

# General response to referees. Precipitation response to Aerosol-Radiation and Aerosol-Cloud Interactions in Regional Climate Simulations over Europe

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## 1 General Comments to Referees

First of all we would like to thank the reviewers for their suggestions and corrections. They have undoubtedly contributed to a considerable improvement of the manuscript.

Both referees point out that the most important limitation of the work was related to the lack of physical explanations. The manuscript has suffered important changes incorporating new figures and adding different analysis on the physical phenomena behind the described changes. A number of suggestions from both referees have also been incorporated, such as improving the description of the experiment, correcting statements and more complete explanations of different phenomena.

Folowing, we present the specific responses to the referees, and a version of the tracked changes version of the manuscript.

# Response to Reviewer #1. Precipitation response to Aerosol-Radiation and Aerosol-Cloud Interactions in Regional Climate Simulations over Europe

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## 1 General Comments

This paper documents relatively long (20 years) simulations of precipitation with the regional WRF-Chem model driven by ERA20C reanalysis. Two simulations with interactive aerosols (one including only the aerosol direct radiative effect, another also the effect on cloud microphysics) are compared with a baseline simulation with fixed aerosols. It is found that the use of interactive aerosols decreases precipitation in Central/Eastern Europe and increases it in the Eastern Mediterranean. Detailed analyses regarding the number of days with precipitation with different thresholds are carried out.

The treatment of aerosols in regional climate models is often rather primitive, and therefore I think the authors have carried out a valuable set of experiments. At the same time, I cannot recommend the publication of this paper in ACP, unless substantial improvements are made in the analysis and reporting of the results. The reasons for my concerns are outlined below.

[We strongly appreciate the positive view of the reviewer and acknowledge the time devoted to the revision the manuscript and the fruitful comments leading to the improvement of the manuscript.](#)

## 2 Major comments

1. My primary concern regarding this paper is that while it documents in some detail how precipitation changes, the physical interpretation of the results is rather lacking. The paper fails to properly address the question, what are the physical mechanisms leading to these changes in precipitation. Only a few cursory statements are made in this respect. The changes in precipitation could be caused by several mechanisms. They could arise

through the impact of aerosols on cloud microphysics, or their impact on surface temperature (which could suppress convection), or through changes in large-scale meteorology (although the latter are probably small due to the use of nudging in the outer model domain).

The revised version of the manuscript extends the discussion on the causes behind the changes, together with the analysis of additional meteorological variables as temperature, radiation and three-dimensional fields (included as supplementary materials and discussed within the text). Additionally, the introduction has been extended in order to further include a description of the interactions leading to modifications in the precipitation regimes. Nonetheless, most of the studies on the current topic available in the scientific literature are case studies or ideal cases, for a certain type of cloud, type of aerosol or meteorological situation (see for example Khain et al (2007)). The aim of our work covers a climatic period and hence the separation of different circumstances is complex due to the internal variability of the model (the inner domain is large enough to generate it) and the mixture of aerosols and situations, in fact we obtain a important decrease of the temporal correlation among the experiments in some parts of the domain. Hence, the analysis presented in the manuscript focuses in statistical changes both in total precipitation and precipitation regimes. In the revised version of the manuscript we have deepened in the discussion of physical processes based on the available scientific literature and on the climate conditions of different European target areas.

2. To make it easier for the reader to interpret the findings, simulation results should be shown for additional physical quantities. It is very difficult to understand precipitation by looking at precipitation (and low clouds) alone. Most obviously, the paper should start with briefly showing how the aerosol fields (AOD, CCN, and aerosol radiative forcing, if available) differ from the baseline simulation, since these differences are the root cause for the changes in precipitation. I realize that some of this information is probably available in the cited papers by Palacios-Pena et al., but this paper should be able to stand alone — it should not be the reader’s task to hunt for necessary information in other papers. Furthermore, changes in surface temperature are potentially important for convection, and they are referred to at a couple of occasions, but it would be better to actually show them. Other quantities that should be checked (and possibly shown, if their changes seem important for precipitation) include meteorological fields like surface pressure, relative humidity and mid-troposphere vertical velocity.

As commented for Item 1, the revised version of the manuscript extends the discussion on the causes behind the changes, together with the analysis of additional meteorological variables as temperature, radiation and three-dimensional fields. Most of the fields represented are added as Supplementary Material in order not to modify largely the structure of the manuscript.

3. The interpretation of the results is also complicated by the fact that data for all seasons are lumped together. Yet, the processes generating precipitation, and potentially their sensitivity to aerosols, depend strongly on the season. Especially concerning central-eastern Europe, which shows the clearest signal in precipitation, convective precipitation dominates in summer, while stratiform precipitation associated with synoptic weather systems dominates in winter. I recommend that the authors first look at precipitation on a season-to-season basis (at least distinguishing between the warm and cold seasons), and then focus the detailed analysis on the season(s) with the most meaningful signals.

In a preliminary analysis, the seasonal interpretation was conducted. However, the most significant signals were depicted for the entire year, probably due simply because of statistical issues. Therefore, in the original manuscript we decided to represent only the annual results. However, following the Reviewer's advice, we present the seasonal analysis of the results, focusing mainly in the analysis of the differences between the simulations. Those analyses are presented as Supplementary Material and the results discussed along the text in the revised version of the manuscript.

4. While the authors have conducted both ARI and ACI simulations, the ARI results are not discussed much, except for Fig. 6. I strongly recommend to show the ARI-BASE and ACI-ARI differences, at least for the time-average precipitation in Fig. 2. It is vital information for understanding to which extent the precipitation changes arise from aerosol direct and indirect effects.

The reviewer is absolutely right. For that, the revised version of the manuscript includes the ARI simulations in the panels of figures. The text has been modified accordingly in order to discuss the new results.

5. There are rather many issues with the use of English language. At the end of the review, I list cases which I found disturbing for correct understanding of the text. This is not intended to serve as a complete language check.

We really appreciate your contribution to the improvement of the language. The final version of the manuscript will be revised by a native English speaker.

