Anonymous Referee #1
Authors' response

The restructuring of the paper's theme has improved the readability and scope dramatically. I now understand how the different model runs are important to present to the scientific community and falls under the scope of GMD.

We are glad to hear that, and sincerely thanks the reviewer for agreed to revise again our manuscript, especially during this hard times we all are living, and for the constructive comments provided.

Overall Comments:

-The reversal of the colorbar between the plots is confusing (sometimes red is an increase and sometimes it's a decrease). Is there a reason for this? Typically, readers associate blue with a reduction and red with an increase. It would help if it was consistent throughout the paper.

Some of us think the same indeed. The reversal of the colorbars for CCT and AOD (and others) intends to facilitate a visual matching (reds-reds, blues-blues) between the RSDS plots and those of their inspected drivers (in particular, CCT and AOD), since one expects that a reduction in CCT (or AOD) leads to increased RSDS. So, where red colors appear in the RSDS plots, indicating an increase, red colors are expected in the CCT (or AOD) plots, indicating a reduction in this case because the colorbars are reverted.

-It may help if some of the supplementary figures are in the paper as official figures. It is hard to flip back and forth, plus the supplementary figures are referenced more than the included plots. The correlations could state supplementary, but the aerosol type and precipitation / environment plots are important and should be included in the manuscript.

Following this suggestion, also indicated by the other reviewer, we have now moved the following figures, previously in Supplementary Material, to the main manuscript:

Previously Supp Fig 4 (top panels), now Fig 2: Contribution of each aerosol species to the JJA-mean total surface aerosol concentration in the period 1991-2010. This is now Fig 2 in the revised manuscript.

Previously Supp Fig 5, now Fig 3: Differences between experiments in the RSOT, TAS, RH & CLD JJA climatologies for 1991-2010. This is now Fig 3 in the revised manuscript.

Previously Supp Fig 6, now Fig 5: Differences between experiments in precipitation-related JJA climatologies for 1991-2010. This is now Fig 4 in the revised manuscript.

Specific Comments:

[39-40] "However, there are relevant processes that GCMs usually model dynamically, but which RCMs usually do not" – my understanding is that GCMs parameterize and specify constant values more than an RCM because RCMs have better resolution? Should GCM and RCM be switched in this sentence? I don't see how WRF would model fewer things dynamically than a GCM, especially related to aerosol-cloud processes. Please correct my ignorance here if I'm reading this wrong.

The sentence is certainly misleading, so we have reformulated as follows:

“However, there are relevant processes that GCMs usually model dynamically, but which are not usually included in RCMs runs.”

It is not that RCMs model fewer things than GCMs, but that RCMs are usually run without a dynamical modeling of *things* such as aerosols, in contrast to the runs that are usually performed with GCMs. This increases the interest of our study. Check, for instance, the RCMs setups regarding aerosols that are being used under the Euro-Cordex umbrella in Gutiérrez et al. (2020). For our surprise, something similar happened with the (non-)inclusion of the time-evolving GHG concentrations in climatic runs performed with RCMs (Jerez et al. 2018).

[43-45] - There are also longwave and shortwave absorbing aerosol types like dust and smoke that can warm aerosol layers aloft while decreasing surface temperatures, leading to stable layers. This sounds like it’s being discussed right after the part on semi-direct effects, but it is a direct effect. The citations are clumped together for these two things when they are distinct.

The reviewer is right in this appreciation. There are different paths for clouds inhibition due to the warming effect of aerosols by absorption of solar radiation: (1) by heating the air and thus reducing the relative humidity, (2) by heating the air and thus provoking the evaporation of clouds (clouds burn-off), and (3) by leading to more stable atmospheric situations (as pointed out by the reviewer). 1 and 2 would be semi-direct, but 3 direct, according to the reviewer appreciation and to the IPCC definition. So we have reformulated as follows:

“Depending on their nature and the ambient conditions, aerosols can act to scatter and/or absorb the solar radiation through ARI, which may result in less or more solar radiation reaching the surface through direct and semi-direct effects. Direct effects might involve that less solar radiation reaches the surface due to its scattering and absorption (Giorgi et al 2002, Nabat et al 2015a, Li et al 2017, Kinne 2019), or more if, for instance, absorption warms aloft atmospheric layers, thereby leading to more stable atmospheric situations (lower surface temperatures than upward) and thus to the inhibition of clouds formation via convective phenomena (Giorgi et al 2002, Nabat et al 2015a). Absorption itself can also lead to clouds inhibition and/or burn-off through thermodynamic effects, i.e. by heating the air (semi-direct effects), thus increasing the amount of solar radiation reaching the surface (Allen and Sherwood 2010).”

[144] - The RACM-GOCART combination produces SOA, but it may only couple to WRF in the form of radiative effects. I don’t know that SOA is connected as an indirect effect. Please check this.

