It is not clear what value is added by including gas-phase chemistry in these simulations. The pathways that contribute to aerosol are not explained.

Chemical reactions in the GOCART model include several oxidation processes by the three main oxidants in the troposphere: OH, NO3, and O3. The OH radical dominates oxidation during the daytime, but at night its concentration drops and NO3 becomes the primary oxidant (Archer-Nicholls et al., 2014). So, the oxidation pathways represented in GOCART include: (a) the dimethyl sulfide (DMS) oxidation by the hydroxyl radical (OH) during the day to form sulfur dioxide (SO_2) and methanesulfonic acid (MSA); (b) the oxidation by nitrate radicals (NO3) at night to form SO_2; and (c) the SO_2 oxidation by OH in air and by H_2O_2 and tropospheric ozone (O_3) in clouds (aqueous chemistry) to form sulfate (Chin et al., 2000). Henceforth, the skilful characterization of gas-phase radicals such as OH and NO3 or compounds like O_3 is essential for the representation of oxidation pathways in the atmosphere leading to the formation of secondary aerosols (Jiménez et al., 2003). Therefore, in this contribution the RACM (Stockwell et al., 1997; Geiger et al., 2003) mechanism was coupled to GOCART trough the kinetics pre-processor (KPP) in WRF-Chem in order to provide the concentrations of radical and gas-phase pollutants needed by the GOCART aerosol model. We have added this explanation in the text (section 2.2).

References:

Archer-Nicholls, S., Lowe, D., Utembe, S., Allan, J., Zaveri, R. A., Fast, J. D., Hodnebrog, Ø., Denier van der Gon, H., McFiggans, G. (2014). Gaseous chemistry and aerosol mechanism developments for version 3.5.1 of the online regional model, WRF-Chem. *Geoscientific Model Development*, 7, 2557–2579.

Chin, M., Rood, R.B., Lin. S.-J., Müller, J.-F., Thompson, M. (2000). Atmospheric sulfur cycle simulated in the global model GOCART: Model description and global properties. *Journal of Geophysical Research*, 105(D20), 24671-24687.

Geiger, H., Barnes, I., Bejan, I., Benter, T., & Spittler, M. (2003). The tropospheric degradation of isoprene: an updated module for the regional atmospheric chemistry mechanism. *Atmospheric Environment*, 37, 1503 - 1519.

Jiménez, P., Baldasano, J.M., Dabdub, D. (2003). Comparison of photochemical mechanisms for air quality modeling. *Atmospheric Environment*, 37, 4179-4194.

Stockwell, W. R., Kirchner, F., Kuhn, M., & Seefeld, S. (1997). A new mechanism for regional atmospheric chemistry modeling. *Journal of Geophysical Research: Atmospheres*, 102, 25 847 - 25 879.

7. Breaking up the contribution to AOD and to ACI by aerosol type would be useful (e.g. carbon and dust will not have the same effect on CCN number as sulfates).

We can not afford to disentangle the contribution of each aerosol type to the effects attributed to the activation of the aerosol-clouds interactions in the simulations. It would require to run the ARCI simulations including only one of the aerosol species (5 in GOCART) at once. But each ARCI run takes months to be performed due to its expensive computational cost. So this is not a feasible task for us in a reasonably time.

On the other hand, we found that the main driver for the differences between the runs with aerosols and the runs without them is cloudiness, while the AOD plays a secondary role, which justifies the low attention paid to disentangling the contribution of each aerosol species to the AOD.

8. The overarching narrative of the paper is not clear. Is the point to compare RCM static aerosol to RCM dynamic aerosol? To assess the value added from moving from GCM

dynamic aerosol to RCM dynamic aerosol? By the end of the paper, I had completely lost track of science question.

We have made an effort to make it clearer, starting by the title. The point is to evince the impact of aerosol-radiation and aerosol-cloud interactions in WRF runs performed with dynamic aerosols by comparison with baseline WRF runs performed without aerosols (nor dynamic, nor static). The baseline set-up is the most common one in the currently available portfolio of regional climate change scenarios provided under the umbrella of benchmark initiatives such as Euro-Cordex.

9. The English needs reviewing throughout the manuscript. More time is needed to revise the grammar and spellings than can be provided here.

Done with the help of a native speaker.

Specific Comments (page),[lines]

1. (2),[34-35] – What are GCMs modeling dynamically that RCMs are not?

It was said: "This is the case of the atmospheric aerosols concentration and their multiple non-linear interactions (eg. Taylor et al 2012 vs. Ruti et al 2016), the so-called aerosol-radiation and aerosol-cloud interactions (Boucher 2015)."

2. (4),[84] – Why WRF-3.6.1? It's on version 4.2.1 now. Why such an old version?

Some of the simulations included in this work were performed time ago. Others have been performed more recently, but we decided to use the same WRF version to be sure of being comparing the same "thing". At that time, when first simulations were carried out, the last stable version of WRF was the 3.6.1. In any case, the physics of the model is the same, no matter of its version.

3. (4),[87] – Why use GCM boundary conditions and not reanalysis? The CORDEX protocol suggests running the present-day experiments in the "perfect boundary condition experiment mode" with reanalysis and then running the future RCP scenarios with GCM boundary conditions.

We used GCM boundary conditions because we were to also asses impacts on future projections (not only sensitivity under present climate). Nonetheless, we have at our disposal a set of identical runs (BASE, ARI and ARCI configurations) using the reanalysis ERA20C as initial and boundary conditions. We are aware that the Euro-Cordex protocol establishes the use of Era-Interim as "perfect boundary conditions", but we needed a longer period (for reasons that are irrelevant here) and used ERA20C instead. The results from these simulations are attached below. These basically resemble those already included in the paper. Therefore, we decided not to include them in the paper for the sake of brevity.

4. (5),[98-99] – What is meant here by aerosol radiation is an external forcing?

This sentence was misleading and has been removed.

5. (5),[130-131] – The manuscript needs to stand on its own. If the focus of the paper is on ACI, then ACI in the model and model limitations in representing ACI within the setup and the resolution need to be described in full detail here.

We have extended the description of the model configuration (section 2) and discussed about it.

6. (5),[139-141] – See major comment #1

We now explain better this aspect of the model configuration.

7. (6),[144-146] – So the data was subset by the researchers for non-cloudy days? Radiation code often outputs clear-sky values. Why not use that to ensure a constant data stream?

Unfortunately, we did not save clear-sky values from the model outputs, so we needed to adopt an alternative methodology.

8. (6),[144-146] – Is clear-sky only for that grid box where the threshold is met or is more data around those grid boxes removed?

The criterion is applied at the grid-box level, for each grid-box individually and independently. This has been also clarified in the text.

9. (6),[144-146] – Why do the clear sky values matter? Need to tell the readers why these are useful metrics to include.

We have included: “The analysis in absence of cloudiness will tell us about the relevance of the direct radiative effect of aerosols.”

10. (6),[154] – I’m lost in how averaging was done throughout this section and which time scales we are looking at. Are these a daily daytime mean that was then averaged into summertime means? Was the data filtered to exclude nighttime values?

We have better explain it in section 2 (in the new subsection 2.3). We simply averaged over all the JJA (or either season) records in the series.

11. (6),[154] - The methodology for calculating the correlations, (especially temporal correlations) needs to be described.

Done in section 2 (in the new subsection 2.3). The codes used are also made available.

12. (6),[156-158] – Wouldn’t the solar industry also be interested in effects under reduced solar output times (i.e. winter)?

We now included winter plots in Supp. Material, but we decided not to go into these results in the manuscript because it would expand it too much.

13. (6),[156-158] – The direct radiative effect is strongest in summer, but what about the indirect effect?

Our results do support the key role of the indirect aerosols effect in summer indeed.

14. (7),[172-173] – Why is the spatial pattern in the response occurring? Why do some parts have an increase and some have a decrease? What is happening microphysically? Is it a difference in aerosol type that is causing this?

The increase in cloudiness in central and northern regions in ARI and ARCI simulations as compared to BASE could be explained through the following feedback mechanism: the cooling effect of the scattering of radiation by the high presence of sea salt, dust and sulfates over these areas cools down surface temperatures, thus increasing relative humidity and favoring the formation of clouds, which leads to less radiation reaching the surface, thus lower surface temperatures, and so on. Nonetheless, these signals would simply indicate that such a enhancing mechanism prevails over others, such as the semi-direct effect that acts to suppress cloudiness.

The reduction in cloudiness southward also appears in both ARI and ARCI simulations, but it is more evident in ARCI. Therefore, both semi-direct and indirect aerosol effects would tend to diminish cloudiness southward, with the latter (indirect effect) having the greatest impact. This could be due to the fact that a high presence of large aerosols over southern Europe, both in form of dust or sulfate in our case, hampers the formation of clouds.

We have added arguments in the main manuscript.

15. (7),[177-181] – The wording here is confusing. Differences of what exactly? Is the point to say that CTT reduces RSDS more than AOD? This needs more explanation.

Yes, that is the point. We have further developed this part to make it clearer.

16. (7),[184-185] – I don’t see how the explanation in the previous paragraph proves this connection.

It is supported by the fact that differences between pairs of experiments in CCT correlates more than differences between pairs of experiments in AOD with the differences between pairs of experiments in RSDS. This showed up both, spatially (see s_corr values in Fig 1d-i) and temporally (Supp Fig 7a-f).

17. (8),[204-205] – How does the previous point imply orbital issues or water vapor? The link is not clear.

Different days (dates) may have different daytime lengths and different atmospheric compositions (thus different atmospheric optical depth or atmospheric transmissivity) that may mask the AOD effect under clear-sky conditions. We have better explained in the text what we meant.

18. (8),[206] – There is no transition into now looking at the future projections. Maybe split up into Section 3.A for present-day and 3.B for future.

Done.

19. (8),[219] – Where was this specified in Section 2?

It was said:

“Anthropogenic emissions coming from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP; Lamarque et al 2010) were kept unchanged in the simulation periods (we considered the 2010 monthly values).”

We have now further emphasized and discussed this feature.

20. (9),[241-243] – 5% compared to what? GCM? No aerosol?

Compared to the BASE experiment (without aerosols). Now specified.

21. (9),[247-248] – Why are RSDS and cloudiness not linked? What are the physics here?

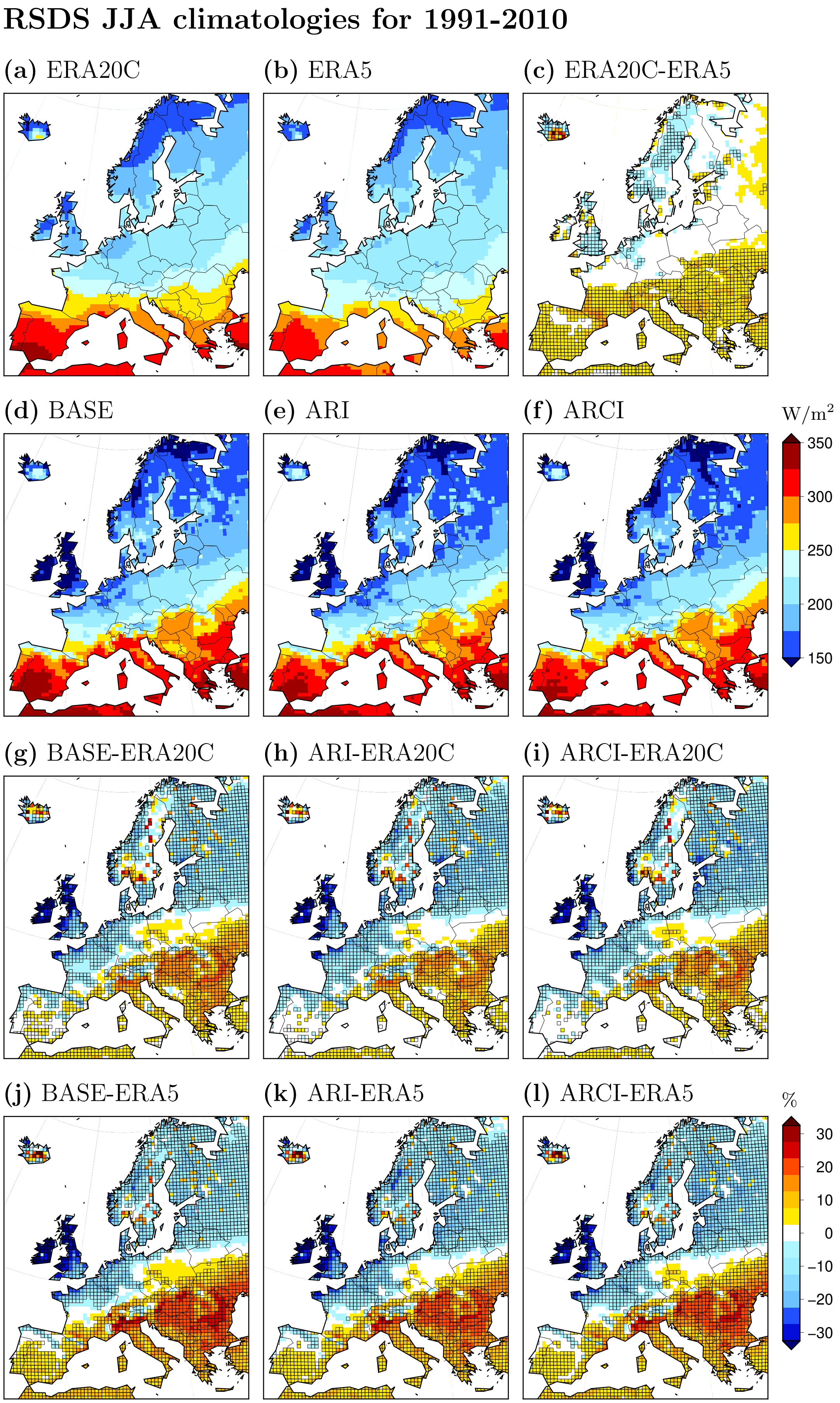
It was said the opposite: “Differences in RSDS between experiments are in overall good agreement with the differences found in cloudiness”

22. (9),[249-250] – What does this statement mean?

That statement was removed. It was certainly confused.

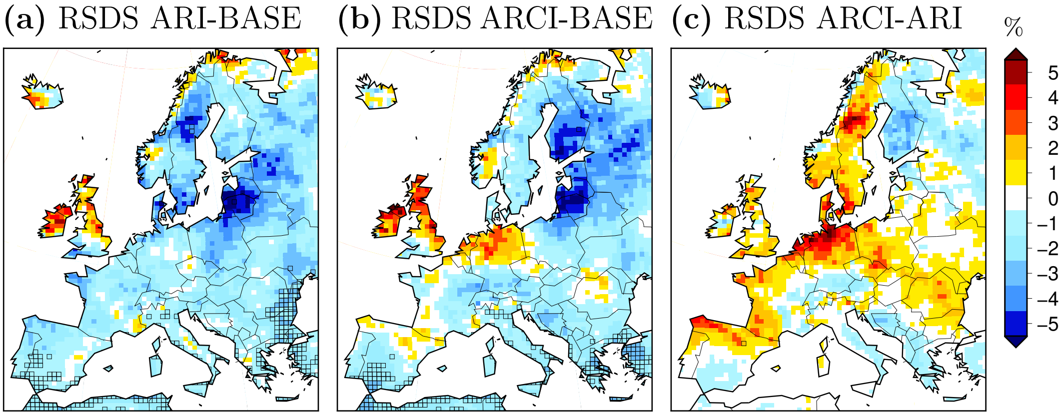
23. (9),[250-253] – Why is this conclusion significant in a broader context?