### 3 Detailed comments

1. line 16: should this be "eastern Mediterranean"?

Yes. It has been corrected as suggested.

2. line 29: Can you add a reference to a publication listing the WCRP five major scientific challenges?

We got this information from the web page of the World Climate Research Programme (WCRP). Checking it again we noted that that page has not been updated from a long time. We decided to remove this sentence from the manuscript.

3. line 32: I suggest replacing “The main tool” with “One of the main tools”. The IPCC AR5 estimates of aerosol radiative forcing use satellite observations to adjust model- based results.

Changed as suggested.

4. lines 40–44: A key point of the convective invigoration mechanism of Rosenfeld et al. (2008) is that the slower cloud-droplet-to-rain conversion allows the droplets to be transported above the freezing level, and therefore, the latent heat released in freezing makes the convection more intense.

Following the Reviewer’s advice, this point has been added to the revised version of the manuscript in the introduction and also is used in the discussion.

5. lines 46–49: It would be useful to give a bit more information on the cited studies (e.g., which regions were considered?).

We have incorporated further information about the state-of-the-art studies cited as well as some more new works, including area, aerosol type and size, etc..

6. lines 59–60: “and abundant number of cloud condensation nuclei (CCN) (Forkel et al., 2015) high enough for clouds to form without this variable being a limited factor”. In fact, the lack of CCN is almost never a limiting factor for cloud formation (this could perhaps happen in remote marine locations in very specific conditions). However, a low CCN value may result in clouds that precipitate more readily, which can reduce the cloud lifetime and therefore the average cloud fraction.

Thanks for your comment. We have incorporated it to the revised version of the manuscript.

7. line 67: “black anthropogenic aerosols”. Do you mean black carbon, or absorbing anthropogenic aerosols in more general? Furthermore, this paragraph gives the impression that anthropogenic aerosols cause warming and natural aerosols cause cooling, which is misleading. Many anthropogenic aerosols, most prominently sulfates, are largely non-absorbing, so the total effect of anthropogenic aerosols is probably one of radiative cooling.

The reviewer is right. We refer to black carbon as it is mainly generated by anthropogenic activity. We have clarified this point in the new version of the manuscript.

8. lines 112, 116: You mention the use of both the Goddard shortwave radiation scheme and the RRTMG scheme. To my knowledge, these are different radiation schemes. Please explain.

The reviewer is right and the information was mistaken. We used the RRTMG scheme. This correction has been incorporated in the revised version of the manuscript.

9. lines 127-129: While AOD (it should be “aerosol optical depth”) has been evaluated by Palacios-Pena et al. (2020), it would be definitely good to show the time-mean AOD fields also in this paper (see major comment 1).

AOD fields and the differences among the experiments has been included in the revised version of the manuscript as supplementary material.

10. line 163: correlation matrix of what?

The correlation matrix of the constructed series for each point. The constructed series are the differences between the number of days of precipitation for several thresholds. The sentence has been revised accordingly for the sake of clarity.

11. lines 174-179: The spatial redistribution of precipitation is interesting, but is very difficult to figure out why it is happening, based on the information given in this paper. Please see the major comments 1-3.

In order to provide clearer information the new figures included in the manuscript are presented and a deeper discussion is included.

12. line 193: “(not shown)”. In fact, you do show the differences between ACI and BASE in Fig. 2.

We showh ACI-BASE but we do not present ARI-BASE. Anyway, new figure 2 of the manuscript is shown, and the differences commented.

13. line 214: According to Fig. 3b, the correlation coefficient in 0.78, not 0.40.

We made a mistake here. We mean ”In the case of PM10 ..... This paragraph has been rewritten including the 0.78 value for AOD and 0.4 for PM10.

14. lines 215–216: The more strongly negative ACI-BASE precipitation differences in Central Europe associated with high PMratio events are a curious result. Why is the ratio of PM2.5/PM10 more important than PM2.5 alone? In general, at least in this region, I would expect that particles with diameter  $< 2.5 \mu\text{m}$  are much more important than larger particles, especially for CCN and usually also for the aerosol direct radiative effects, because of their much larger number concentration. A somewhat remote possibility is that this result is related to giant aerosols enhancing precipitation, and thereby opposing the effect of smaller aerosols (this could be checked by looking at events defined wrt. to the difference PM10-PM2.5). Another possibility is that the result is coincidental, that is, more related

to the different meteorological conditions associated with high vs. low values of the PMratio, rather than to the impact of aerosols on cloud microphysics. This risk is enhanced by the fact that all seasons, with different precipitation formation mechanisms, are lumped together.

We really appreciate this comment. We have been revising some papers about the role of Giant Aerosols by Feingold et al. and this could be key point that helps us to improve our explanation on the decrease of precipitation (amount and number of days) in that area as well as the increase in the eastern Mediterranean. Some more discussion will be added to the new version of the manuscript about these processes.

15. lines 217–220: Why would the greater amount of small particles lead to reduced low cloudiness? Note that according to Fig. 6(d,e), the reduction in low clouds seems to be related mostly to the aerosol direct (and possibly semidirect) radiative effects rather than their effect on cloud microphysics.

We agree with the reviewer that the reduction in low clouds is related to the aerosol direct and semidirect radiative effects. But, the reduction of low clouds in ACI is larger than in ARI, therefore the role of microphysics could be important. In fact, an analysis performed similar to the one presented in Figure 3 shows how that this relationship exists. Anyway, we understand that our explanation is not complete. As mentioned before, some more plots including ARI experiment results have been added, as well as a much more extended explanation linking the reduction/increase of low clouds and precipitation based on both experiments (ARI and ACI) to direct, semidirect, and indirect effects.

16. line 236: “(significant differences)”. Please refer to Fig. 2b to make it easier for the reader.

The reference to figure has been added.