The reviewer is right, SOA is not connected as an indirect effect. We did not say that, but just that RACM is used to provide GOCART the concentrations of radical and gas-phase pollutants (which may form SOA) that it needs.

[159-160] - WRF-Chem does have fully coupled aerosol-cloud-radiation modules, including MADE and MOSAIC, they just were not selected here most likely because they are computationally expensive.

From a climatic point of view, the aerosols exerting the highest influence in climate are sea salt and desert dust. MADE and MOSAIC aerosol schemes do not include the aforementioned types of aerosols in their formulation, so the use of GOCART is not only because of its cheaper computational time, but because of the need of taking into account dust and sea salt aerosols in our simulations. The limitations of MADE and MOSAIC are negligible for specific episode formulations where the influence of natural aerosols might be negligible, but that is not the case for climatic simulations. We have added this clarification in the manuscript.

[165-167] - "The WRF-Chem model makes it possible to transform the single- into a double-moment scheme" – this sentence is misleading and needs to be phrased more like "The WRF-Chem model assumes XXX to infer an aerosol number concentration from aerosol mass" and the parts about converting from single to double moment should be removed.

The sentence follows the title of the publication by Li et al. (2008): "Implementation of a two moment bulk microphysics scheme to the WRF model to investigate aerosol cloud interaction."

Nonetheless, we have reformulated, to expand the description of the implemented mechanisms, as follows:

"(...) although the Lin microphysics is originally presented as a single moment scheme (Lin et al 1983), a modified Lin double-moment microphysical scheme is implemented in WRF-Chem (Lin et al 2008) and used here to conduct the ARCI simulations. In this scheme, both the mass and the total number of cloud droplets are predicted. The prognostic treatment of cloud droplet number involves water vapor, cloud water, rain, cloud ice, snow and graupel (Ghan et al 1997), and is activated through the "mixactivate" module of WRF-Chem. In that module, WRF-Chem calculates the aerosol number per volume concentration by using, for each aerosol type, the information about the size (the mean volume-diameter of each aerosol mode, obtained from the aerosol mechanism implemented in the simulation), and fixed densities and molecular weight of each type of aerosols. With all this information and the total mass, WRF-Chem estimates the aerosol number for each mode assuming spherical particles. 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 et al (2008) scheme. Thus, the droplet number will affect both the calculated droplet mean radius and cloud optical depth. 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 (i.e. increase in droplet number associated with increases in aerosols), and with the Lin microphysics, representing the second indirect effect (i.e. decrease in precipitation efficiency associated with increases in aerosols)."

I think my point in the first round of comments was missed. The Ghan et al. (1997) CCN formulas still require an input of aerosol number. GOCART and Lin microphysics does not predict aerosol number because it's single moment. Thus, some assumption must be made to get at aerosol number with this setup. This conversion between mass and number doesn't magically transform a single moment scheme into a double moment scheme because there is no value-added information: it is an assumption to make the model work. I'm asking the authors to check in the code or reach out to the WRF-Chem team to understand how this setup gets number information from mass.

I urge the authors to not use the model as a black box and understand what is being represented, what is being assumed, and what is not in the model whatsoever. The authors may think I'm being unreasonable here, but this is important for understanding the limitations of this study and to inform researchers who may look to this setup for future work.

We perfectly understand the reviewer and have followed his/her suggestions in this sense. We have expanded the description of how the model works under the chosen setup to make the limitations of this study clearer.

[169] – The calling of a different autoconversion scheme should be mentioned in the model setup section too and not just at the end. It's good to know limitations before looking at the data.

Done, we have added the following in section 2.2:

"An important aspect of the differences in the model setup between experiments is that the autoconversion scheme necessarily changes in the ARCI simulations as compared to the model configuration used for ARI and BASE. The flag *progn* of the WRF namelist should be set to 0 for running ARI experiments in order to keep disabled the interaction of the online-estimated aerosols with cloud microphysics, hence ensuring the use of prescribed aerosols (as in the case of the BASE simulations) as this regards. Conversely, *progn* should be set to 1 for running ARCI experiments in order to feed the cloud microphysics scheme with the online-estimated number and physico-chemical properties of aerosols (this effectively turns the Lin scheme into a second-moment microphysical scheme)."

[247-248] "With higher aerosol concentrations over most of the domain, reducing it by up to a half" – does this mean that where there are higher aerosol concentrations, the reduction is stronger?

No, that was not the sense of the sentence, which was probably poorly redacted. We have reformulated as:

"the indirect aerosols effects tend to counteract the joint direct and semi-direct effects seen in the ARI minus BASE pattern, reducing it by up to a half over most of the domain"

[259] – More stratiform clouds? More convective clouds? Because lower surface temperatures, despite an increase in RH, can lead to less convection.