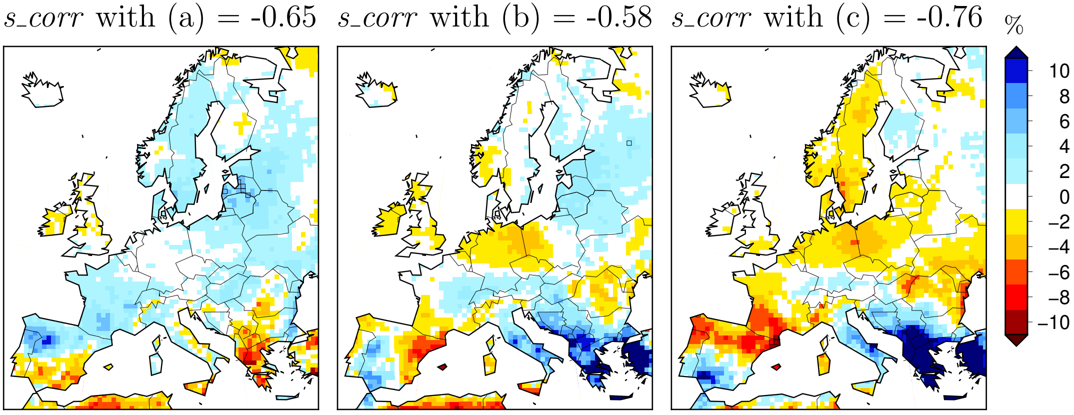
We now argument about the importance of the signals under clear-sky conditions.

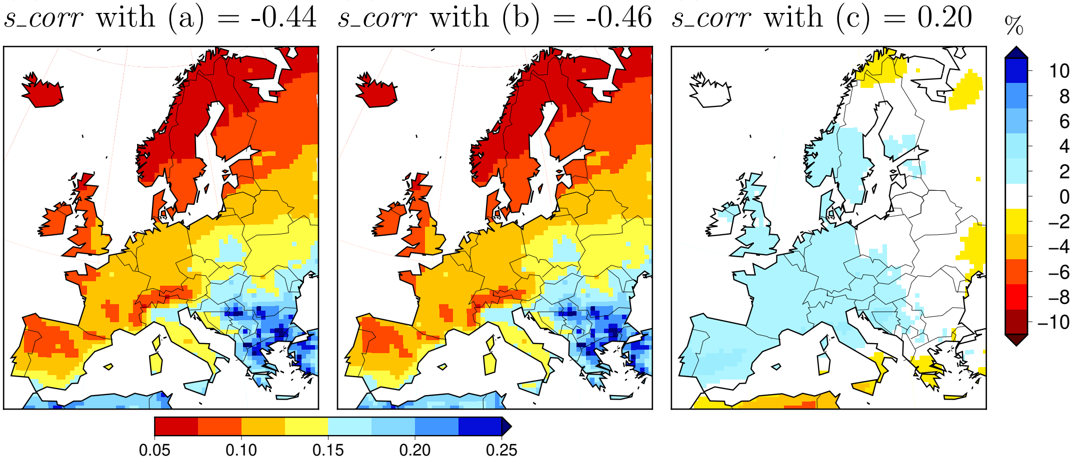


RSDS summer climatologies in the present period from ERA20C (a), ERA5 (b) and the ERA20C-driven WRF simulations (d to f); units: Wm^{-2}, same colorbar in all cases (the upper one). Panel c depicts relative differences between ERA20C and ERA5, panels g to i between each WRF simulation and ERA20C, and panels j to l between each WRF simulation and ERA5, squared if statistically significant ($p<0.05$); units: %, same colorbar in all cases (the bottom one).

RSDS, CCT & AOD JJA climatologies for 1991-2010: differences between experiments


(a) RSDS ARI-BASE **(b)** RSDS ARCI-BASE **(c)** RSDS ARCI-ARI

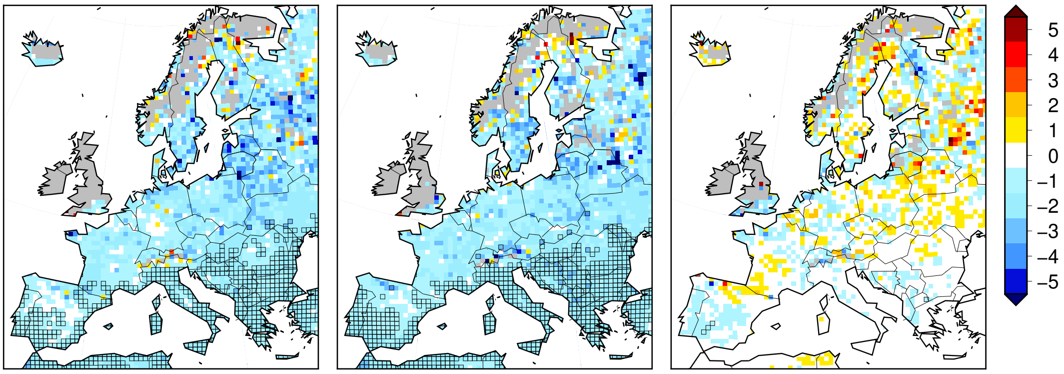

(d) CCT ARI-BASE
s_corr with (a) = -0.65
(e) CCT ARCI-BASE
s_corr with (b) = -0.58
(f) CCT ARCI-ARI
s_corr with (c) = -0.76


(g) AOD ARI
s_corr with (a) = -0.44
(h) AOD ARCI
s_corr with (b) = -0.46
(i) AOD ARCI-ARI
s_corr with (c) = 0.20

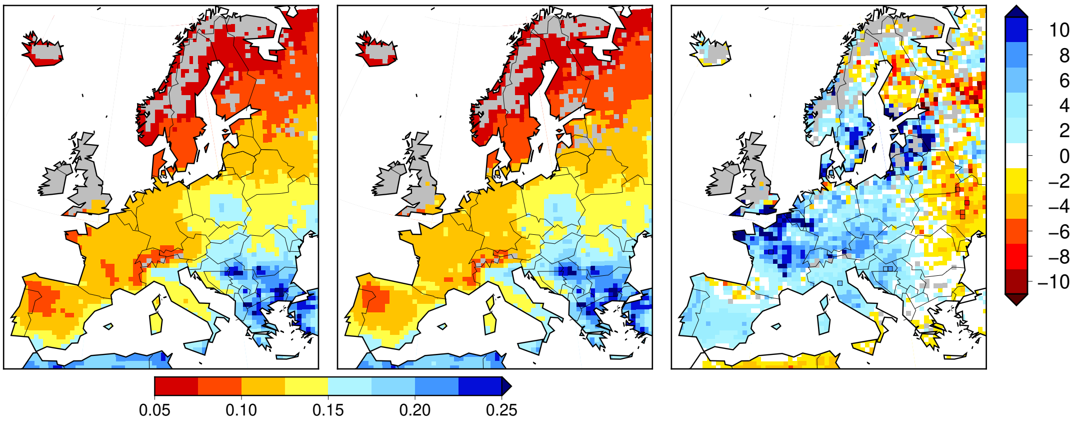
Relative differences between the ERA20C-driven WRF simulations in the RSDS (a to c), CCT (d to f) and AOD at 550 nm (g to i) summer (JJA) climatologies in the present period (1991-2010), squared if statistically significant ($p<0.05$); units: %. Note that panels g and h are referred to the horizontal colorbar just below them and simply represent the AOD summer climatologies in ARI and ARCI respectively. Spatial correlations (*s_corr*) between the patterns in the second and third rows and the respective patterns in the first row are indicated in the headers.

RSDS$_{cs}$ & AOD$_{cs}$ JJA climatologies for 1991-2010: differences between experiments

(a) RSDS$_{cs}$ ARI-BASE **(b)** RSDS$_{cs}$ ACI-BASE **(c)** RSDS$_{cs}$ ACI-ARI

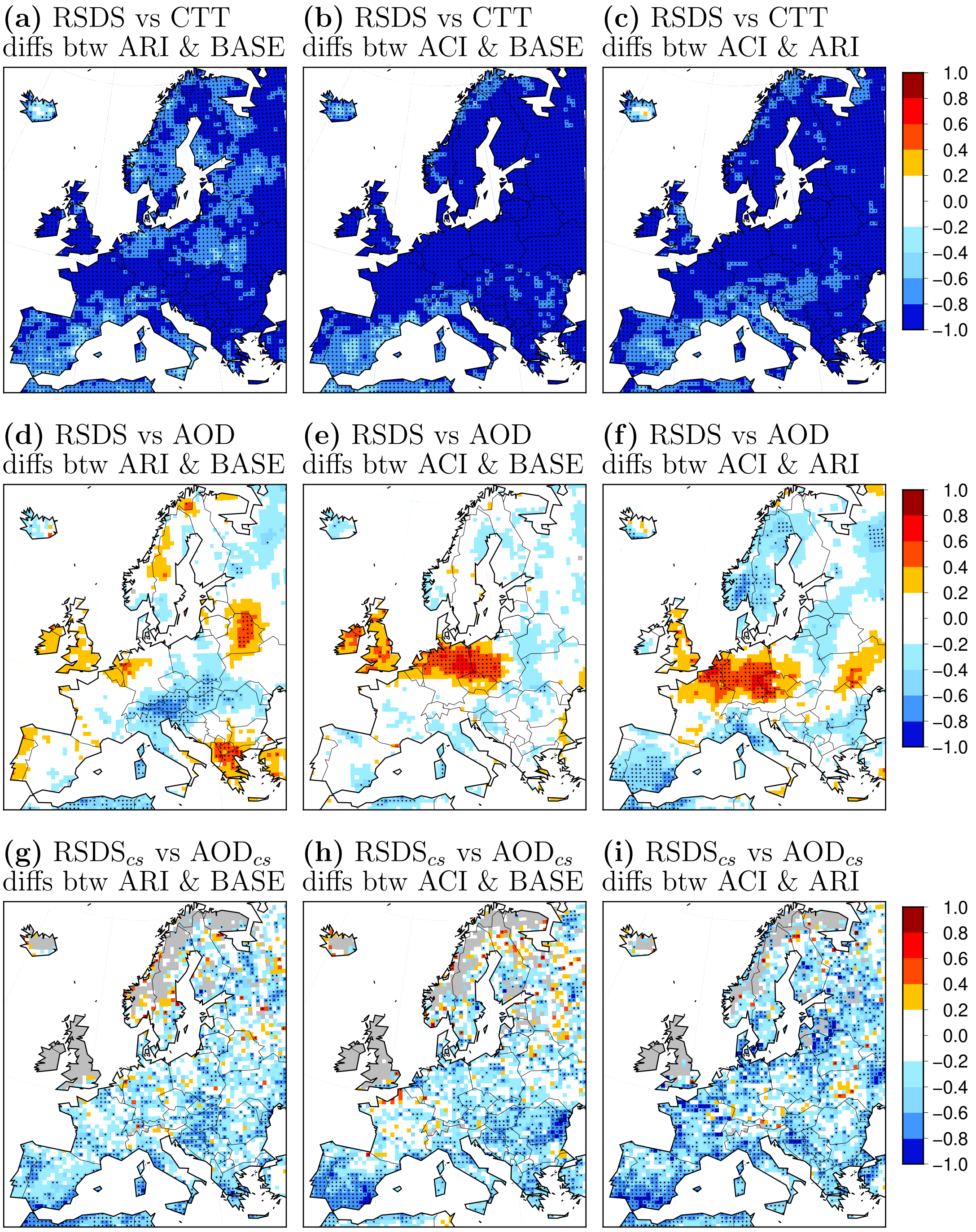


(d) AOD$_{cs}$ ARI *s_corr* with (a) = -0.24 **(e)** AOD$_{cs}$ ACI *s_corr* with (b) = -0.24 **(f)** AOD$_{cs}$ ACI-ARI *s_corr* with (c) = -0.23



Relative differences between the ERA20C-driven WRF simulations in the RSDS$_{cs}$ (a to c) and AOD$_{cs}$ at 550 nm (d to f) summer (JJA) climatologies, this is under clear-sky conditions, in the present period (1991-2010), squared if statistically significant ($p<0.05$); units: %. Note that panels d and e are referred to the horizontal colorbar just below them and simply represent the AOD summer climatologies in ARI and ARCI respectively. Gray shaded areas depict grid point where less than 75% of the summer mean values in the time series of RSDS$_{cs}$ and AOD$_{cs}$ were not missing values. Spatial correlations (*s_corr*) between the patterns in the second row and the respective patterns in the first row are indicated in the headers.

Temporal correlations between difference series of RSDS, CCT & AOD: 1991-2010 JJA-mean series


(a) RSDS vs CTT diffs btw ARI & BASE

(b) RSDS vs CTT diffs btw ACI & BASE

(c) RSDS vs CTT diffs btw ACI & ARI

(d) RSDS vs AOD diffs btw ARI & BASE

(e) RSDS vs AOD diffs btw ACI & BASE

(f) RSDS vs AOD diffs btw ACI & ARI

(g) $RSDS_{cs}$ vs AOD_{cs} diffs btw ARI & BASE

(h) $RSDS_{cs}$ vs AOD_{cs} diffs btw ACI & BASE

(i) $RSDS_{cs}$ vs AOD_{cs} diffs btw ACI & ARI

As obtained from ERA20C-driven WRF experiments, temporal correlations between JJA-mean temporal series of differences in RSDS and CTT (a to c), RSDS and AOD (d to f), and $RSDS_{cs}$ and AOD_{cs} (g to i; gray-shaded areas where the number of time steps in the clear-sky series is below 75% of total time steps) between ARI and BASE (first column), ARCI and BASE (second column), and ARCI and ARI experiments (third column) in the present period (1991-2010). Little stars indicate statistical significance ($p<0.05$).

Anonymous Referee #2
Authors’ response

This manuscript, submitted to Geoscientific Model Development, presents a sensitivity study on the role of dynamic aerosols in regional climate simulations over Europe, carried out with the WRF model. The authors consider both present and future simulations, and discuss the role of aerosol-radiation and aerosol-cloud interactions respectively. They conclude that the response of downwelling surface shortwave radiation (rsds) to aerosols is mainly driven by the impact of aerosols on cloudiness. Overall this question is very interesting and needs to be studied, I found the present manuscript presents major problems of methodology, that is the reason why I would suggest not to publish it in GMD.

We do thank the reviewer for the time devoted to read and thoughtfully comment on our work. Below we provide detailed answers to each comment, hoping to have been clear enough in our explanations. Attending these comments and the ones posted by the other reviewers and the Editor, the new version of the manuscript:

1 – Has been entirely revised by a native speaker in order to improve the redaction.

2 – Has a new title. The change intends to avoid that the reader interprets that we are comparing simulations with dynamic vs. static aerosols. The new title is:

“Sensitivity of surface solar radiation to aerosol-radiation and aerosol-cloud interactions over Europe in WRFv3.6.1 climatic runs with fully interactive aerosols”

In this line, we have made an effort to make the scientific purpose of the manuscript clearer throughout the whole text.