17. lines 237-240, 248-249: Given the very spatially scattered distribution of Region 3, it is hard to believe that this cluster really represents physically meaningful results, in spite of the apparent statistical significance. It seems more likely that the cluster analysis has just picked separately a group of points with increased frequency of large precipitation amounts, even if this increase itself might be caused by internal climate variability (i.e., be random). Note that grid points belonging to Region 3 are often neighbored by grid points belonging to Regions in which the frequency of heavy precipitation actually decreases.

We agree that Region 3 has no spatial structure. We perfectly understand the doubts of the reviewer about the physical meaning of this region. However, from the statistical point of view, we obtain that a important portion of grid cells presents an coherent increase of moderate and intense precipitation events. At the same time, we can found in the literature that this increase is supported by some physical processes. We think that it is important to keep the message, but at the same time to warn the reader

about the need of deeper studies about that, since it could be an artifact of the statistical methodology used.. We have rewritten the description of the behaviour of Region 3 trying to send the above message.

18. lines 251–262: You should consider the statistical significance of the differences also in the case of Fig. 6. Some of the details discussed in this paragraph might not be robust.

As commented before, we have now included all plots showing ACI and ARI experimented. In addition we have add the statistical significance as in figure 2, and when discussing the results we take into account the statistical significance.

19. line 270: “Zone 5” should be “Zone 4” (or “Region 4”).

It has been fixed up.

20. lines 304-305. It is not clear to what this sentence refers to. Please explain better, or remove.

We have removed that sentence. It do not provide any important message.

21. Fig. 2: Note that in statistical testing, one should be aware of the risk of false positives. If a test is conducted at the significance level  $p=0.05$ , on average 5% of grid points will show “significant” differences, even if the differences between the two fields are actually random. It would be good to compute the fraction of significant differences and show it e.g. in the figure titles (it seems not to be much larger than 5% visually?). A more rigorous technique for looking at this would be “controlling the false discovery rate”, see Wilks et al. (2016): Wilks, D.S., 2016: “The stippling shows statistically significant grid points”: How research results are routinely overstated and overinterpreted, and what to do about it. Bull. Amer. Meteor. Soc., 97, 2263–2273, <https://doi.org/10.1175/BAMS-D-15-00267.1>.

We really appreciate the suggestion of the reviewer. We have calculated the fraction of significant differences and we refer them along the text. Anyway, we fix our attention on *significant areas* (group of nearby significant points ) that are far of being false positive as stated in Wilks et al 2016.

22. Consider marking the statistically significant differences also in Fig. 6.

Thanks for your advice. As mentioned above, all maps of differences show the statistical significance.

## 4 Technical and language corrections

1. line 9: do you mean “time-mean spatially averaged”?

Yes. Corrected.

2. line 11: this should be “precipitation intensity regimes”.  
Corrected.
3. line 69: “dispersion” probably refers to “scattering”?  
Yes. Corrected
4. lines 73, 282, 285, 302 and 310. The use of “color” for describing clouds or aerosols is not clear, and certainly not standard scientific terminology. In the present context, “optical properties” would perhaps be the best term; for aerosols, “refractive index” could also be used.  
We acknowledge your suggestion, now we use *optical properties*
5. line 159: replace “on a non-regular basis“ with “in a non-linear scale”.  
Done.
6. line 256: add “causes” before “a reduction”.  
Done.
7. lines 277-279: The last sentence of Section 3 is not clear. Do you mean that in high PM10 conditions, clouds are preferentially located in the southern part of the area?  
We mean that high load of PM10 are usually associated with synoptical conditions that transport the PM10 (dust) from the south. We have rewritten the sentence in order to make it clearer.
8. line 302: replace “order of magnitude ...” with “quantitatively this improvement is small”.  
Done
9. line 310: replace “competence of CCN” with “efficiency of CCN”.  
Done
10. In Figure 3, it is impossible to see black numbers plotted on black or dark blue background. Also, the units of the color bar should be % (not “score”) in panels (c) and (d).  
Done
11. Caption of Fig. 4. The series used as the basis of the cluster analysis are not “time series” (in a time series, you would have time on the x-axis; here you have the precipitation threshold).  
Rigth. Now the caption reads ..” Cluster analysis of rainy days: each color depicts a cluster with a different behavior of the ACI-BASE difference in number of days of precipitation over a threshold ..... ”..
12. In Fig. 5, “Zona” is Spanish. “Zone” or “Region” would be English.  
Fixed

# Response to Reviewer #2. Precipitation response to Aerosol-Radiation and Aerosol-Cloud Interactions in Regional Climate Simulations over Europe

JP. Montávez

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## 1 Main comments

This paper shows results from 20 year run with regional climate model WRF-chem. Experiment setup includes simulations with different aerosol interaction. One clear conclusion of this paper is that both ACI and ARI lead to decrease of precipitation in Europe. Aerosols regional climate effects are still very uncertain and authors have carried out valuable simulations to increase our knowledge of aerosols regions effect on precipitation. Main question of this paper is what is the role of ACI and ARI in regional precipitation observations. However, I find some major comments on authors study. This paper is in scope of ACP and I recommend it to be published after major revisions.

We strongly appreciate the very positive and constructive comments of the reviewer and kindly acknowledge the time devoted to the revision of the manuscript. Please find below an item-by-item response to the Reviewer's #2 comments.

## 2 Major comments

1. Authors clearly list their findings on how ARI and ACI affects on rainy days, overall precipitation and low clouds. In figures term CLL is not opened, however in text this is indicated as low clouds. Text should mention what aerosol-cloud processes are included in the simulations, direct, indirect, semi-indirect, how these depend on aerosol type. How the aerosols itself formed in these experiments?