Effectively, so we have reformulated as follows (see also the new Fig 4):

"Compared to BASE, both ARI and ARCI lead to more cloudiness in central and northern regions (albeit quite slight increases, well below 5%). This could respond to the direct effect of the scattering of the solar radiation due to the high presence of sea salt, dust and sulfate over these areas (Fig 2), as an increase in RSOT over these areas is also appreciated in both ARI and ARCI simulations (Fig 3a-b). In addition, this direct effect could be triggering the following feedback mechanism: the cooling effect downward (where less solar radiation is received because of its scattering) cools down surface temperatures (Fig 3d-e), thus increasing relative humidity (Fig 3g-h), which may favor the formation of clouds (these should be non-convective, mostly low-level, clouds as the decrease in TAS leads to more stable atmospheric layers; Fig 4a,b), thus less radiation reaches the surface, thus lower surface temperatures, and so on. Noteworthy, both the reduction in RSDS and the accompanying increase in RSOT is more marked in ARI than in ARCI over central regions (Fig 1c and Fig 3c), where the indirect effects included in the ARCI simulation, such as in-cloud aerosol scavenging processes, could lead to cleaner atmospheres than ARI simulates."

[260-262] – The semi-direct effect would be in both the ACR and ACIR simulations, correct? This also applies to discussions of the semi-direct effect and it's attribution throughout the paper.

Correct, both ARI and ARCI includes the semi-direct effect. The alluded sentence was wrong and has been removed (probably it was retained by mistake from intermediate versions of the article during the revision process). We revised all the attributions made in this sense to the aerosol effects along the manuscript.

[269] - Large aerosols, or GCCN, can accelerate cloud processes such as nucleation and collision-coalescence. What do you mean by large aerosols would prevent cloud formation?

Although wrongly expressed, we meant the same thing as the reviewer says in the last part of his/her comment regarding the acceleration of collision-coalescence processes: that large aerosols, by favoring the conversion of cloud droplets into rain droplets, "hamper the formation of clouds" because they fasten that precipitation occurs and thus clouds disappear. So we have reformulated as:

"(…) a high presence of large aerosols over southern Europe, both in form of dust or sulfate in our case (Fig 2), can accelerate collision-coalescence processes fastening that precipitation occurs and thus shortening the lifetime of clouds (...)"

[278] – Could it be that because most of the aerosol mass is dust, that the absorption is creating stable layers and preventing convection?

Could be, but we did not find a clear evidence for that. We have reformulated, inspecting new hypothesis, as follows (see also the new Fig 4):

"both ARI and ARCI lead to less cloudiness southward as compared to BASE, especially ARCI (reductions up to 10% in Mediterranean regions; Fig 1d-e). 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 (Fig 2), can accelerate collision-coalescence processes fastening that precipitation occurs and thus shortening the lifetime of clouds (Lee et al 2008), which is most plausible in the warm season over warm areas (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 3~~5~~j-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 (Fig 5). The reduction in convective precipitation (the prevailing form of precipitation over this area during the summer season) suggests that absorption might be creating more stable atmospheric situations (by heating aloft layers) and thus preventing clouds formation via convective phenomena and increasing the incoming surface solar radiation. But we did not find any clear evidence of that either (Fig 4c). So the thermodynamic effect of aerosols on clouds inhibition and burn-off might justify the reduction in CCT (mainly at low levels; Fig 4d) and the accompanying increase in RSDS in the southernmost areas. These signals are intensified when we add the indirect aerosols effects, likely due to the removal of aerosols via scavenging processes, which cleans the atmosphere favoring that the solar radiation reaches the surface."

[293] – The clear sky correlations could be impacted by aerosol-environment co-variability. For instance, dust is associated with dry, hot, cloud-free weather. Those aerosol particles can impact the environment and make it hotter and warmer. Do you think that is at play here?

Correlations are negative, so the higher the AOD, the lower the RSDS, which is in the opposite direction to the co-variability between dust and cloud-free environments indicated the reviewer. So, if it plays a role, it is not a prevailing role.

[317] - Evidence to support this argument that cloudiness is the most important?

The the spatial and temporal correlation values in Supp Fig 6d-i and Supp Fig 7a-f, respectively, are higher between RSDS and CCT than between RSDS and AOD. We have now specifically indicated this argument in the manuscript.

[Figure 1] – Why is the correlation so low between AOD and RSDS? Even if there is an indirect connection between these two variables via cloudiness, I'm surprised it's so low.

As described along the manuscript, the variety of indirect mechanisms leading to the different signals in RSDS mask a direct link between AOD and RSDS patterns in Fig 1.

Anonymous Referee #2
Authors' response

Review of the manuscript entitled Sensitivity of surface solar radiation to aerosol-radiation and aerosol-cloud interactions over Europe in WRFv3.6.1 climatic runs with fully interactive aerosols, by S. Jerez et al.