3 – Includes further details and arguments on the experimental set-up and the methodology. Section 2 has been divided into 3 subsections.

4 – The formerly labeled ACI simulations are now named ARCI to emphasize that these include both aerosol-radiation and aerosol-cloud interactions.

5 – Includes a brief validation exercise. We now face the outputs of our simulations with ERA5.

6 – Includes two subsections within the Results section: one for the historical simulations and another for the future projections. Both has been expanded providing physical interpretation of the results.

7 – Includes a deeper discussion of the results attending the reviewers’ comments.

8 – Includes a link where all the data and codes to reproduce our study have been made publicly available: http://doi.org/10.23728/b2share.a65d25c2b3ba49e1a46e970783e9476e.

We are confident that these major changes have improved significantly the manuscript and provides a larger support to its key findings.

Main comments:

- The authors are ambiguous about the objective of their study, to begin with the title. I do not understand if they want (1) to show the added values of representing interactive dynamic

aerosols in regional climate simulations, compared to regional climate simulations with climatological aerosols, or (2) if they want to show the mean impact of aerosols in regional climate simulations compared to simulations which would not have any aerosols. Given the title, I was expected the first option, which is a very interesting question, not very much documented in literature, but this requires a rigorous protocol in which we compare regional climate simulations with the same aerosol content on average. This is not the case here. So I suppose the authors were in the second option, which is much less interesting, as it has already been studied in different publications. In that case, I suggest to remove the word dynamic from the title, and avoid overly affirmative expressions such as “a reduction about 5% in RSDS was found when aerosols are dynamically solved by the RCM”.

We understand the title may lead to misinterpretations, so we changed it.

As we are comparing RCM outputs from simulations with and without aerosols, we were, effectively, in the second option mentioned by the reviewer. Although there exist previous works in this second option, none of them attempted to unveil the impact of aerosols from a purely modeling approach such as the one used here, where no prescribed aerosol concentrations are used. So the word ‘dynamic’ actually makes the difference with previous studies, that’s why we included it in the title.

- Another major concern about this study is the fact that the authors draw conclusions on the impact of aerosols on rsds future evolution, while they keep constant anthropogenic emissions in their future simulation. The authors are aware of discrepancies in the rsds future evolution between global and regional climate simulations, which could be due to the use of constant aerosols in RCMs contrary to GCMs (Boé et al. 2020). That is the reason why I do not understand the authors keep anthropogenic aerosol emissions constant in future simulations, while they should evolve as in the GCM simulation.

This approach permits a better isolation of the signals from the aerosol-radiation-cloud interactions due to the so-called climate change penalty alone, while reduces the reliability of the future projections obtained, in fact. We now we make more emphasis on this point in the manuscript (see Discussion).

- The last major concern is about the RCM used in this study. The version of WRF used here, namely 3.6.1 is quite old (reference paper from 2008), and above all a precise description of how aerosols and their effects on climate are represented is missing. For example, I wonder what aerosol climatology is used in the BASE simulation (if it is not zero). I am also very worried about the very low values of summer AOD shown in Figure 1g-h, which shows that WRF clearly underestimates AOD over Europe. WRF values range from 0.05 to 0.09 over Europe, while observations typically range from 0.1 to 0.2 (Papadimas et al. 2008, Nabat et al. 2013, Schultze and Rockel 2018). That could lead to an underestimation of aerosol effects. In such a study, an evaluation of AOD (even brief) is needed in order to ensure the consistency of the results.

Some of the simulations included in this work were performed time ago. Others have been performed more recently, but we decided not to change the WRF version to be sure of being comparing the same “thing”. At that time, when first simulations were carried out, the last stable version of WRF was the 3.6.1. In any case, the physics of the model is the same, no matter of its version.

Addressing the appropriate reviewer concern about the lack of a deep description of how aerosols are treated by the model, we have now added more details on that. For instance, regarding the BASE experiments, we now say in section 2:

“BASE: aerosols are not considered in the simulations. No aerosol climatology is used, and no aerosol interactions are taken into account by the model. WRF-alone considers a constant number of cloud condensation nuclei (250 per cm^3, set in the model by default) to enable the formation of clouds.”

Regarding the ARCI experiments, we now explain in section 2:

“Aerosol-cloud interactions were implemented by linking the simulated cloud droplet number with the microphysics schemes (Chapman et al 2009) affecting both the calculated droplet mean radius and the cloud optical depth. Although this WRF-Chem version (3.6.1) does not allow a full coupling with aerosol-cloud interactions, the microphysics implemented here is a single moment scheme that turns into a two-moment scheme in the simulations denoted ARCI. One-moment microphysical schemes are unsuitable for assessing the aerosol-cloud interactions as they only predict the mass of cloud droplets and do not represent the number or concentration of cloud droplets (Li et al. 2008). The prediction of two moments provides a more robust treatment of the particle size distributions, which is key for computing the microphysical process rates and cloud/precipitation evolution. In this sense, although the Lin microphysics is presented as a single moment scheme, the WRF-Chem model makes it possible to transform the single- into a double-moment scheme. A prognostic treatment of cloud droplet number was added (Ghan et al. 1997), which treats water vapor and cloud water, rain, cloud ice, snow, and graupel. The autoconversion of cloud droplets to rain droplets depends on droplet number (Liu et al. 2005). Droplet-number nucleation and (complete) evaporation rates correspond to the aerosol activation and resuspension rates. Ice nuclei based on predicted particulates are not treated. However, ice clouds are included via the prescribed ice nuclei distribution, following the Lin scheme. Finally, the interactions of clouds and incoming solar radiation were implemented by linking the simulated cloud droplet number with the Goddard shortwave radiation scheme, representing the first indirect effect, and with the Lin microphysics, representing the second indirect effect (Skamarock et al. 2008). Thus, the droplet number will affect both the calculated droplet mean radius and cloud optical depth.”

References:

Ghan, S. J., Leung, L. R., Easter, R. C., & Abdul Razzak, H. (1997). Prediction of cloud droplet number in a general circulation model. *Journal of Geophysical Research: Atmospheres*, *102*(D18), 21777-21794.

Li, G., Wang, Y., & Zhang, R. (2008). Implementation of a two moment bulk microphysics scheme to the WRF model to investigate aerosol cloud interaction. *Journal of Geophysical Research: Atmospheres*, *113*(D15).

Lin, Y. L., Farley, R. D., & Orville, H. D. (1983). Bulk parameterization of the snow field in a cloud model. Journal of Climate and Applied Meteorology, 22(6), 1065-1092.

Liu, Y., Daum, P. H., & McGraw, R. L. (2005). Size truncation effect, threshold behavior, and a new type of autoconversion parameterization. *Geophysical research letters*, *32*(11).

Mitchell, D. L., Rasch, P., Ivanova, D., McFarquhar, G., & Nousiainen, T. (2008). Impact of small ice crystal assumptions on ice sedimentation rates in cirrus clouds and GCM simulations. *Geophysical research letters*, *35*(9).

Skamarock, W.C.; Klemp, J.B.; Dudhia, J.; Gill, D.O.; Barker, D.M.; Wang, W.; Powers, J.G. A Description of the Advanced Research WRF Version 3; Technical Report NCAR Tech. Note TN-475+STR; NCAR: Boulder, CO, USA, 2008.

Tao, W. K., Simpson, J., & McCumber, M. (1989). An ice-water saturation adjustment. *Monthly Weather Review*, *117*(1), 231-235.

And acknowledge in the discussion section:

"In the ARCI simulations, the autoconversion scheme called so that cloud droplets can turn into rain droplets is different to the autoconversion scheme activated in the ARI simulations. This change in the WRF-Chem configuration can lead to ARCI-ARI differences that do not come necessarily from the of the aerosol-cloud interactions from a physical point of view (Liu et al 2005). In fact, the activation of the aerosol-cloud interactions requires further changes in the model configuration (as compared to the configuration used for the simulations labeled as ARI) beyond the autoconversion scheme, such as the activation of aqueous chemistry processes, that could also have an added impact to effect that can be strictly attributed to the aerosol-cloud interactions. However, technically, the encoding of the WRF-Chem model hampers to better isolate the effect of the aerosol-cloud interactions. Therefore, ARCI-ARI differences can not be attributed to the aerosol-cloud interactions from a purely physical point of view, but to the activation of the aerosol-cloud interactions from a modeling point of view, since the autoconversion schemes necessarily change between ARI and ARCI."

Reference:

Liu, Y., Daum, P. H., & McGraw, R. L. (2005). Size truncation effect, threshold behavior, and a new type of autoconversion parameterization. *Geophysical research letters*, *32*(11).

Regarding the inclusion of gas-phase chemistry in the simulations, in section 2 we added:

"Chemical reactions in the GOCART model include several oxidation processes by the three main oxidants in the troposphere: OH, NO3, and O3. The OH radical dominates oxidation during the daytime, but at night its concentration drops and NO3 becomes the primary oxidant (Archer-Nicholls et al., 2014). So, the oxidation pathways represented in GOCART include: (a) dimethyl sulfide (DMS) oxidation by the hydroxyl radical (OH) during the day to form sulfur dioxide (SO_2) and methanesulfonic acid (MSA); (b) oxidation by nitrate radicals (NO3) at night to form SO_2; and (c) SO_2 oxidation by OH in air and by H_2O_2 and tropospheric ozone (O_3) in clouds (aqueous chemistry) to form sulfate (Chin et al., 2000). Henceforth, the skilful characterization of gas-phase radicals such as OH and NO3 or compounds like O_3 is essential for the representation of oxidation pathways in the atmosphere leading to the formation of secondary aerosols (Jiménez et al., 2003). Therefore, in this contribution the RACM (Stockwell et al., 1997; Geiger et al., 2003) mechanism was coupled to GOCART trough the kinetics pre-processor (KPP) in WRF-Chem in order to provide the concentrations of radical and gas-phase pollutants needed by the GOCART aerosol model."

References:

Archer-Nicholls, S., Lowe, D., Utembe, S., Allan, J., Zaveri, R. A., Fast, J. D., Hodnebrog, Ø., Denier van der Gon, H., McFiggans, G. (2014). Gaseous chemistry and aerosol mechanism developments for version 3.5.1 of the online regional model, WRF-Chem. *Geoscientific Model Development,* 7, 2557–2579.

Chin, M., Rood, R.B., Lin. S.-J., Müller, J.-F., Thompson, M. (2000). Atmospheric sulfur cycle simulated in the global model GOCART: Model description and global properties. *Journal of Geophysical Research*, 105(D20), 24671-24687.

Geiger, H., Barnes, I., Bejan, I., Benter, T., & Spittler, M. (2003). The tropospheric degradation of isoprene: an updated module for the regional atmospheric chemistry mechanism. *Atmospheric Environment*, 37, 1503 - 1519.

Jiménez, P., Baldasano, J.M., Dabdub, D. (2003). Comparison of photochemical mechanisms for air quality modeling. *Atmospheric Environment*, 37, 4179-4194.

Stockwell, W. R., Kirchner, F., Kuhn, M., & Seefeld, S. (1997). A new mechanism for regional atmospheric chemistry modeling. *Journal of Geophysical Research: Atmospheres*, 102, 25 847 - 25 879.

Finally, regarding the 'low' AOD values shown in Figure 1g-h, we must acknowledge that we certainly used wrong AOD values. These had been computed from the TAUAER3 and TAUAER4 variables, which do exhibit a weird evolution along the year. After inspection, we figured out that these and the EXTCOF55 variables had been wrongly recorded in the wrfout files (not new, apparently, see e.g.: https://forum.mmm.ucar.edu/phpBB3/viewtopic.php?t=9313&p=17464). So we have now adopted an alternative method to compute AOD following Palacios-Peña et al (2020), where, in fact, the representation of AOD by these model configurations (ARI and ARCI) were deeply evaluated. The new AOD files were estimated using the reconstructed mass-extinction method (Malm et al 1994) from the well-recorded concentrations of the various aerosol species in the wrfout files, namely: black carbon, organic carbon, dust and sea salt. Sulfates were estimated from SO2 and OH recorded concentrations using the same kinetic reaction as the one implemented in the RACM-KPP module. We want to remark that the mistake occurered during the postprocessing of the wrfout files, while WRF-Chem run satisfactorily. These wrfout files were removed after postprocessed, so we have now generated a sample one (using the ARI configuration) and uploaded it for checking together with all the other data files. Importantly, this change in the methodology for estimating AOD values did not alter the the overall results of the paper. Attached here a figure with the AOD climatologies from ARI and ARCI and those from MACv2.

References:

Malm, W. C., Sisler, J. F., Huffman, D., Eldred, R. A., & Cahill, T. A. (1994). Spatial and seasonal trends in particle concentration and optical extinction in the United States. *Journal of Geophysical Research: Atmospheres*, *99*(D1), 1347-1370.

Palacios-Peña, L., Montávez, J. P., López-Romero, J. M., Jerez, S., Gómez-Navarro, J. J., Lorente-Plazas, R., ... & Jiménez-Guerrero, P. (2020). Added Value of Aerosol-Cloud Interactions for Representing Aerosol Optical Depth in an Online Coupled Climate-Chemistry Model over Europe. Atmosphere, 11(4), 360.

Other comments:

- page 2 line 31: land use change is not specific to regional climate simulations, I think it is even more used in global climate simulations.

We simply intend to note that at higher resolutions, land uses can be represented at a finer scale.

- page 3 lines 57-63: please avoid such long lists of references, and clarify the conclusions of each of them.

This paragraph has been reformulated accordingly.

- page 3 lines 70-71: “which still remain largely a mystery”. Other studies such as Giorgi et al. (2016), Sørland et al. (2018) and Boé et al. (2020) have also underlined differences between RCMs and GCMs in future projections. The role of aerosols is even discussed in Boé et al. (2020), which should be mentioned here.

In fact. This is now acknowledged in the paper.

- page 5 lines 140-141: it is not clear for me how aerosol-cloud interactions are represented in the simulations.

We now provide further details in the manuscript. See our response about this above.

-page 6 lines 144-146: This way of calculating clear-sky variables in simulations is not common in modeling studies. It would be appropriate for a comparison to observations (it is exactly how satellites do for example), but in models, you generally compute clear-sky variables at each time step, removing clouds in radiative transfer. This would avoid the numerous missing values.

Unfortunately, we did not save clear-sky values from the model outputs, so we needed to adopt an alternative methodology.

- page 6 section 3: This section should be divided in several sub-sections, with more precise titles than only “Results”.

Done.

- page 6 line 165: “The inclusion of interactive aerosols reduce the JJA mean values of RSDS”. This is typically an example of my first main comment. This decrease in rsds is likely due to the mean effect of aerosols, and not their interactive pattern.

We agree that the sentence was misleading and has been reformulated. Although that statement is true in the context of our work, it wrongly gave the message that such a reduction in RSDS is due to the interactive aerosols modeling approach adopted here as compared to a more conservative (and common) approach based on non-interactive aerosols, which is something that we did not inspect.

- page 7 line 172: “ARI and ACI lead to more cloudiness in central and northern regions”. This is not really the case when looking at the figure.

Blue colors prevail in central and northern regions in Figure 1d-f indeed. Please note that the color palette is inverted here with the aim of facilitating a visual identification of the matching between the patterns of the drivers (CCT, AOD) and those of RSDS.