CLL stands Clouds at Low Levels. The definition of this abbreviation has been added to the revised version of the manuscript. We agree with the Reviewer that the definition of the processes included in the different experiments lacks some detail. In the revised version of the manuscript,

the Section devoted to the description of the experiments has been widely extended. Here, detailed descriptions of the processes involved in each experiment and the differences among them have been included. Basically, the BASE experiment does not include interactive aerosols. The ARI experiment introduces the aerosol-radiation interactions and the ACI experiments adds the aerosol interactions with the microphysics (aerosol-cloud interactions) in addition to the ARI simulations. Moreover, we have added some text explaining the origin and the formation of the different types of aerosols in the simulations. Basically, natural aerosols are generated by the interactions of atmospheric conditions with the land characteristics (vegetation, soil moisture, composition, etc.). Anthropogenic emissions of aerosols are taken from the ACCMIP initiative (Lamarque et al., 2010), as stated in the revised version of the manuscript.

2. It's unclear was there simulation where both ACI and ARI were included. Authors mention that there are areas where ACI and ARI effects cancel each other out. However due to non-linearities of aerosol-cloud effects, this conclusion would benefit from additional simulation where both ACI and ARI are included.

As previously stated, the revised version of the manuscript includes a more detailed description of the experiments, where the issues raised by the Reviewer have been clarified. The ARI experiment includes only the aerosol-radiation interactions (mainly direct effects); in addition, the ACI experiments includes both the interactions of aerosols with radiation and with the cloud microphysics (indirect effects).

3. Also basic aerosols effect information should be shown, radiative forcing, direct and indirect. This helps reader to better understand the real effect of aerosols.

We thank the Reviewer for his/her comment. In the revised version of the manuscript the results of all the experiments are shown regarding different aerosol-related variables, like AOD, PM10, PM2.5 and PMratio. Undoubtedly, this will help the reader to better understand the processes involved. Moreover, some complementary information has been added regarding the seasonal cycle of these variables

4. Only uncertainty regarding the model here is the aerosol setup. What is the role of model uncertainty? Example how much base case precipitation changes differs if you have slightly different initial condition in the model?

The Reviewer raises a good point. Evidently, the internal variability plays an important role. In previous works of the research group (e.g. Jerez et al., 2020) the role of the model initialization has been widely studied. However, in the revised version of the manuscript we analyze the impact of the aerosols on precipitation on a climatological scale. All the simulations have been identically initialized starting from the same chunks composing the different numerical experiments. We have to start from the hypothesis

that the differences between the simulations come from the effects of the aerosols and their different treatment (only aerosol-radiation interactions or adding aerosol-cloud interactions). These aforementioned differences will be related both with direct, semi-direct and indirect effects, and their interaction with the internal variability of the model. Running new experiments analyzing that effect is unaffordable from a computational point of view at this time. In addition, the scientific literature consulted points to a negligible influence of the internal variability in this kind of experiments. On the other hand, the analysis conducted searches for the relationship between the changes obtained with the different concentration of different types of aerosols. In this analysis we include the statistical significance, so that we can corroborate the differences that can depart from the mere internal variability.

5. ARI simulations are not discussed except in Figure 6. Similar analysis should be made also for ARI as done for ACI. I highly recommend also showing the results for ARI simulations.

In the original version of the manuscript we decided to include only the ARI analysis when the differences between the simulations were caused essentially by the changes induced by the microphysics of the model. This was initially done in order to minimize the number of Figures and the length of the text. Nevertheless, we fully understand the Reviewer's concern. The revised version of the manuscript includes the analysis of the differences of the fields obtained both for ARI and ACI experiments.

6. In conclusion paper says that aerosol both decrease or increase precipitation, here it should also be stated why and where, what are the mechanisms causing these changes based on these simulations. Example in line 313 author says that decrease of precipitation is due to decrease of rainy days. What causes the decrease of rainy days?

The scientific literature that covers the topic of the effects of aerosols on precipitation -and the physical processes involved- focus mainly on study cases. The objective of the work includes the analysis of changes in precipitation, amount and regimes, together with its relationship with different types of aerosols from a climatological perspective. This approach slightly hampers the direct association to physical processes, because the effects of aerosols depend on the meteorological situation, the type of aerosols, and in our case of the differences in the time evolution. The straightforward effect produced can evolve in time and space indirectly due to the internal variability of the model, since simulations do not use nudging in the inner domain and simulations are transient (continuous). The statistical analysis carried out shows how diverse areas respond differently to the aerosol feedbacks. While in some areas precipitation is reduced when including aerosol interactions (Central Europe), this impact is low for total precipitation. However, if we focus in the number of rainy days, this impact is noticeable, affecting days with less precipitation. Conversely, in

the Mediterranean the response of precipitation is the contrary, and the type of aerosols and the environmental conditions also differs. Therefore, we understand that the physical explanations of the results found are not fully included in the manuscript; however, in the revised version, this discussion about physical processes has been extended based on the results from other studies. As an example, Khain et al. (2008) indicate the high variability of the changes in precipitation due to modifications in the type of aerosols and environmental conditions.

7. Model aerosol configuration should be explained clearly, what natural and anthropogenic aerosols are included.

As aforementioned, the Methodology section has now included a detailed description on the setup of the experiments and the aerosols involved in the simulations.

### 3 Minor comments

1. Figure text in figure 2. I suggest changes letters to begin of each sentence. (Toprow) (a) Relative differences for precipitation between ACI and BASE experiments;(b)number of days of precipitation $\geq 0.1\text{mm}$  ; (c) and low clouds. Squares indicate points whose differences are significant for a p-value of 0.05.

Done as suggested.

2. In abstract line 9 spatially averaged should also mention the spatial region of the simulations which is the averages.

The averages are estimated over the whole domain. Done as suggested.

3. In method section I would recommend to include model section to describe the model itself

As mentioned before, a much more detailed description of model and experimental setup has been added to the manuscript.

4. In line 91. Author states “In the BASE experiment aerosols are not treated interactively.... ” Is this meaning that aerosol itself develops from vapors or aerosols are interaction with clouds?

This section has been modified. In the BASE experiment aerosol properties affecting the physics of the model are constant in space and time (for radiation, AOD; and for microphysics, the cloud condensation nuclei are constant).

5. In line 131. “). The simulations were run splitting the full period into sub-periods of 5 years with a spin-up period of 4 months,” this is unclear what has been done?