This is the revised version of the manuscript, submitted to Geoscientific Model Development, which presents a sensitivity study on the role of dynamic aerosols in regional climate simulations over Europe, carried out with the WRF model.

The authors have made substantial efforts to improve the manuscript, and to take into account the different suggestions of the reviewers. The objective of the paper and the results are clarified and better presented. English spelling has also been improved. However, before the publication in GMD, I recommend the following corrections.

We sincerely thanks the reviewer for agreed to revise our manuscript, especially during this hard times we all are living, and for the constructive comments provided.

Main comments:

- The conclusions about the prevailing of aerosol indirect effects over direct effects should be moderated, since they could be very model-dependent. They could also depend on the choice of the parameterization of cloud-aerosol interactions. More discussions about this aspect should be added in the text.

Nuanced attributions have been made, and the fact that we rely on a single model configuration has been acknowledged in the discussion section.

- Many figures are in supplementary material, and are often used in the text of the manuscript. Some sections entirely rely on supplementary figures. At the end, the revised version has only 4 figures in the main text. I think that more figures (not all obviously) should be included in the main text rather than in the supplementary. These figures are essential to better understand the study.

Following this suggestion, also indicated by the other reviewer, we have now moved the following figures, previously in Supplementary Material, to the main manuscript:

Previously Supp Fig 4 (top panels), now Fig 2: Contribution of each aerosol species to the JJA-mean total surface aerosol concentration in the period 1991-2010. This is now Fig 2 in the revised manuscript.

Previously Supp Fig 5, now Fig 3: Differences between experiments in the RSOT, TAS, RH & CLD JJA climatologies for 1991-2010. This is now Fig 3 in the revised manuscript.

Previously Supp Fig 6, now Fig 5: Differences between experiments in precipitation-related JJA climatologies for 1991-2010. This is now Fig 4 in the revised manuscript.

- Section 3.1 : The brief evaluation of AOD (as shown in Figure page 21 in your replies) should be added to the manuscript (at least for JJA). It is an important point to understand the rest of the study. It would come in addition to the brief validation of RSDS in the beginning of section 3.1 (line 229).

Since the simulated patterns of AOD are already included in Fig 1, we have added a comment on the performance of the simulations at this regards using the paper by Pavlidis et al. (2020) as a reference (see Fig 1 in that paper) and the reviewer's comment on the impact of keeping the 2010 values of anthropogenic emissions along the simulated periods. See the second paragraph of the discussion section.

- Sections 3.1 and 3.2 could be separated in different subsections in order to avoid too long paragraphs, and to make reading more fluent.

Done.

- The authors have mentioned in their replies that they have included in the discussions the justification of keeping constant emissions in future simulations to evaluate the climate change penalty. However I did not find that in the revised version.

It was mentioned, but probably not clearly enough, true. We have made emphasis on it in the second paragraph of the conclusion section.

Other comments:

- page 1 line 12: please avoid undefined acronyms (IPCC) in the abstract

Removed.

- page 1 line 19: Since the period of simulations is 1991-2010, "historical period" would be better than "present-day conditions" (1991 is 30 years ago!). In the whole paper, present could be replaced by historic (or past).

Ok. We replaced present-day period by historical period throughout the manuscript.

- page 5 line 121: Is the RRTM radiative scheme used both for shortwave and longwave or longwave only? Please mention the radiative scheme for shortwave in the second option.

The RRTM scheme is used for both long- and short-wave radiation. Clarified in the text.

- page 5 line 132: please use subscript characters for chemical species such as NO3 and O3

Done.

- page 5 line 142: through instead of trough

Thanks.

- page 6 line 148: "Anthropogenic emissions ... were kept unchanged in 148 the simulation periods (we considered the 2010 monthly values)". Anthropogenic emissions have been dramatically reduced between the 1980s and 2010, so keeping 2010 values and comparing simulated aerosols over the whole 1991-2010 period could lead to an underestimation of AOD.

True (in fact, we observe an underestimation as compared to the MACv2 AOD climatology in the historical period), and to an overestimation during the future period. We have include this appreciation in the discussion section (second paragraph).

- page 6 line 155: “aerosol optical properties assuming wet particle diameters”. Which humidity is used for the calcuation of aerosol optical properties? Is the variation of humidity taken into account on-line in the simulation to allow variations of optical properties (through pre-defined intervals for example)?

Yes, the variation of humidity is taken into account in the on-line simulations to allow variation of optical properties. We have clarified in the text.

- page 8 line 216: Could you give the level of significance for the t-test?

Done.

- page 13 line 389-390: This point about the autoconversion scheme seems to me very important. Could you explain why you could not use the same scheme, but for example with constant vallue of autoconversion in the case without aerosols?

It could it be seen as a model limitation, but there is no room for choice. The flag *progn* should be 0 for ARI and 1 for ARCI.