- page 7 lines 184-187: This conclusion is not justified.

Both the spatial correlations shown in Supp. Figure 9 and the temporal correlations shown in the previous Supp. Figure 12 (note that Supp. Figure numbers changed in the new version) support that the CTT differences prevail over the AOD differences in driving the RSDS differences between pairs of experiments, not only in the present-day climate simulations, but also under future conditions.

- Figures 1-4: From my point of view it would be easier to understand to have differences in absolute values rather than in percentages. Indeed, I suspect here we look at very low values which could be unsignificant.

Figures 1 to 4 have been replicated to show plain differences. These new figures have been included as Supp. Material and used to describe the results.

- Figures 1-4: Why consider only land points ? It would be interesting to show also ocean points on figures.

We prefer to focus only on land points to get a clearer message tailored to the modeling applications for the solar energy sector.

- Figure 3: When comparing the evolution of rsds, cct and aod in the simulations, I suspect a possible bug in the figure or in the simulation. Indeed, the strong decrease in rsds in northern latitudes (for example in Iceland), is neither explained by cct nor by aod.

The negative signals in rsds must be related to the increase in cct, even if small. Maybe better to see the plots with the differences in absolute values provided in the new version of the Supp. Material. This is also supported by the high spatial correlations between rsds and cct changes.

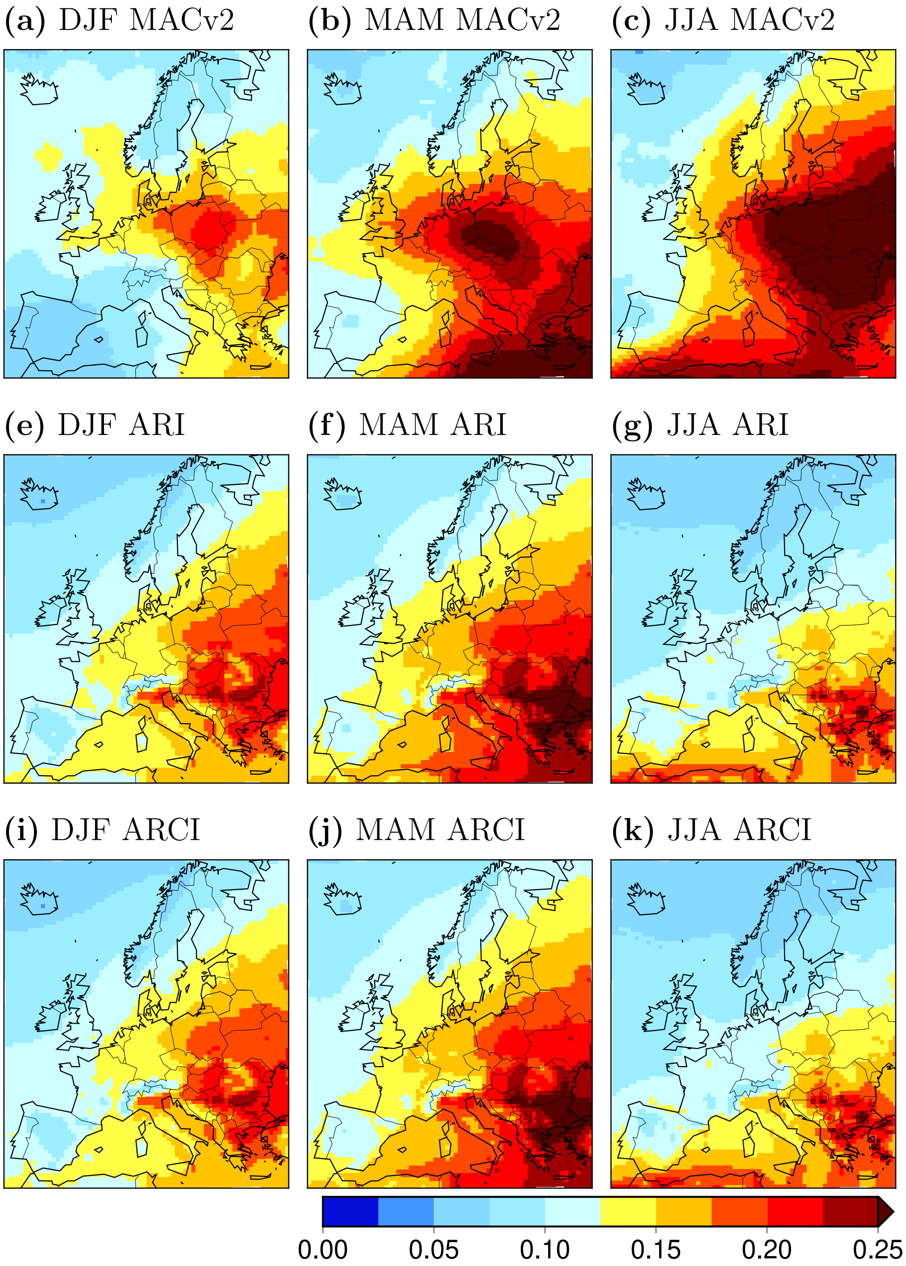
- Page 8 lines 218-219: If “the anthropogenic component is disregarded”, there should be no possible conclusion on the future evolution of rsds.

We do not attempt to provide reliable projections for RSDS, but to unveil how aerosols can affect them. See our response to the main comment #2 and discussion in section 4.

- The manuscript suffers from many typographical and English spelling errors that need to be corrected.

The manuscript has been entirely revised with the help of a native speaker.

AOD climatologies for 1991-2010



Anonymous Referee #3
Authors' response

This manuscript, submitted to Geoscientific Model Development, aims to identify the role of interactively modeling aerosol in regional climate simulations over Europe, by conducting a sensitivity study with the WRF model. The focus is on solar radiation at the surface during summer. Both a present and a future period are considered. Changes in cloudiness are presented as the main driver of the changes in solar radiation. There are some interesting features in this study, such as long simulations with the WRF-Chem model using interactive aerosol that are computationally demanding. However, I believe that the main problem is that the aim of the study is not actually addressed. I believe that separating the "interactive" part of aerosol modeling and making general comments about it is not possible in the current study. Thus it is a problem of methodology and structuring of the whole manuscript. Moreover I believe that a significant clarification is need in the current methodology regarding the BASE simulation that is the basis for comparison. I would hesitate to recommend it for publication in its current form. However, I believe that it could stand as a sensitivity study aiming to describe the impact of the specific model and aerosol treatments used. I would suggest major revisions regarding: the aims of the study, including a validation, possibly changing the analysis under clear-sky conditions, clarifying the aerosol treatment in the simulations. In the end, I think the study could provide some interesting points to the community.

We do thank the reviewer for the time devoted to read and thoughtfully comment on our work. Below we provide detailed answers to each comment, hoping to have been clear enough in our explanations. Attending these comments and the ones posted by the other reviewers and the Editor, the new version of the manuscript:

1 – Has been entirely revised by a native speaker in order to improve the redaction.

2 – Has a new title. The change intends to avoid that the reader interprets that we are comparing simulations with dynamic vs. static aerosols. The new title is:

"Sensitivity of surface solar radiation to aerosol-radiation and aerosol-cloud interactions over Europe in WRFv3.6.1 climatic runs with fully interactive aerosols"

In this line, we have made an effort to make the scientific purpose of the manuscript clearer throughout the whole text.

3 – Includes further details and arguments on the experimental set-up and the methodology. Section 2 has been divided into 3 subsections.

4 – The formerly labeled ACI simulations are now named ARCI to emphasize that these include both aerosol-radiation and aerosol-cloud interactions.

5 – Includes a brief validation exercise. We now face the outputs of our simulations with ERA5.

6 – Includes two subsections within the Results section: one for the historical simulations and another for the future projections. Both has been expanded providing physical interpretation of the results.

7 – Includes a deeper discussion of the results attending the reviewers' comments.

8 – Includes a link where all the data and codes to reproduce our study have been made publicly available: http://doi.org/10.23728/b2share.a65d25c2b3ba49e1a46e970783e9476e.

We are confident that these major changes have improved significantly the manuscript and provides a larger support to its key findings.

We must also notice that we used wrong AOD values in the previous version of the paper, as it was noted by the reviewer2. These had been computed from the TAUAER3 and TAUAER4 variables, which do exhibit a weird evolution along the year. After inspection, we figured out that these and the EXTCOF55 variables had been wrongly recorded in the wrfout files (not new, apparently, see e.g.: https://forum.mmm.ucar.edu/phpBB3/viewtopic.php?t=9313&p=17464). So we have now adopted an alternative method to compute AOD following Palacios-Peña et al (2020), where, in fact, the representation of AOD by these model configurations (ARI and ARCI) were deeply evaluated. The new AOD files were estimated using the reconstructed mass-extinction method (Malm et al 1994) from the well-recorded concentrations of the various aerosol species in the wrfout files, namely: black carbon, organic carbon, dust and sea salt. Sulfates were estimated from SO2 and OH recorded concentrations using the same kinetic reaction as the one implemented in the RACM-KPP module. We want to remark that the mistake occurered during the postprocessing of the wrfout files, while WRF-Chem run satisfactorily. These wrfout files were removed after postprocessed, so we have now generated a sample one (using the ARI configuration) and uploaded it for checking together with all the other data files. Importantly, this change in the methodology for estimating AOD values did not alter the the overall results of the paper.

Major comments:

1. One of my major concerns is that the nature of the BASE experiment is not clear to me. It is stated that it works with a specific aerosol concentration and that “the aerosol radiative effect is assumed to come as an external forcing.” I am not sure what this means. Does the BASE experiment let these aerosols interact with radiation? In this case the AOD field needs to be shown. Or their only impact is that they are just used by the microphysics to facilitate cloud formation? In any case, the nature of aerosol in the BASE experiment needs to be clearly stated so that the reader understands the results of the comparison. Moreover if BASE has an AOD that interacts with radiation, how much does it differ from the AOD of ARI and ACI? Are the differences between BASE and these simulations attributed to the difference in AOD and not to the introduction of dynamic aerosol?

We agree that the BASE experiment was poorly described. Now we say:

“BASE: aerosols are not considered in the simulations. No aerosol climatology is used, and no aerosol interactions are taken into account by the model. WRF-alone considers a constant number of cloud condensation nuclei (250 per cm^3, set in the model by default) to enable the formation of clouds.”

2. It is very interesting to try and identify the impact of interactively modeled aerosols. However, I am not sure that this is achieved in the study. You can make a statement that, for example, the ARI experiment that uses “this specific” interactive aerosol treatment in WRF-Chem has “this specific impact” on radiation. This statement could be useful to the community as a sensitivity study of the model and aerosol scheme. However, I do not think that you can attribute this impact only to the “interactive” part. Probably, a first step towards that direction would be to have additional experiments enabling aerosol-radiation and cloud interactions using static aerosol fields with the same mean AOD as the ones in ARI and ACI.

We also agree here. We were wrongly giving the message that signals were due to the interactive aerosols modeling approach adopted here as compared to a more conservative (and common) approach based on non-interactive aerosols, which is something that we did not inspect. We have accordingly reformulated the title and redaction of the manuscript.

3. I believe a validation (even a quick one) of the simulations, especially regarding rsds and AOD, should be part of the study in order to assert that they do capture the basic patterns of the examined variables. I do understand that they are compared against the GCM (and that the GCM has been probably validated), but still a validation would make the results more robust.

The manuscript now includes a brief comparison of the present-day simulations with ERA5 (for RSDS). The representation of AOD by these model configurations (ARI and ARCI) were deeply evaluated in Palacios-Peña et al. (2020). Nonetheless, find attached here a figure with the AOD climatologies from ARI and ARCI and those from MACv2.

4. The methodology to calculate Clear sky conditions was a bit unusual to me. I am aware that the radiation code in WRF (and I think this is the case for version 3.6.1) provides the clear-sky radiation at every time step simultaneously with rsds. It would probably be better to use that feature. I also have a question regarding the methodology. It is stated (page 6, 150-152) that in order to consider a specific grid point in the analysis you need to have at least 15 records per period that are not missing values. Ok so far. It is stated (page 6, lines 153-154) that "(which, according to our methodology, would occur only if all days within a summer season have CTT values >1%)." So, if I understand correctly even if one day within a summer season has a CCT value <1, that summer season gains a valid value based only on that day and is considered in the analysis?

Unfortunately, we did not save clear-sky values from the model outputs, so we needed to adopt an alternative methodology.

Regarding the methodology, the reviewer's interpretation is right. In any case, we show seasonal climatological values (or differences), thus the results are independent of that (we simply average over all days with CCT<1%). The number of seasons with non-missing values just affects the interannual variability of the seasonal series, thus playing a role when assessing the statistical significance of the differences between that climatological values. Therefore, outliers values (in case) should affect very little the overall results.

5. The use of no time evolving anthropogenic aerosol in the future period by ARI and ACI experiments is not ideal. It is good that this deficiency is stated in the manuscript (page 8, line 218). Moreover, it would be interesting to see what are the rsds differences between the GCM and ARI/ACI for the future period.

This approach permits to better isolate the signals from the aerosol-radiation-cloud interactions due to the so-called climate change penalty alone, while reduces the reliability of the future projections obtained, in fact. We now we make more emphasis on this point in the manuscript (see Discussion).

Attached a figure with ARI-GCM and ARCI-GCM differences in rsds in the future period. Not that different to those in the present period.

Minor comments:

-Page 1, line 20 “reduction about 5% in RSDS was found when aerosols are dynamically solved”. This is compared to BASE? It must be clearly stated.

Done.

-Page 2, line 33 The phrase “all about cumulus” I believe should be clarified a bit better. Is this about convective phenomena, the cloud fraction scheme or both?

It is more correct to say “convective phenomena” indeed. Amended.

-Page 4 lines 97-98. In the BASE experiment “the by-default WRF setup was used, which considers 250 cloud condensation nuclei per cm3 to form clouds”. I think the term “by-defalut” might be a bit misleading. I understand that this concentration of CCN is probably related to the Lin microphysics scheme used in the experiments and this should be stated.

This part has been reformulated. Anyway, this CCN value (250 per cm3) is not linked to the microphysics scheme, but something more general in the model.

-I do not understand how ACI (page 5, lines139-141) works. What is meant by “Although this WRF-Chem version (3.6.1) does not allow a full coupling with aerosol-cloud interactions. . .”? I believe it should be clearly stated which are the parts of the aerosol-clouds interactions that are missing. Also I think it should be stated to which variables the single and double moment treatment is applied.