The total period simulated for each experiment (BASE, ARI and ACI) is of 20 years. Instead of doing a run of 20 years long, we split each simulation in 4 chunks of 5 years with an spin-up period of 4 months. This spin-up time is removed and the 4 chunks are pasted. This is done following the recommendation of Jerez et al. (2020) in order to make experiments faster.

6. In line 134, “The evolution of greenhouse gases CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O were considered in accordance with the recommendation of Jerez et al. (2018).” This should be opened and explained the Jerez et.al paper

Done as suggested.

7. In line 150, “the relative differences..” relative to what?

The relative differences are calculated as the differences among the experiments (ACI-BASE) divided by the BASE case and multiplied by 100, therefore relative to the BASE case.

8. In line 151 they refer tern “criteria” is unclear what criteria.

The criteria defined in the above paragraph, the intensity and and extension over the defined thresholds. It has been clarified in the new version of the manuscript.

9. In line 160, clustering method used should be mentioned.

The clustering method is composed by several steps, the final one is the K-means method. This has been clarified in the text.

10. Titles in figure 5 should be changed to clusters. Also results in figure 4 and 5 should be discussed more. Figure 5 is somewhat puzzling.

As suggested, some more discussion has been added and zones are renamed as clusters in Figure 5.

# Precipitation response to ~~Aerosol-Radiation~~ aerosol-radiation and ~~Aerosol-Cloud Interactions~~ aerosol-cloud interactions in ~~Regional Climate Simulations~~ regional climate simulations over Europe

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**Abstract.** The effect of aerosols on regional climate simulations presents large uncertainties due to their complex and non-linear interactions with a wide variety of factors, including aerosol-radiation (ARI) and aerosol-cloud (ACI) interactions. These interactions are strongly conditioned by the meteorological situation and the type of aerosol. Despite increasing, there is nowadays a very limited number of studies covering this topic from a regional and climatic perspective.

5 Hence, this contribution aims at quantifying the impacts on precipitation of the inclusion of ARI and ACI processes in regional climate simulations driven by ERA20C reanalysis. A series of regional climatic simulations (years 1991-2010) for the Euro-CORDEX domain have been conducted including ARI and ACIARI+ACI (ARCI), establishing as reference a simulations where aerosols have not been included interactively (BASE).

The results show that the effects of ARI and ACI on mean-time-mean spatially averaged precipitation over the whole domain 10 are limited. However, a spatial redistribution of precipitation occurs when introducing the ARI and ACI processes in the model; as well as some changes in the intensity-precipitation-precipitation intensity regimes. The main differences with respect to the base-case simulations occur in central Europe, where a decrease in precipitation is associated with a depletion in the number of rainy days and low-clouds-clouds at low level (CLL). This reduction in precipitation presents a strong correlation with the ratio PM2.5/PM10, since the decrease is specially intense during those events with high values of that ratio (pointing to high 15 levels of anthropogenic aerosols) over the aforementioned area. The precipitation decrease occurs for all ranges of precipitation rates. On the other hand, the model produces an increase in precipitation over the eastern Mediterranean basin associated with an increase of clouds and rainy days when ACI are implemented. Here the change is caused by the high presence of PM10 (low PM2.5/PM10 ratios, pointing to natural aerosols). In this case, the higher amount of precipitation affects only to those 20 days with low rates of precipitation. Finally, there are some disperse areas were the inclusion of aerosols leads to an increase in precipitation, specially for moderate and high precipitation rates.

*Copyright statement.* TEXT

## 1 Introduction

The importance of atmospheric aerosols has multiple aspects, all of them of great scientific and socioeconomic relevance. First, the World Health Organization (WHO, 2013) has recognized that the degradation of air quality by atmospheric aerosols is a threat to human health. Second, the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) points to atmospheric aerosols as one of the main sources of uncertainty in current climate simulations (Boucher et al., 2013). Myhre et al. (2013) indicate that the uncertainty in the radiative forcing produced by aerosols greatly exceeds that of all other forcing mechanisms combined. ~~Thus, the World Climate Research Program (WCRP) has identified the study of the role of aerosols in climate (especially, the characterization of how aerosols interact with clouds) as one of the five major scientific challenges in the field of climate research.~~

Despite the increasing number of articles published on the interactions between aerosols and climate during the last 20 years (Fuzzi et al., 2015), the uncertainty associated with the estimated radiative forcing attributed to the interactions between aerosols and clouds has not diminished during the last four cycles of the IPCC (Seinfeld et al., 2016). One of the main tools for estimating the impact of atmospheric aerosols on climate is the use of global and regional climate models (Boucher et al., 2013). However, many of the simulations attempting to reproduce both the present climate and future climatic scenarios, or the extreme events that occur in situations of present or future climates, do not take into account the role of aerosol-radiation and aerosol-clouds interactions (ARI and ACI, respectively, according to the terminology of AR5).

In addition to their radiative effect, aerosols act as condensation nuclei for cloud formation and therefore, can affect precipitation in several ways (Andreae and Rosenfeld, 2008; Rosenfeld et al., 2008). Rosenfeld et al. (2008) studied the role of aerosols in polluted and pristine atmospheres for tropical areas. In polluted atmospheres, as there is a larger amount of condensation nuclei for the same humidity, the cloud drops are smaller and therefore aerosols hamper precipitation. ~~This allows an additional absorption of latent heat and a greater transport of heat towards high layers, giving rise to instability and a larger amount of rain than in pristine atmospheres. That is, in polluted atmospheres there will be a slower conversion so that the drop reaches the critical conditions of precipitation, but it will precipitate with more intensity~~The slower cloud-droplet-to-rain conversion allows the droplets to be transported above the freezing level, and therefore, the latent heat released in freezing makes the convection more intense. However, this has no general validity, since this behavior could change locally depending on the area. In fact, understanding and characterizing the role that aerosols play in the development of convective clouds is today a cutting-edge scientific challenge (Archer-Nicholls et al., 2016). Authors such as Seifert et al. (2012); Fan et al. (2013) find a very weak effect on precipitation by introducing aerosol-cloud interactions. Da Silva et al. (2018) analyzes the effects on microphysics for the year 2013 and concludes that precipitation decreases when there is a higher amount of aerosols.