We have amended the lack of description of the WRF setup used to perform the simulations labeled as ARCI by including the follwoing in the text (in section 2):

“Aerosol-cloud interactions were implemented by linking the simulated cloud droplet number with the microphysics schemes (Chapman et al 2009) affecting both the calculated droplet mean radius and the cloud optical depth. Although this WRF-Chem version (3.6.1) does not allow a full coupling with aerosol-cloud interactions, the microphysics implemented here is a single moment scheme that turns into a two-moment scheme in the simulations denoted ARCI. One-moment microphysical schemes are unsuitable for assessing the aerosol-cloud interactions as they only predict the mass of cloud droplets and do not represent the number or concentration of cloud droplets (Li et al. 2008). The prediction of two moments provides a more robust treatment of the particle size distributions, which is key for computing the microphysical process rates and cloud/precipitation evolution. In this sense, although the Lin microphysics is presented as a single moment scheme, the WRF-Chem model makes it possible to transform the single- into a double-moment scheme. A prognostic treatment of cloud droplet number was added (Ghan et al. 1997), which treats water vapor and cloud water, rain, cloud ice, snow, and graupel. The autoconversion of cloud droplets to rain droplets depends on droplet number (Liu et al. 2005). Droplet-number nucleation and (complete) evaporation rates correspond to the aerosol activation and resuspension rates. Ice nuclei based on predicted particulates are not treated. However, ice clouds are included via the prescribed ice nuclei distribution, following the Lin scheme. Finally, the interactions of clouds and incoming solar radiation were implemented by linking the simulated cloud droplet number with the Goddard shortwave radiation scheme, representing the first indirect effect, and with the Lin microphysics, representing the second indirect effect (Skamarock et al. 2008). Thus, the droplet number will affect both the calculated droplet mean radius and cloud optical depth.”

References:

Ghan, S. J., Leung, L. R., Easter, R. C., & Abdul Razzak, H. (1997). Prediction of cloud droplet number in a general circulation model. *Journal of Geophysical Research: Atmospheres*, *102*(D18), 21777-21794.

Li, G., Wang, Y., & Zhang, R. (2008). Implementation of a two moment bulk microphysics scheme to the WRF model to investigate aerosol cloud interaction. *Journal of Geophysical Research: Atmospheres*, *113*(D15).

Lin, Y. L., Farley, R. D., & Orville, H. D. (1983). Bulk parameterization of the snow field in a cloud model. Journal of Climate and Applied Meteorology, 22(6), 1065-1092.

Liu, Y., Daum, P. H., & McGraw, R. L. (2005). Size truncation effect, threshold behavior, and a new type of autoconversion parameterization. *Geophysical research letters*, *32*(11).

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We have also acknowledged in Discussion the following:

“In the ARCI simulations, the autoconversion scheme called so that cloud droplets can turn into rain droplets is different to the autoconversion scheme activated in the ARI simulations. This change in the WRF-Chem configuration can lead to ARCI-ARI differences that do not come necessarily from the of the aerosol-cloud interactions from a physical point of view (Liu et al 2005). In fact, the activation of the aerosol-cloud interactions requires further changes in the model configuration (as compared to the configuration used for the simulations labeled as ARI) beyond the autoconversion scheme, such as the activation of aqueous chemistry processes, that could also have an added impact to effect that can be strictly attributed to the aerosol-cloud interactions. However, technically, the encoding of WRF-Chem model hampers to better isolate the effect of the aerosol-cloud interactions. Therefore, ARCI-ARI differences can not be attributed to the aerosol-cloud interactions from a purely physical point of view, but to the activation of the aerosol-cloud interactions from a modeling point of view, since the autoconversion schemes necessarily change between ARI and ARCI.”

Reference:

Liu, Y., Daum, P. H., & McGraw, R. L. (2005). Size truncation effect, threshold behavior, and a new type of autoconversion parameterization. *Geophysical research letters*, *32*(11).

-I believe it is useful to know which statistical test is used (t-set, non parametric Mann-Whitney. . .) to determine statistical significance.

We used the t-test. Section 2 has now been splitted into several subsections. The last one includes more methodological details, as this one.

-Total cloud cover values over southern Europe in summer are usually small. Thus, the changes in CCT between the experiments could be in some cases negligible but the relative (percentage) change could be inflated. I believe this should be stated in the manuscript. Also, it would be interesting to see a plot with the plain difference in CCT between experiments in the supplement.

Figures 1 to 4 have been replicated to show plain differences. These new figures have been included as Supp. Material and used to describe the results.

-Page 7, lines 185-186. “Contrary, the effect of interactive aerosols schemes. . .” The way it is written gives the impression that the authors are talking about interactive schemes in general. I think it would be better to avoid generalizing the results of this specific sensitivity study.

The reviewer is right. We have followed this suggestion all along the revised manuscript.

-Page 8, lines 209-210. “These latter are more widespread in ARI than in BASE, which makes the ARI pattern the most similar to the change pattern from the GCM”. I do not clearly see this in Figure3.

The ARI pattern (Fig 3c) shows the most widespread positive signals south-eastward, and the lowest negative signals northward.

Technical corrections:

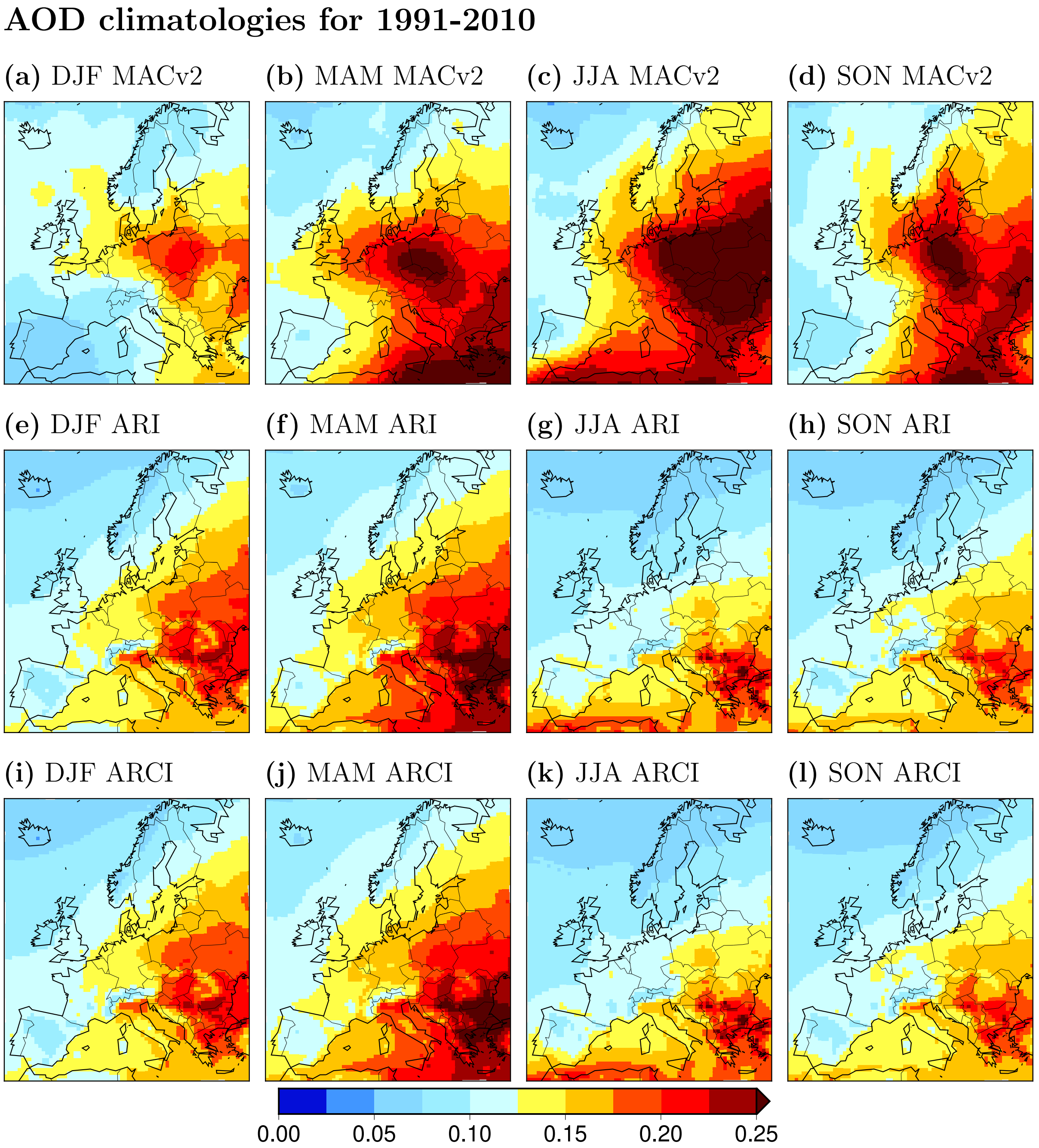
Page 7 line 183 “varables” -> variables

Page 7, line 188 I am not aware of the word “devanishes”. Could this be a spelling mistake?

Page 10, line 274 experimts -> experiments

Page 1, line25 much more softer -> much softer

Thanks for these corrections. The entire manuscript has been revised by a native speaker.

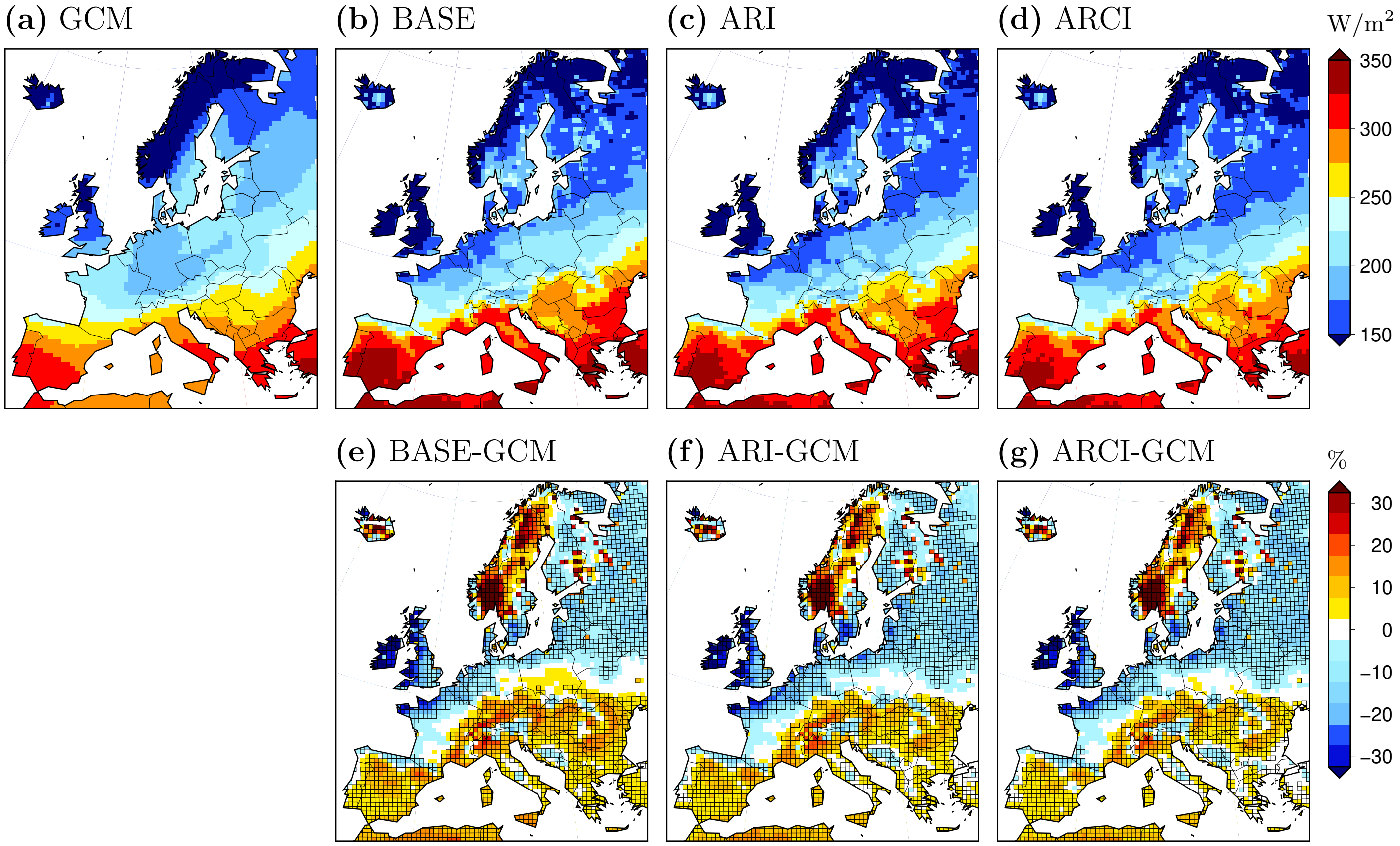

AOD climatologies for 1991-2010

(a) DJF MACv2 **(b)** MAM MACv2 **(c)** JJA MACv2 **(d)** SON MACv2

(e) DJF ARI **(f)** MAM ARI **(g)** JJA ARI **(h)** SON ARI

(i) DJF ARCI **(j)** MAM ARCI **(k)** JJA ARCI **(l)** SON ARCI

RSDS JJA climatologies for 2031-2050



RSDS summer climatologies in the future period from the GCM (a) and the WRF simulations (b to d); units: W/m2. Panels e to g depict relative differences between each WRF simulation and the GCM, squared if statistically significant ($p<0.05$); units: %.

~~Gains and losses in surface solar radiation with dynamic aerosols in regional climate simulations for Europe~~

Sensitivity of surface solar radiation to aerosol-radiation and aerosol-cloud interactions over Europe in WRFv3.6.1 climatic runs with fully interactive aerosols

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Abstract

The amount of solar radiation reaching the Earth's surface can be highly determined by atmospheric aerosols, which the IPCC has called as the most uncertain climate forcing agents, through their direct (scattering), semi-direct (absorption) and indirect (cloud properties modification) effects. Nonetheless, Regional Climate Models hardly ever dynamically model the atmospheric concentration of aerosols and their interactions with radiation (ARI) and clouds (ACI). The objective of this work is to evince the role of modeling ARI and ACI in Weather Research and Forecast (WRF) model simulations with fully interactive aerosols (online resolved concentrations) with a focus on summer mean surface downward solar radiation (RSDS) over Europe. Under present-day conditions (1991-2010), both ARI and ACI reduce RSDS by a few percentage points over central and northern regions. This reduction is larger when only ARI are resolved, while ACI counteract the effect of the former by up to half. The response of RSDS to the activation of ARI and ACI is mainly led by the aerosol effect on the cloud coverage, while the aerosol effect on the atmospheric optical depth plays a very minor role. This suggests that semi-direct and indirect aerosol effects prevail over the direct effect. Consistently, differences in RSDS among experiments with and without aerosols

are softer under clear-sky conditions. In terms of future projections (2031-2050 vs. 1991-2010), the baseline pattern (from an experiment without aerosols) shows positive signals southward and negative signals northward. While ARI enhance the former and reduce the latter, ACI work in the opposite direction and provide a flatter RSDS change pattern, further evincing the opposite impact from semi-direct and indirect effects and the non-banal influence of the latter.