Therefore, a better understanding of the ARI and ACI interactions is essential for the identification of climate change and its manifestation through changes in the frequency and severity of precipitation events (~~Fuzzi et al., 2015~~)(Huang et al., 2007; Khain et al., 2007; Shrivastava et al. (2013); Forkel et al. (2015); Turnock et al. (2015); Yahya et al. (2016); Palacios-Peña et al. (2018, 2019); Pavlidis et al. (2018, 2019); Along the same lines, works such as ~~Shrivastava et al. (2013); Forkel et al. (2015); Turnock et al. (2015); Yahya et al. (2016); Palacios-Peña et al. (2018, 2019); Pavlidis et al. (2018, 2019);~~ highlight that it is necessary to use regional climate/chemical coupled models to investigate ACI interactions in more detail.

These studies cover mainly continental US, Asia and Europe and investigate chemical and meteorological variables, such as precipitation, temperature and radiation. As indicated by Seinfeld et al. (2016), a critical challenge for climate modeling studies is to improve the estimation of the aerosol impact on clouds and reduce the associated uncertainty. Despite the errors and uncertainties related to the role of aerosols in the climate system (Jiménez-Guerrero et al., 2013), only a small number of scientific papers consider the analysis of climatic events using simulations that include ARI and ACI interactions, which may strongly condition the representation and definition of events associated with precipitation and cloudiness (Prein et al., 2015; Baró et al., 2018).

Traditionally, in regional climate models the representation of the radiative effect of aerosols (ARI) is established by a constant aerosol optical thickness (AOD) value and a predetermined and abundant number of cloud condensation nuclei (CCN) (Forkel et al., 2015) high enough for clouds to form without this variable being a limiting factor. Although the lack of CCN is almost never a limiting factor for cloud formation (this could perhaps happen in remote marine locations in very specific conditions) a low CCN value may result in clouds that precipitate more readily, which can reduce the cloud lifetime and therefore the average cloud fraction (Stevens and Feingold, 2009). To obtain a more realistic model, ARI and ACI interactions, which require models in which meteorology–climatology, radiation, clouds and aerosol atmospheric chemistry are coupled in a fully interactive way, must be included in the simulation (Grell and Baklanov, 2011; Baklanov et al., 2014). Fully coupled climate–chemistry models (*on-line*) provide the possibility to explain the feedback mechanisms between simulated aerosol concentrations and meteorological variables.

In simulations including ARI, the number of CCN remains unchanged, but the concentration of aerosols and their impact on the radiative balance is dynamically modeled (Houghton et al., 2001; Andreae et al., 2005). A region with a high emission of black ~~anthropogenic aerosols~~ carbon will absorb more radiation and increase the temperature of that layer of the atmosphere, favoring the destruction of clouds. However, an area with emissions of clear natural aerosols (e.g. sea salt) will favor radiative cooling due to the ~~dispersion~~ scattering of radiation (Yu et al., 2006).

Also, a further refinement in the configuration of the model adds the aerosol-cloud interactions. In this case, an on-line estimation of aerosol concentrations is conducted in each timestep of the model (as in the previous case), but this dynamical estimation is used both for the calculation of the radiative budget (as in ARI), but also used for the estimation of CCN for cloud formation. This will affect both the number of drops within the cloud and their size, modifying the ~~color~~ optical properties and thus, its radiative balance (Twomey, 1977), and whether they reach the critical size to precipitate or not (Rosenfeld et al., 2008).

Introducing ACI interactions adds a level of complexity that brings the model configuration closer to real processes; however, it has a great computational cost and can increase calculation times between 6 and 10 times (López-Romero et al., 2016; Palacios-Peña et al., 2020). It is henceforth reasonable that most of the studies that have been carried out so far with regional models taking into account these interactions have been for episodic case studies (Yang et al., 2012; Brunner et al., 2015; Palacios-Peña et al., 2019) and only a very limited number of contributions cover climatic periods with a general analysis (e.g. ~~Witha et al. (2019)~~ Witha et al. (2019); Pavlidis et al. (2020)).

90 Hence, in this work the role of ARI and ACI on precipitation and cloudiness over Europe has been exhaustively explored. For this purpose, regional climate simulations (1991-2010) for the Euro-CORDEX (Jacob et al., 2014) domain have been carried out with WRF-Chem in order to account for the influence of atmospheric aerosols on the aforementioned variables.

## 2 Data and Methods

### 2.1 ~~Experiments~~Experimental setup

95 Regional climate simulations were carried out using WRF-Chem model (v.3.6.1), both uncoupled from chemistry (WRF stand-alone configuration, Skamarock et al. (2008)) and including a full on-line coupling with atmospheric chemistry and pollutant transport (for including ARI and ACI processes) (Grell et al., 2005).

Three different experiments were performed in this contribution. ~~A scenario~~The first experiment, BASE, consist in prescribing AOD and CCN ~~is defined as the BASE case (WRF simulations without ARI nor ACI interactions). Two additional scenarios~~  
100 ~~including ARI and ACI are simulated in order to quantify the affects of these interactions, and ACI and ARI interactions are not included. The second experiment, ARI, includes only Aerosol Radiation Interactions (direct and semidirect effects). The third experiment, ARCI, include both aerosol-radiation and aerosol-cloud interactions (direct, semidirect and indirect effects). In ARI and ARCI aerosols are calculated online. These experiments will permit untangling the effects of the aerosols on clouds and precipitation from a climatic perspective.~~

105 In the BASE experiment, aerosols are not treated interactively, but using the default WRF configuration which considers 250 CCN per cm<sup>3</sup> and ~~sets 0.12 AOD to calculate the radiation extinction. AOD is set to 0.~~ In the ARI experiment, aerosols are treated online and ARI processes are activated in the model (Fast et al., 2006), but CCN remain as in the stand-alone version. The ~~ACI-ARCI~~ experiment includes the aforementioned ARI and, in addition, permits ~~the use of aerosols estimated on-line aerosols~~ to interact with the microphysics processes. The description of ~~ACI-ARCI~~ as implemented in the simulations can be  
110 found in Palacios-Peña et al. (2020) ~~as well as validation of the AOD fields.~~ Summarizing, ~~ACI-ARCI~~ in WRF-Chem were implemented by linking the simulated cloud droplet number with the Lin (Lin et al., 1983) microphysics ~~schem~~, turning this scheme into a two-moment scheme. Therefore, the droplet number affects both the calculated droplet mean radius and the cloud optical depth (Chapman et al., 2009).