~~The solar resource can be highly influenced by clouds and atmospheric aerosol, which has been named by the IPCC as the most uncertainty climate forcing agent. Nonetheless, Regional Climate Models (RCMs) hardly ever model dynamically atmospheric aerosol concentration and their interaction with radiation and clouds, in contrast to Global Circulation Models (GCMs). The objective of this work is to evince the role of the interactively modeling of aerosol concentrations and their interactions with radiation and clouds in Weather Research and Forecast (WRF) model simulations with a focus on summer mean surface downward solar radiation (RSDS) and over Europe. The results show that the response of RSDS is mainly led by the aerosol effects on cloudiness, which explain well the differences between the experiments in which aerosol-radiation and aerosol-radiation-cloud interactions are taken into account or not. Under present climate, a reduction about 5% in RSDS was found when aerosols are dynamically solved by the RCM, which is larger when only aerosol-radiation interactions are considered. However, for future projections, the inclusion of aerosol-radiation-cloud interactions results in the most negative RSDS change pattern (while with slight values), showing noticeable differences with the projections from either the other RCM experiments or from their driving GCM (which do hold some significant positive signals). Differences in RSDS among experiments are much more softer under clear-sky conditions.~~

1 – Introduction

Regional Climate Models (RCMs) are powerful tools providing high**-**resolution climate information by dynamically downsca~~l~~ling coarser datasets, e.g. from Global Circulation Models (GCMs). Their added value **comes** ~~is~~ not only **from** ~~about~~ the increased resolution, but also **from** ~~about~~ the fact that such an increased resolution allows modeling and considering fine scale processes and features that are missed or misrepresented otherwise, e.g. local circulations and land uses (Rummukainen 2010, Jacob et al 2014, 2020, Schewe et al 2019). Still, certain phenomena need to be parametrized, e.g. the turbulence within the planetary boundary layer, ~~the~~ microphysics processes and **convective**

phenomena ~~all about cumulus~~. However, there are relevant processes that GCMs usually model dynamically, but **which** RCMs usually do not. This is the case of the atmospheric aerosol~~s~~ concentration and their multiple non-linear interactions (e.g. Taylor et al 2012 *vs.* Ruti et al 2016), the so-called aerosol-radiation and aerosol-cloud interactions (**ARI and ACI respectively;** Boucher 2015).

Depending on their nature and ~~on~~ the ambient conditions, aerosols can act to scatter and/or absorb the solar radiation **through ARI**, which may result **in** ~~on~~ less or more solar radiation reaching the surface; less because of its scattering (direct effect), more if absorption (semi-direct effect) leads to clouds burn-off and/or inhibition (Giorgi et al 2002, Nabat et al 2015a, Li et al 2017, Kinne 2019). Aerosols also act as cloud condensation nuclei (indirect effect **or ACI**), which may also result **in** ~~on~~ less or more solar radiation reaching the surface. Abundance of cloud condensation nuclei rebounds on enhanced scattering **via** ~~by~~ whitened clouds of smaller drops with increased size and lifetime, and on ~~the~~ drizzle suppression which reduces bellow-cloud wet deposition processes (Seinfeld et al 2016, Kinne 2019). **On the c**~~C~~ontrary, in-cloud aerosol scavenging processes lead to out-of-cloud~~s~~ cleaner atmospheres (Croft et al 2012). All these processes **can potentially** ~~have the potential to~~ alter local and regional circulations, therefore impacting beyond the radiative balance (Kloster et al 2010, Wilcox et al 2013, Nabat et al 2014, Wang et al 2016, Pavlidis et al 2020).

In the current context of climat**e**~~ic~~ crisis, the scientific challenge is ~~getting~~ **becoming** twofold: (1) **to gain** a good understanding of **the** processes that occur in the atmosphere and of what will occur in the future, because this is crucial (IPCC 2013) in order ~~to~~ (2) **to** advance effective measures both at global and regional scales (IPCC 2014). In particular, climate change mitigation strategies require ~~that~~ low-carbon energies **to** grow **rapidly** ~~very fast~~ in the coming decades (Rohrig et al 2019, IRENA 2019). This rapid transition of the energy sector towards renewable~~s~~-powered decarbonized systems makes ~~the~~ energy production, transmission and distribution increasingly sensitive to weather and climate variability (~~Jerez et al 2013,~~ Bloomfield et al 2016, Collins et al 2018, Kozarcanin et al 2018, Jerez et al 2019~~, Troccoli et al 2018, Germer & Kleidon 2019, Turner et al 2019, van der Wiel et al 2019, van Ruijven et al 2019~~). Thus, several works have been devoted to assess**ing** this issue through the use of climate modeling tools. **In particular, for the solar resource, Crook et al (2011), Gaetani et al (2014), Wild et al (2015) and Müller et al (2019) showed a generalized increase in Europe by making use of GCM simulations, while Jerez et al (2015), Gil et al (2019) and Tobin et al (2018) reported a different behavior, with RCM simulations projecting a slight general decrease in the amount of solar radiation reaching the**

surface over Europe. ~~(Crook et al 2011, Gaetani et al 2014, Jerez et al 2015, Tobin et al 2015, Wild et al 2015, Tobin et al 2016, Bartók et al 2017, Tobin et al 2018, Ravestein et al 2018, Schlott et al 2018, Gil et al 2019, Jerez et al 2019, Müller et al 2019, Soares et al 2019, Solaun & Cerdá 2019, Zappa et al 2019).~~

From the **previous** ~~extensive~~ literature, we **point out** ~~rescue~~ here ~~four~~ **three** key features that motivated the present work. First, the increasing use of RCM to ~~perform~~ evaluat**e**~~ions of~~ the renewable energy resources and their supply~~ing~~ potential (e.g. Jerez et al 2013, 2015, 2019, ~~Tobin et al 2015, 2016,~~ Gil et al 2019, Soares et al 2019, **van der Wiel et al 2019**). Second, the key role of aerosols regarding the accuracy of the simulated solar resource by climate models (Gaetani et al 2014, Nabat et al 2015b, ~~Gutiérrez et al 2018, 2020, Boé et al 2020,~~ Pavlidis et al 2020)**, particularly attributed to their direct and semi-direct effects, which would help to explain the aforementioned discrepancy between the GCM and RCM future projections (Boé et al 2020, Gutiérrez et al 2020)**. ~~Third, the reported discrepancies between GCMs and RCMs future projections for the solar resource (Jerez et al 2015, Bartók et al 2017), which still remain largely a mystery.~~ **Third** ~~And fourth~~, none of the previous studies has **so far dealt with** ~~unveiled so far~~ the non-evident **RCM sensitivity to** ~~role of~~ interactively modeled atmospheric aerosol concentrations and the resulting aerosol-radiation and aerosol-cloud interactions **in order to simulate** ~~for simulating~~ the solar resource ~~using regional climate models~~ under present and future climate scenarios.

Hence, our objective here is to shed light on ~~that~~ **the third point above by assessing the sensitivity of long-term RCM simulations to the inclusion of ARI and ACI using fully interactive (online diagnosed) aerosols**. For **this** ~~that~~, we made use of a widely applied RCM, the Weather Research and Forecasting (WRF) model (Skamarock et al 2008) and its coupled form with Chemistry (WRF-Chem; Grell et al 2005), to perform sets of present (period 1991-2010) and future (period 2031-2050) simulations over Europe in three ways: (1) without **including atmospheric aerosols** ~~dynamic aerosol modeling~~, (2) with dynamic aerosols and aerosol-radiation interactions activated, and (3) with dynamic aerosols and both aerosol-radiation and aerosol-cloud interactions activated.

Section 2 describes experiments and methods; section 3 presents the results; the discussion and conclusions are **provided** ~~summarized~~ in Section 4.

2 – Experiments, ~~and~~ data and methods

2.1 – General description of the WRF simulations

We performed three experiments using the WRF model version 3.6.1 (Skamarock et al 2008; available at https://www.mmm.ucar.edu/weather-research-and-forecasting-model~~, last accessed on 2019-11-28~~). In all cases, the simulated periods were 1991-2010 (present) and 2031-2050 (future). Initial and boundary conditions were taken from GCM simulations: the r1i1p1 MPI-ESM-LR historical and RCP8.5-forced runs (Giorgetta at al. 2012a,b; available at https://cera-www.dkrz.de~~, last accessed on 2019-11-28~~) from the Coupled Model Intercomparison Project Phase 5 (CMIP5; https://pcmdi.llnl.gov/mips/cmip5/; Taylor et al 2012). The Representative Concentration Pathway RCP8.5 (Moss et al 2010) depicts the highest radiative forcing along the XXI century among all RCPs, with doubled CO_2, CH_4, and N_2O concentrations by 2050 compared to the last record of the historical period. Both the observed (past) and estimated (future) temporal evolution of the concentration of these species was appropriately considered in the WRF executions (Jerez et al 2018).

The three experiments consisted of, and are named as:

~~**BASE: aerosols are not treated interactively, the by-default WRF setup was used, which considers 250 cloud condensation nuclei per cm^3 to form clouds, and the aerosol radiative effect is assumed to come as an external forcing.**~~

BASE: aerosols are not considered in the simulations. No aerosol climatology is used, and no aerosol interactions are taken into account by the model. WRF-alone considers a constant number of cloud condensation nuclei (250 per cm^3, set in the model by default) to enable the formation of clouds.

ARI: aerosols are treated interactively (see bel~~l~~ow) and aerosol-radiation interactions are activated in the model.

ARCI: aerosols are treated interactively **(see below)** ~~, as in ARI experiments,~~ and both aerosol-radiation and aerosol-cloud interactions are activated in the model.

The WRF spatial configuration consisted of two one-way nested domains (Supp Fig 1). The inner one (target domain) is an Euro-Cordex (https://www.euro-cordex.net/; Jacob et al 2014, 2020) compliant domain covering Europe with a~~n~~ horizontal resolution of 0.44º in latitude and longitude. The outer one has a horizontal resolution of 1.32º and covers the most important areas of Saharan dust emission as in Palacios-Peña et al 2019a. This configuration was necessary to generate and include the information of the Saharan dust intrusions through the boundaries of our target domain for the ARI and A**R**CI experiments, because the boundary conditions from the GCM do not provide this information. In the vertical dimension, 29 unevenly spaced eta levels were specified in the two domains, with more levels near the surface than upward, and the model top was set to 50 hPa. The physics configuration of the WRF model consisted of the Lin microphysics scheme (Lin et al. 1983), the RRTM radiative scheme (Iacono et al. 2008), the Grell 3D ensemble cumulus scheme (Grell 1993, Grell and Dévényi 2002), the University of Yonsei boundary layer scheme (Hong et al. 2006) and the Noah land surface model (Chen & Dudhia 2001, Tewari et al. 2004). Boundary conditions from the GCM were updated every 6 hours, including the low boundary condition for the sea surface temperature. Nudging was applied to the outer domain, but not to the target domain.

2.2 – Including aerosols in WRF

To perform **the** ARI and A**R**CI experiments, we used the WRF model coupled with Chemistry (WRF-Chem) version 3.6.1 (Grell et al 2005, Chin et al 2002). WRF-Chem runs with GOCART aerosol module (Ginoux et al 2001). This scheme includes five species, namely sulfate, mineral dust, sea salt aerosol, organic matter and black carbon, and was coupled with RACM-KPP (Stockwell et al 1997, Geiger et al 2003) as chemistry option. **Chemical reactions in the GOCART model include several oxidation processes by the three main oxidants in the troposphere: OH, NO3, and O3. The OH radical dominates oxidation during the daytime, but at night its concentration drops and NO3 becomes the primary oxidant (Archer-Nicholls et al., 2014). So, the oxidation pathways represented in GOCART include: (a) dimethyl sulfide (DMS) oxidation by the hydroxyl radical (OH) during the day to form sulfur dioxide (SO_2) and methanesulfonic acid (MSA); (b) oxidation by nitrate radicals (NO3) at night to form SO_2; and (c) SO_2 oxidation by OH in air and by H_2O_2 and tropospheric ozone (O_3) in clouds (aqueous chemistry) to form sulfate (Chin et al., 2000). Henceforth, the skilful characterization of gas-phase radicals such as OH and NO3 or compounds like O_3 is essential for the representation of oxidation pathways in the atmosphere leading to the formation of**

secondary aerosols (Jiménez et al., 2003). Therefore, in this contribution the RACM (Stockwell et al., 1997; Geiger et al., 2003) mechanism was coupled to GOCART trough the kinetics pre-processor (KPP) in WRF-Chem in order to provide the concentrations of radical and gas-phase pollutants needed by the GOCART aerosol model. The Fast-J module (Wild et al 2000) was used as photolysis option. Biogenic emissions were calculated using the Guenther scheme (Guenther et al 2006). ~~The simulated aerosols included five species, namely sulphate, mineral dust, sea salt aerosol, organic matter and black carbon.~~ Anthropogenic emissions coming from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP; Lamarque et al 2010) were kept unchanged in the simulation periods (we considered the 2010 monthly values). Natural emissions depend on ambient conditions and varied accordingly in our simulations following Ginoux et al 2001 for dust and Chin et al 2002 for sea salt.

The inclusion of aerosol-radiation ~~and aerosol-cloud~~ interactions in **the called** ARI ~~and ACI~~ simulations ~~are extensively described in Palacios-Peña et al 2020. However, a brief summary is included here. The former (aerosol-radiation) are included following~~ **follows** Fast et al 2006 and Chapman et al 2009. The overall refractive index for a given size bin was determined by volume averaging associating each chemical constituent of aerosol with a complex index of refraction. The Mie theory and the summation over all size bins were used to determine the composite aerosol optical properties assuming wet particle diameters. Finally, aerosol optical properties **were** ~~are~~ transferred to the shortwave radiation scheme. Aerosol-cloud interactions were implemented by linking the simulated cloud droplet number with the microphysics schemes (Chapman et al 2009) affecting both the calculated droplet mean radius and the cloud optical depth. Although this WRF-Chem version (3.6.1) does not allow a full coupling with aerosol-cloud interactions, the microphysics implemented here is a single moment scheme that turns into a two-moment~~s~~ scheme in the simulations denoted ~~as~~ ARCI. **One-moment microphysical schemes are unsuitable for assessing the aerosol-cloud interactions as they only predict the mass of cloud droplets and do not represent the number or concentration of cloud droplets (Li et al. 2008). The prediction of two moments provides a more robust treatment of the particle size distributions, which is key for computing the microphysical process rates and cloud/precipitation evolution. In this sense, although the Lin microphysics is presented as a single moment scheme, the WRF-Chem model makes it possible to transform the single- into a double-moment scheme. A prognostic treatment of cloud droplet number was added (Ghan et al. 1997), which treats water vapor and cloud water, rain, cloud ice, snow, and graupel. The autoconversion of cloud droplets to rain droplets depends on droplet number (Liu et al. 2005).**

Droplet-number nucleation and (complete) evaporation rates correspond to the aerosol activation and resuspension rates. Ice nuclei based on predicted particulates are not treated. However, ice clouds are included via the prescribed ice nuclei distribution, following the Lin scheme. Finally, the interactions of clouds and incoming solar radiation were implemented by linking the simulated cloud droplet number with the Goddard shortwave radiation scheme, representing the first indirect effect, and with the Lin microphysics, representing the second indirect effect (Skamarock et al. 2008). Thus, the droplet number will affect both the calculated droplet mean radius and cloud optical depth.

2.3 – Data and methods

The WRF and WRF-Chem outputs were recorded every hour for Surface Downward Solar Radiation (RSDS), Total Cloud Cover (CCT) and the concentrations of various aerosol species (dust, black carbon, organic carbon and sea salt). The concentration of sulfates was indirectly computed from the recorded concentrations of SO2 and OH using the same kinetic reaction implemented in the RACM-KPP module. From the concentrations of the five aerosol species, the Atmospheric Optical Depth (AOD) at 550 nm was estimated using the reconstructed mass-extinction method (Malm et al 1994), as in Palacios-Peña et al (2020). The RSDS and CCT data simulated by the driving GCM runs were used for comparison purposes. We also retrieved the AOD at 550 nm as seen by the GCM from the MACv2 data (Kinne et al 2019), whose anthropogenic changes are in accordance with the RCP8.5 while its coarse mode (of natural origin) was not allowed to change. Also, RSDS values from the ERA5 reanalysis (Hersbach et al 2020) were used for validation purposes. Seasonal means means of all the variables were used in the analysis. These means involve all the records within each season in the series.

We also studied the sensitivity to resolving aerosol interactions of RSDS and AOD under clear-sky conditions. The analysis in absence of cloudiness will tell us more about the relevance of the direct radiative effect of aerosols. RSDS and AOD clear-sky ($RSDS_{cs}$ and AOD_{cs}, respectively) mean seasonal series were constructed as follows. First, hourly series of CCT, RSDS and AOD were time averaged up to the daily timescale. Second, days with CCT values lower than 1% were retained (this criterion is applied at the grid-box level, for each grid-box individually); otherwise we put a missing value. These clear-sky daily series were then time averaged up to the seasonal time-scale. When pairs of experiments were compared,

only coincident clear-sky dates (days) in the series were selected (missing values were also assigned in this case to the non-coincident dates with clear-sky conditions) before performing the seasonal time average. This restriction aims to avoid the masking effect of Earth orbit related issues, of large scale climate drivers and/or local forcings such as water vapor content, since different days may have different daytime lengths and different atmospheric compositions (different atmospheric optical depth or atmospheric transmissivity) that may mask the AOD effect under clear-sky conditions. The analysis involving $RSDS_{cs}$ and AOD_{cs} was carried out only over those grid points where at least 75% of the summer mean values in the series (i.e. at least 15 records per period) were not missing (which, according to our methodology, would occur only if all days within a summer season had CTT values ≥1%).

Spatial correlations between climatological patterns were computed excluding sea grid points, considering absolute values in case they involved differences (while these were depicted in the Figures in relative terms, i.e. in %), using the CDO *fldcor* function (https://code.mpimet.mpg.de/projects/cdo/embedded/cdo.pdf**). Temporal correlations were computed at the grid point level between the seasonal series, considering absolute values in case they involved differences, using the R *cor* function (**https://www.rdocumentation.org/packages/stats/versions/3.6.2/topics/cor**; *Pearson* correlation coefficient selected). The statistical significance of any signal was assessed with a t-test.**

We focus on the summer season (JJA), when solar energy is at its maximum, AOD typically reaches high values and the aerosol radiative effect has been proven to be strongest (Pavlidis et al 2020).

In order to investigate the underlying mechanisms explaining the signals found in RSDS and CCT, additional variables and statistics were used, namely: JJA-mean top-of-the-atmosphere outgoing short-wave radiation (RSOT), surface (2 m height) air temperature (TAS), surface (1000 hPa pressure level) relative humidity (RH), total precipitation (PR) and convective precipitation (PRC); number of cloudy days (CLD, defined as days with mean CCT>75%) in the summer series; 90th percentile of the JJA day-mean PR series; and number of rainy days (RD, defined as days with mean precipitation > 1 mm) in the JJA daily PR series.

~~**The WRF outputs were recorded every hour, in particular for the variables of interest here, namely Surface Downward Solar Radiation (RSDS) and Total Cloud Cover (CCT). We also**~~

~~compute AOD at 550 nm from the WRF-Chem outputs following Palacios-Peña et al (2019b). RSDS$_{cs}$ and AOD$_{cs}$ will denote the RSDS and AOD values under clear sky conditions, computed here at the daily time scale from those days with values of CCT lower than 1%. The RSDS and CCT data simulated by the driving GCM runs were used for comparison purposes. We also retrieved the AOD at 550 nm as seen by the GCM from the MACv2 data (Kinne et al 2019), whose anthropogenic changes are in accordance with the RCP8.5 while its coarse mode (of natural origin) was not allowed to change. Summer (JJA: June-July-August) means of all the variables were used in the analysis. The analysis involving RSDS$_{cs}$ and AOD$_{cs}$ will be considered only over those grid points where at least 75% of the summer mean values in the time series (i.e. at least 15 records per period) are not missing values (which, according to our methodology, would occur only if all days within a summer season have CTT values ≥1%).~~

3 – Results

3.1 – Present-day climatologies

~~We focus on the summer season (JJA), when solar energy provides its most, AOD tipically reaches the highest values and the aerosol radiative effect has been proven to be strongest (Pavlidis et al 2020).~~ As a first test, Supp Fig 2 provides the GCM**, ERA5** BASE, ARI and A**R**CI JJA climatologies of RSDS in the present period **and the results of a brief validation exercise**. Although the ~~four~~ **five** patterns depict similar structures **(Supp Fig 2a,b,d-f)**, **Supp Fig 2g-i reveals significant** ~~a closer look to the~~ deviations of the climatologies from the WRF experiments with respect to the GCM ~~(Supp Fig 2g-i) reveals significant differences through resembling patterns~~: positive values (higher RSDS values in the RCM experiments) south and northward (up to 20 and 30% respectively), and negative values in between (10-15%, eventually up to 25%). **These differences are very similar to those obtained when WRF climatologies are compared with the ERA5 pattern (Supp Fig 2j-l), with a notable exception over the Scandinavian region where the agreement between the WRF experiments and ERA5 is higher than between the WRF experiments and the GCM. In fact, the GCM pattern strongly underestimates RSDS over such a region (over 30%; Supp Fig 2c), while showing a better agreement with ERA5 elsewhere as compared to the WRF simulations.**

Although the three WRF experiments (BASE, ARI and ARCI) perform similarly when compared to the GCM or ERA5 ~~Nonetheless~~, there **are** still ~~exist significant~~ **noticeable** differences **between** ~~among~~ them ~~within the set of WRF experiments~~ (Fig 1a-c **and Supp Fig 3a-c**)~~.~~**, and it is there that**~~, in which~~ this research ~~puts the~~ focuse**s**. The inclusion of ~~interactive~~ aerosols (ARI and A**R**CI experiments) reduce**s** the JJA mean values of RSDS in central and northern parts of our domain by a few percent**age point**s **(i.e. by ~10 Wm^{-2})** as compared to the BASE experiment (Fig 1a,b **and Supp Fig 3a-b**). This reduction is generally stronger in ARI than in A**R**CI. Consequently, the A**R**CI minus ARI pattern (Fig 1c **and Supp Fig 3c**) depicts mostly positive values **(by ~5 Wm^{-2})** over central and southern regions. **This result already indicates that the indirect aerosols effects tend to counteract the direct effect of lower RSDS with higher aerosol concentrations over most of the domain, reducing it by up to a half, which is in agreement with previously reported findings (Pavlidis et al 2020).**

In order to **better** ~~try to~~ understand the~~se~~ patterns **of differences in RSDS between experiments**, Fig 1 (**and Supp Fig 3**) also provides differences in ~~the~~ CCT and AOD **(panels d to f and g to i, respectively)** ~~summer climatologies between experiments~~ and the spatial correlations (*s_corr*) between these patterns and those of RSDS differences ~~(panels d to f and g to i, respectively)~~. Compared to BASE, both ARI and A**R**CI lead to more cloudiness in central and northern regions **(albeit quite slight increases, well below 5%). This could be explained through the following feedback mechanism: the cooling effect of the scattering of radiation by the high presence of sea salt, dust and sulfate over these areas (Supp Fig 4a-j and Supp Fig 5a-b) cools down surface temperatures (Supp Fig 5d-e), thus increasing relative humidity (Supp Fig 5g-h) and favoring the formation of clouds, which leads to less radiation reaching the surface, thus lower surface temperatures, and so on. Nonetheless, these signals would simply indicate that this enhancing mechanism prevails over others. For instance, the semi-direct effect, which acts to suppress cloudiness due to the thermodynamic effect of dark particles, that could explain that this CCT reduction was more evident in ARCI than in ARI (Fig 1c, Supp Fig 3c); or the wet deposition and in-cloud aerosol scavenging processes leading to cleaner atmospheres, which could explain why RSOT was larger in ARI than in ARCI in spite of the former (Supp Fig 5c,f,i). Conversely, both ARI and ARCI lead to** ~~and~~ less cloudiness southward, **e**specially ~~in~~ ARCI (**reductions up to 10% in Mediterranean regions;** Fig 1d-e)~~, which is well correlated with the spatial distribution of the differences between experiments in RSDS~~. **Consistently, the ARCI minus ARI pattern (Fig 1f) depicts negative values (around 5%) along the Mediterranean strip. Therefore, both semi-direct and indirect aerosol effects would tend to**

diminish cloudiness southward, with the latter (indirect effect) having the greatest impact. This could be due to the fact that a high presence of large aerosols over southern Europe, both in form of dust or sulfate in our case (Supp Fig 4a-j), hampers the formation of clouds (e.g. Xue et al 2008) and may even shortens their lifetime by enhancing precipitation (e.g. Lee et al 2008), which is most plausible in the warm season over warm areas (e.g. Yin et al 2000), as long as aerosol-cloud interactions are resolved by the model. However, we did not find such an enhanced precipitation effect in our simulations (maybe the signal does not hold at the climatic scales assessed here), only a decrease in both mean cloudiness and number of cloudy days (Supp Fig 5j-l) together with consistent pictures of lower mean precipitation, lower mean convective precipitation, fewer rainy days and lower extreme precipitation values emerging over those areas where the aerosol effects diminish cloudiness (Supp Fig 6). Whatever the underlying mechanisms are, the patterns of differences between experiments in CCT are well correlated with the corresponding patterns of differences in RSDS, thus indicating a key role of CCT in driving the latter. Indeed, the temporal correlation at the grid point level between the seasonal series of RSDS and CCT differences is above 0.8 (negative) in most of the domain (Supp Fig 7a-c).

~~**Also, the**~~ **The inclusion of aerosols also** ~~**dynamic treatment of aerosols**~~ leads to ~~**noticeable**~~ differences **of a few percentage points (2-5%)** ~~**(up to 10%)**~~ in the AOD values between A**R**CI and ARI **simulations over western areas** (Fig 1i), and the AOD climatologies from these two experiments provide~~s~~ a consistently non-nul**le** picture (Fig 1g,h; nul**le** values can be considered for BASE). However, the patterns for AOD do not correlate with those for RSDS~~**. In fact, the temporal correlation at the grid point level between the series of differences in RSDS and in CTT is above 0.8 (negative) in most of the domain, while**~~ **and the seasonal series of** differences in AOD hardly correlates ~~**in time**~~ with **the seasonal series of** differences in RSDS **except for certain locations of central and southeast Europe** (Supp Fig ~~5~~7d-f). **Interestingly, over these locations, the temporal correlation between differences in RSDS and differences in AOD are positive, further indicating the secondary role of the direct radiative effect of the aerosols there: if the larger the AOD, the larger the RSDS, it is because semi-direct and indirect effects counteract the impact of the direct scattering effect.** ~~**Hence, the CTT differences prevail over the AOD differences in driving the RSDS differences between pairs of experiments in the present-day climate simulations. This also holds under future conditions, while the patterns of differnces in the analyzed varables show different structures (Supp Fig 4 and 5a-f).**~~

Thus~~Therefore~~, there is an overall ~~a direct and~~ predominant link between the aerosol~~s~~ effect on cloudiness and its impact on the amount of solar radiation reaching the surface **that totally masks any other mechanism related to the variation in AOD and its direct impact on RSDS**. ~~Contrary, the effect of interactive aerosols schemes on AOD seems to play a minor and more local role in certain locations, where it eventually can help to straightly explain the differences in RSDS between ACI and ARI as the matching between the RSDS and CCT differences devanishes. For instance, a closer look to local differences between ARI/ACI and BASE reveals regions (in central and eastern Mediterranean Europe) where, in spite of the less CCT simulated in experiments with interactive aerosols (Fig 1d,e), they also simulate less RSDS than BASE (Fig 1a,b). This could be explained by the differences in AOD and its locally relevant impact on RSDS over these regions, as pointed out by Supp Fig 3d. Also, over areas of central Europe, while differences between ACI and ARI in CTT are small (Fig 1f), ACI provides higher values of RSDS than ARI (Fig 1c), which could be explained by the larger AOD values in the ARI simulation (Fig 1i).~~ **On the contrary, as expected, u**~~U~~nder clear-sky conditions ~~(Fig 2)~~, both the **negative** spatial correlations between **the** patterns of AOD$_{cs}$ and RSDS$_{cs}$ differences **between experiments (Fig 2)**, and the **negative** temporal correlations between the respective series computed at the grid point level (Supp Fig ~~5~~**7**g-i~~, 7g-i and 6~~), support the relevant role of the AOD$_{cs}$ variable for the simulation of RSDS$_{cs}$. ~~Nonetheless,~~**The** differences in RSDS$_{cs}$ ~~are lower than differences in RSDS~~ **between ARI or ARCI and BASE are negative (around 5 Wm^{-2}; Fig 2 and Supp Fig 8) over the study area (restricted to the southern half of the domain since the clear-sky series northward lack of sufficient records to perform a robust statistical analysis), illustrating the direct radiative effect of aerosols and further supporting its smaller impact at the time-scales considered here as compared to the overall impact of semi-direct and indirect effects (that make the negative clear-sky signals softer and even positive, as shown in Fig 1a,b). ARCI minus ARI differences in RSDS$_{cs}$ are** basically **null** ~~nule between ACI and ARI~~ **since semi-direct and indirect effects are largely irrelevant in the absence of cloudiness**. ~~It is important to note that this analysis considers coincident clear-sky dates between the pairs of experiment being faced (the percentage of days retained under this approach can be seen in Supp Fig 7). Without this restriction (see the percentage of days retained in Supp Fig 8) the match between both variables devanishes both in the present and the future periods (Supp Fig 9 and 10), may indicating the masking effect of Earth orbit related issues, of large scale climate drivers and/or local forcings such as water vapor content.~~

3.2 – Future projections

The overall results described above also hold under future climate conditions, while some differences were identified and deserve mention. The inclusion of aerosols reduces RSDS over most of the domain due to direct and indirect effects (Supp Fig 9a-c). In particular, this occurs significantly southward, along the Mediterranean strip (Supp Fig 9a-c), in contrast to the previous results. Over some locations, mainly in central Europe, this reduction is stronger in ARI than in ARCI, as detected under present-day conditions. However, the opposite (larger RSDS reduction in ARCI than in ARI) occurs elsewhere, interestingly over the Mediterranean strip, which also contrasts with the results found under present-day conditions (Supp Fig 9a-c). These results further support the sensitivity of the simulations to both aerosol-radiation and aerosol-cloud interactions under changed climates, in such a way that cloudiness still appears to be the most important explanatory variable for the differences in RSDS between experiments, although the role of AOD gains much relevance as compared to the analysis under present-day conditions (Supp Fig 9d-i and Supp Fig 12a-f). Under clear-sky conditions (Supp Fig 12g-i and Supp Fig 13), the results are identical to those reported in the previous section.