The spatial configuration consists of two unidirectionally-nested domains (one-way nesting). The domains used are shown  
115 in Figure 1). The inner domain is compliant with Euro-Cordex recommendations (Jacob et al., 2014). It covers Europe with a spatial resolution of 0.44° in latitude and longitude (~ 50km). The outer domain has a spatial resolution of about 150km and extends southward to approximately a latitude of 20°N. The design of this domain aims to cover the most important dust emission areas of the Saharan desert (Goudie and Middleton, 2001; Middleton and Goudie, 2001; Rodriguez et al., 2001; Goudie and Middleton, 2006) that are introduced to the inner domain through boundary conditions (Palacios-Peña et al., 2019).  
120 Nudging has been used for the outer domain so that atmospheric dynamics do not significantly vary (Liu et al., 2012). In the vertical, 29 non-uniform sigma levels were used, with higher density levels near the surface. The upper limit was set at the 50 hPa level.

The physical configuration of the ~~WRF~~-model was designed based on the compatibility with the chemical module and previous works (Baró et al., 2015; Palacios-Peña et al., 2016; Baró et al., 2017; Palacios-Peña et al., 2017, 2019). In addition to microphysics (~~previously described~~Lin scheme), another important ~~parameterizations~~parameterization is related to radiation. The interactions of ~~clouds and~~aerosol and clouds with incoming solar radiation have been implemented by linking simulated cloud droplet number with the ~~Goddard-shortwave-radiation~~RRTMG scheme and with Lin microphysics (further details in Palacios-Peña et al. (2020)). Therefore, droplet number will affect both the calculated droplet mean radius and cloud optical depth. This should allow the dynamical treatment of aerosols and greenhouse gases in order to estimate the radiative budget. The radiative scheme used for both long wave and short wave was the radiative scheme RRTMG (Iacono et al., 2008). Regarding the cumulus parameterization, the Grell 3D scheme (Grell, 1993; Grell and Devenyi, 2002) was used. The boundary layer is modelled with the Yonsei University scheme (Hong et al., 2006). The surface layer is parameterized using the Jiménez et al. (2012) scheme. Finally, the land-soil model chosen to simulate the land-atmosphere interactions was the NOAH model (Tewari et al., 2004).

~~The~~As aforementioned, aerosols are treated on-line, i.e. the model uses changing aerosols departing from anthropogenic emissions and generating natural aerosols throughout the interaction between atmospheric conditions and surface properties. Regarding the configuration and treatment of aerosols an gases, the gas-phase chemical mechanism ~~used in WRF-Chem is~~ RACM-KPP was used (Stockwell et al., 2001; Geiger et al., 2003) coupled to GOCART aerosol scheme (Ginoux et al., 2001a; Chin et al., 2002). The photolysis module Fast-J (Wild et al., 2000) was used for feeding photochemical reactions. Biogenic emissions were online calculated using the Model of Emissions of Gases and Aerosols from Nature model (MEGAN) (Guenther et al., 2006). Dust and marine spray are simulated with GOCART (Ginoux et al., 2001b; Chin et al., 2002). Simulated aerosols include five species: sulfate, mineral dust, sea salt, organic matter and black carbon. Anthropogenic emissions are taken from the Intercomparison Project of Atmospheric and Climate Chemistry Models (Lamarque et al., 2013) and remained unchanged during simulation period (monthly values for 2010). The ability of this configuration for representing the ~~Atmospheric~~ Aerosol Optical Depth has been already extensively evaluated in Palacios-Peña et al. (2020). More details about the treatment of aerosols and its interaction can be found in Jerez et al. (2020b). The means fields of these aerosols as well as the AOD is presented as supplementary material.

The simulated historical period (20 years) for the three simulations covers from 1991 to 2010. Boundary and initial conditions were extracted from the ECMWF reanalysis: ERA20C (ECMWF, 2014; Hersbach et al., 2015), which has a horizontal resolution of approximately 125 km (~~spectral-truncation~~T159). The simulations were run splitting the full period into sub-periods of 5 years with a spin-up period of 4 months, then beginning with the direct interpolation of the soil data of the reanalysis. ~~This period~~After removing the spin-up period, which was chosen in accordance with the results of Jerez et al. (2020a)-~~The boundary conditions~~, the model outputs are merged. This methodology has been tested in Jerez et al. (2020a). Boundary conditions for the outer domain were updated every 6 hours. Model outputs are recorded every hour. The observed evolution of greenhouse gases CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O were ~~considered in accordance with the recommendation of Jerez et al. (2018)~~ incorporated as recommended in Jerez et al. (2018), varying CO<sub>2</sub> from 353 to 390 along the simulated period.

## 2.2 Methods

This contribution focuses on the impacts of ARI and ACI on precipitation. Hence, the climatologies for precipitation amount, number of days with precipitation over a given threshold and cloudiness of the different experiments have been intercompared for BASE, ARI and ~~ACI~~ARCI simulations. The data used to evaluate the added value of the aerosol experiments was the ERA5 (Hrarsbach and Dee, 2016) reanalysis, since it has already been validated for precipitation (Albergel et al., 2018; Christensen et al., 2019; Hwang et al., 2019). In addition, the comparison of the annual and seasonal climatologies for other atmospheric fields such as sea level pressure (slp), geopotential height (Z) and temperature (T) at 1000,750 and 500mb, maximum minimum temperatures (tasmax,tasmin), daily temperature range (dtr) and solar radiation at surface (rsds) as well as mean temporal mean fields of the particulate matter (PM10,PM2.5), BC (black Carbon) and AOD fields are represented. All these fields as presented as supplementary material.