Therefore, what contrasts most with the previous results is that (1) both ARI and ARCI simulations provide diminished values of RSDS (of a few percentage points but statistically significant) over southern locations as compared to BASE (Supp Fig 9a,b), which should primarily respond to the direct aerosol effect of scattering the radiation (enhanced RSOT can be appreciated in Supp Fig 10a,b) since it occurs, in particular, in spite of the diminished CCT values simulated by the ARI experiment there (Supp Fig 9d); and (2) such a reduction in RSDS over such southern locations is reinforced when indirect effects are included (Supp Fig 9c), as these do cause higher CCT values than BASE (Supp Fig 9e) and, consequently, higher RSOT values there than ARI (Supp Fig 10a-c). This latter could also respond to the added role of aerosols in modifying the optical properties of clouds. When ACI are considered, aerosols act as cloud condensation nuclei, which can lead to whiter clouds with higher albedo. Interestingly, but out of the scope of this study, different PR shifts east and west across Mediterranean Europe were detected when ARCI and ARI experiments were compared between them, and then ARCI and ARI with BASE (Supp Fig 11). Over the Balkan Peninsula (south-east of the domain), ACI enhances precipitation, whether in the form of convective precipitation, total precipitation, intense precipitation or number of rainy days, more than ARI does, whereas over the Iberian Peninsula (south-west of the domain), ARI leads to higher

precipitation rates and intensity, while reducing the frequency of rainy days as compared to ARCI. These signals suggest that the fact that different aerosol species prevail in these areas (the concentration of sulfate is larger eastward, while the concentration of dust particles is larger westward; Supp Fig 4), and how this affects the ratio between large and fine particulate matter, should also have an impact along with the aforementioned mechanisms (López-Romero et al 2020).

Since the patterns of differences in the analyzed variables show different structures under present and future climate conditions, the RSDS change patterns vary when ARI and ACI are taken into account by the model, as described below.

~~**Cloudiness also seems to lead the future projections for the RSDS summer climatologies (Fig 3). BASE and ARI**~~ **The** change patterns for RSDS **are similar in both the BASE and ARI experiments** (Fig 3b,c **and Supp Fig 14b,c**)~~**resemble each other**~~, ~~**with**~~ **showing** negative signals **in northernmost regions** (up to 10%**, ~15 Wm^{-2}**)~~**appearing in northernmost regions, while**~~ **and** positive signals **southward** (up to 5%**, again ~15 Wm^{-2}**) ~~**appear southward within our target domain**~~. The~~se~~ latter are more widespread in ARI than in BASE, which makes the ARI pattern the most similar to the change pattern from the GCM (Fig 3a **and Supp Fig 14a**). However, when aerosols-cloud interactions are included in the WRF runs, such a positive RSDS change signals mostly disappear, while the northern negative ones reinforce in some parts as compared to the ARI pattern (Fig 3d **and Supp Fig 14d**). ~~**All this is**~~ **These results are** in quite good agreement with the corresponding change patterns for CCT (Fig 3e-h **and Supp Fig 14e-h**) – including the fact that the negative change signals for CCT appearing southward in the GCM, BASE and ARI experiments are ~~**way**~~ **much** less evident in A**R**CI – and occur~~s~~ in spite of two constraining facts regarding the AOD simulation approach in our WRF experiments: (1) AOD remains unchanged in the BASE experiment (as illustrated by Fig 3j), and (2) AOD changes from the ARI and A**R**CI experiments are hardly realistic because their anthropogenic component is disregarded (as specified in Section 2), and thus depict patterns (Fig 3k,l) that have nothing to do with the GCM projection in Fig 3i (which does consider time evolving anthropogenic aerosols). In fact, the spatial correlation between the patterns of AOD and RSDS changes is lower than between **those** ~~**the patterns**~~ of CTT and RSDS changes~~**, specially in ACI, the experiment in which aerosols also act on clouds**~~. **Therefore, direct and semi-direct aerosol effects have little impact on the RSDS future projections here, while indirect effects play a major role by reducing the future decrease in CCT southward within our domain and thereby dispelling the future increase in RSDS in this region.**

The change signals for RSDS$_{cs}$ and AOD$_{cs}$ (Fig 4 **and Supp Fig 15**) depict ~~softer and with a~~ different spatial structure**s** to those for RSDS and AOD~~ in the ARI and ACI experiments~~, turning mostly negative southward and positive northward for RSDS$_{cs}$ **(with negative signals around 5% and positive up to 10%, in both cases implying changes up to 20 Wm^{-2})**~~, which~~ **. Although this** occurs similarly in the three experiments (BASE, ARI and A**R**CI)**, BASE provides the softest signals, which does evince a certain role of the direct aerosol effect**. **However, t**~~T~~here is not a clear relationship between AOD$_{cs}$ change patterns and RSDS$_{cs}$ changes (low spatial correlation), except for some local signals ~~in areas at~~ **in** the ~~North-East~~ **north-east where the direct aerosol effect enhances RSDS$_{cs}$ in areas with reduced AOD$_{cs}$**. However, as discussed above, the role of retaining, or not, coincident clear-sky dates between pairs of experiments is important **in filtering** ~~to filter~~ out the true role of AOD$_{cs}$ on RSDS$_{cs}$. Thus, the fact that change patterns are constructed over different dates **could** ~~may~~ partially explain the apparently negligible role of AOD$_{cs}$ on RSDS$_{cs}$ in this case. But only partially, as the BASE change pattern for RSDS$_{cs}$ (simulated on the ground of nule AOD$_{cs}$ changes) resemble**s** the respective patterns from ARI and A**R**CI experiments.

4 - Discussion and conclusions

We presented here a research on the role of dynamically modeled atmospheric aerosols in regional climate simulations with a focus on **the** impacts on the solar resource during the summer season from a climatic perspective, including projected changes to a medium-range horizon and analysis under clear-sky conditions. For **this,** ~~that~~ we evaluated a set of 20-yr long runs (spanning both present and future periods) **without including aerosols and** with resolved aerosol-radiation and aerosol-radiation-cloud interactive (two-way) interactions **performed with the WRF model (BASE, ARI and ARCI experiments, respectively)**~~, on the ground of which we drew original conclusions~~.

We interpreted the signals on the basis that the differences between ARI and BASE can be attributed to direct and semi-direct aerosol effects and the differences between ARCI and ACI to the indirect aerosol effect. Nonetheless, we should acknowledge that the autoconversion scheme called so that cloud droplets can turn into rain droplets in the ARCI simulations is different to the autoconversion scheme activated in the ARI (and BASE) simulations. This change in the WRF-Chem configuration can lead to differences between ARCI and ARI experiments that do not come necessarily from the aerosol-cloud interactions from a physical

point of view (Liu et al 2005). In fact, the activation of the aerosol-cloud interactions requires further changes in the model configuration (as compared to the configuration used for the simulations labeled ARI) beyond the autoconversion scheme, such as the activation of aqueous chemistry processes, which could also have an added impact to the effect that can be strictly attributed to the aerosol-cloud interactions. However, technically, the encoding of the WRF-Chem model hampers better isolation of the effect of the aerosol-cloud interactions (the mentioned aspects necessarily change between ARI and ARCI run modes). Therefore, ARCI-ARI differences can not be attributed to the aerosol-cloud interactions from a purely physical point of view, but to the activation of the aerosol-cloud interactions from a modeling point of view. It should also be borne in mind that the set of experiments performed allows any attribution to the interactive aerosol modeling approach adopted here to be made, while it is a distinct feature with respect to previous studies aimed at providing more consistent signals from a physical point of view. Last, and more general, internal variability plays a role in the simulations (e.g. Gómez-Navarro et al 2012), and a single member, as was used for the sensitivity experiment, may not be sufficient to obtain generally occurring responses. Under these constraints, we draw the following conclusions.

~~In general, t~~The inclusion of ~~interactive~~ aerosols **in the WRF simulations** reduces **in general** the amount of solar radiation reaching the surface by a few percent**age** points (~5%) under **both** present **and future** climate **scenarios**, as expected (Nabat et al 2015a, Gutiérrez et al 2018, Pavlidis et al 2020). **Under present-day conditions, t**~~T~~his effect is larger when the aerosol-cloud interaction remains turned off, because its activation leads to less cloudiness (over ~~the~~ Mediterranean Europe) and lower AOD values (over ~~the~~ Atlantic Europe), as evidenced when A**R**CI and ARI simulations were compared. **The d**~~D~~ifferences in RSDS between experiments are in overall **good** ~~well~~ agreement with **those** ~~the differences~~ found in cloudiness, while they seem to be unlinked with the differences in AOD in many parts of the domain. In agreement with Pavlidis et al (2020), AOD plays its major role under clear-sky conditions. However, the ~~signals supporting its importance under such conditions would be masked unless coincident dates (at the daily time-scale) are considered. Anyway,~~ differences in JJA-mean values of RSDS under clear skies between experiments with and without dynamic aerosols are hardly about 1%, while still significant in some of the southernmost parts of our European domain, and almost nul**l**~~e~~ between A**R**CI and ARI.

Our results suggested a variety of drivers underlying the mechanisms to explain the signals obtained, depending on the region (and season; winter plots are provided in Supp Fig 16-19 as

an example for interested readers), and varying under future climate conditions. These involve the effect of large aerosols in hampering the formation of clouds, increased scattering of solar radiation with the consequent cooling downward, supression of cloudiness due to thermodynamic effects, modification of the clouds' optical properties, or in-cloud scavenging processes. As these prevailing mechanisms change (up to a point) in the future, the sensitivity of the WRF simulations under future climate conditions, represented through the patterns of differences in RSDS, is somehow depicted differently than under present-day conditions. Therefore, the future projections also show sensitivity to the way the model considers aerosols.

~~Regarding the future projections, t~~The patterns of change for RSDS and ~~those for~~ CCT again show ~~again~~ high spatial correlations in all the GCM and RCM (BASE, ARI and ARCI) projections. Although lower, still high spatial correlations define the match~~ing~~ between the RSDS change patterns and those for AOD in the GCM, while this is not the case in either the ARI or ARCI experiments~~and the ARI experiment~~. The GCM, BASE and ARI experiments agree in projecting positive RSDS change signals in southern and eastern areas (around 5%), while clear differences are found between the GCM and the BASE or ARI RSDS change patterns (with ~~these two~~ the latter two ~~being~~ very similar) in central and northeastern areas, where the positive signals from the GCM turn~~s~~ notably negative in both ~~in~~ BASE and ARI. ARCI provides the most singular and negative picture of RSDS changes among all those shown, with widespread decreasing signals of a few percentage points, further reinforcing the fact that the indirect effect tends to counteract the direct and semi-direct effect of aerosols and enlarges the distance between the RCM and the GCM projections~~, apparently unlinked to the changes projected in AOD~~.

Previous works (Jerez et al 2015, Sørland et al 2018) had already detected inconsistencies in the change signals between RCM projections and those from their driving GCM, which have~~d~~ been related to the way aerosols had been represented in the RCM through their ~~its~~ impact on the simulated AOD (~~Bartók et al 2017,~~ Gutiérrez et al 2020, Boé et al 2020), and in particular ~~to the time-evolving aerosols in scenarios~~ to their direct and semi-direct effects and their reduced concentrations in the future as long as anthropogenic emissions are projected to decrease. In agreement with these previous findings, insofar as we kept the anthropogenic aerosol emissions unchanged throughout the simulation period, our projections differ from those obtained with the GCM. Nevertheless, the ARI experiment brings our results slightly nearer to those of the GCM as compared to the BASE experiment, perhaps also indicating the key role of the direct and semi-direct aerosol effects for reducing the GCM-RCM discrepancies, as

reported in these previous works. However, pushing our understanding further, by turning off the already reported effect of reduced aerosol concentrations in the future via the direct and semi-direct effects, our approach made it possible to identify ~~Our results constitute an example of the impact of cloudiness and AOD in RSDS through aerosol-related physical mechanisms while keeping unchanged the anthropogenic aerosol emissions through the simulation period, revealing in this case~~ the prevailing role of CCT changes **(over the dynamically simulated natural changes in AOD)** to explain **our signals of change in** RSDS ~~changes~~, and the capacity of the aerosol-radiation-cloud interactions to significantly alter **our** ~~the~~ RSDS change patterns (much more than ~~what~~ aerosol-radiation interactions alone do). **Thus, a**~~A~~lthough change patterns for RSDS **certainly** look ~~much more~~ uniform among experiments under clear-sky conditions **(likely because we suppressed the anthropogenic component for the changes in AOD, which was identified by Boé at al (2020) as a main factor for these signals indeed)**, the results presented here ~~may~~ **further** indicate that **the joint effect of aerosol-radiation-cloud interactions should be considered in the RCM simulations that serve to build up action-oriented messages in the challenging context of current climate change,** ~~action-oriented messages from modeling experimts that did not consider the role of aerosols, in particular in a dynamic way, could be potentially misleading, thus~~ calling **for caution otherwise and** for future research efforts in this line.

Author contribution

S. J. conceived this study. L. P.-P., P. J.-G. and J. P. M. designed the experiments and J. M. L.-R. **and E. Pravia-Sarabia** carried them out. S. J. performed the analysis and prepared the manuscript with contributions from all co-authors.

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Code and data availability

~~**All data and codes used here are available for research purposes by contacting the corresponding author.**~~

All data (netcdf files) and relevant codes (scripts for data analysis and WRF namelists) for reproducing this study are publicly accessible at http://doi.org/10.23728/b2share.a65d25c2b3ba49e1a46e970783e9476e**.**

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Figure caption

Figure 1. Relative differences between the WRF simulations in the RSDS (a to c), CCT (d to f) and AOD at 550 nm (g to i) summer (JJA) climatologies in the present period (1991-2010), squared if statistically significant ($p<0.05$); units: %. Note that panels g and h are referred to the horizontal colorbar just below them and simply represent the AOD summer climatologies in ARI and A**R**CI respectively. Spatial correlations (*s_corr*) between the patterns in the second and third rows and the respective patterns in the first row are indicated in the headers.

Figure 2. Relative differences between the WRF simulations in the $RSDS_{cs}$ (a to c) and AOD_{cs} at 550 nm (d to f) summer (JJA) climatologies, this is under clear-sky conditions, in the present period (1991-2010), squared if statistically significant ($p<0.05$); units: %. Note that panels d and e are referred to the horizontal colorbar just below them and simply represent the AOD summer climatologies in ARI and A**R**CI, respectively. Gray shaded areas depict grid points where less than 75% of the summer mean values in the time series of $RSDS_{cs}$ and AOD_{cs} were not missing ~~**values**~~. Spatial correlations (*s_corr*) between the patterns in the second row and the respective patterns in the first row are indicated in the headers.

Figure 3. Projected changes for the RSDS (a to d), CCT (e to h) and AOD at 550nm (i to l) summer (JJA) climatologies by the GCM (first column) and the WRF experiments (second to fourth columns); units: %. Squares highlight statistically significant signals ($p<0.05$). Note that panel i is referred to the horizontal colorbar just below it. Spatial correlations (*s_corr*) between the patterns in the second and third rows and the respective patterns in the first row are indicated in the headers.

Figure 4. Projected changes for the $RSDS_{cs}$ (a to c) and AOD_{cs} at 550nm (d to f) summer (JJA) climatologies, this is under clear-sky conditions, by the WRF experiments, squared if statistically significant ($p<0.05$); units: %. Gray shaded areas depict grid points where less than 75% of the summer mean values in the time series of $RSDS_{cs}$ and AOD_{cs} were not missing **in either the present or** ~~**values in both the present and**~~ the future period. Spatial correlations (*s_corr*) between the patterns in the second row and the respective patterns in the first row are indicated in the headers.