The statistical significance of the differences among the climatologies reproduced by the simulations is checked by using a Bootstrap method with ~~1000~~1,000 repetitions and a p-value < 0.05 was applied. More details about the method can be found in Milelli et al. (2010).

In order to assess the relationship between the obtained changes in precipitation and different variables representing the aerosol load: PM10 (Particulate Matter <10 $\mu$ m), PM2.5 (Particulate Matter <2.5 $\mu$ m), AOD at 550nm (hereinafter AOD) the ratio between PM2.5 and PM10 (hereinafter called PMratio), several events (days) are grouped according to its intensity and extension. The intensity of an event is defined as the minimum value given by a threshold variable that the simulation cells must meet. The extension of the event is defined as the number of cells meeting the previous condition.

The relative differences (ARCI-BASE/BASEx100) among the experiments are represented in a two-dimensional heat map, where the axes denote the extent and intensity. The number of days on which the criteria defined above are met is indicated inside each element of the matrix. The total number of days analyzed is 7305, corresponding to the 20 years simulated. This type of graph allows us to identify whether there is a relationship between the different variables and the magnitude of the change, allowing to establish the relative importance of each one of the factors involved. In the intervals where a relationship appears, a multiple linear regression fit has been made, giving the multiple correlation coefficient as indicator of the skill of the relationship.

On the other hand, the effect of aerosols could depend on the area, and affecting in a different way weak and strong precipitation events (Rosenfeld et al., 2008). The series of relative differences between the ~~ACI-BASE~~ARCI-BASE simulations have been generated for common and non-common days with rainfall exceeding a certain threshold for all points in the domain. The threshold ranges from 0 to 20mm/day on a ~~non-regular-basis~~non-linear scale (with a higher density of values near 0) with a total of 41 values. In order to investigate areas where the effect of aerosols on precipitation could be different, a clustering method was applied to the constructed series. The algorithm used for the spatial classification is similar to that used in other works (Jiménez et al., 2008; Lorente-Plazas et al., 2015) and composed by several steps. First, an analysis of principal components (Von Storch, 1999) is made, which is applied to the correlation matrix of the constructed series. Second, a two-step clustering method to a number of the retained principal components is applied. A hierarchical method is applied on a first basis;

in this case, the Ward's algorithm (Ward Jr, 1963). This classification provides the number of clusters and the initial seeds (also called centroids) for the ~~subsequent no-hierarchical last step, the application of the non-hierarchical~~ method K-means which optimizes the grouping (Hartigan and Wong, 1979). More details about the algorithm can be found in Lorente-Plazas et al. (2015). Finally the mean regional series are calculated as the average of ~~time-series~~ belonging to a cluster (which corresponds  
195 to a spatial region in this study).

### 3 Results and discussion

#### 3.1 Precipitation differences in ARI and ARCI simulations

The sensitivity of precipitation to the aerosol treatment in climate simulations is analyzed by comparing BASE, ARI and ~~ACI-ARCI~~ simulations over Europe during a ~~20-year-20-year~~ period. The differences between ~~ACI-BASE-ARCI-BASE~~  
200 in spatially-averaged total precipitation are ~~small~~limited, around 0.5%. Figure 2a shows the differences (~~percentage respect~~  
relative differences with respect to BASE) in the mean annual rainfall. The results depict a ~~great-large~~ spatial variability with  
differences ranging from 10% to -10%. Two zones with opposite behaviors are identified: (1) the central and eastern part of  
Europe, with a precipitation decrease up to 8% (statistically significant,  $p < 0.05$ ), and the ~~Eastern-eastern~~ Mediterranean area,  
with increases up to 10% (although changes are not significant,  $p > 0.05$ ). ~~In the rest of the domain, there are other-Other~~  
205 areas, such as the Iberian Peninsula, ~~with-present~~ a strong spatial variability (e.g. increasing rainfall ~~on-over~~ the Mediterranean  
coast and decreasing ~~in-the-over~~ northeastern areas). Overall, the role of introducing ARI and ACI interactions leads to a  
~~spatial redistribution of~~ redistribution of the annual precipitation. The ~~differences between ARI~~ most remarkable difference is  
a reduction of annual precipitation over central Europe for ARI that is enhanced when ACI interactions are included, being  
more intense and extended spatially. This reduction of precipitation is linked mainly to a reduction of the number of days with  
210 precipitation  $> 0.1$ mm ( $N_{p01}$ ) and clouds at low level (CLL); in fact, the most significant and widespread changes are obtained  
for CLL. Moreover, a statistically significant increase of  $N_{p01}$  appears over the eastern Mediterranean, but in this case only in  
ARCI experiments linked to an increase of CLL. At seasonal scale (see Supplementary Material for further information) the  
decrease of precipitation, CLL and  $N_{p01}$  in central Europe is reproduced during all seasons but for summer. In addition, the  
increase in the eastern Mediterranean is reproduced along the whole year, being stronger during wintertime.

215 These changes are also related to other changes in several variables; for instance,  $rsds$  decreases in ARI and ARCI experiments  
mainly over the half-south part of the domain, due to the higher AOD. However, there are some parts of central Europe where  
 $rsds$  rises due to the increase of clouds, specially in autumn and spring. Changes in temperature are converse for  $tasmax$   
and ~~BASE simulations present a similar pattern (not shown)- $tasmin$~~ , reaching differences around 0.5K with spatial patterns  
quite similar to those of CLL. The most remarkable changes are obtained for  $dtr$  with a pattern characterized by an important  
220 increase in the north (lower CLL) and a decrease in the south (higher AOD). The modification of energy fluxes also affects the  
circulation. The  $SLP$  fields, as well as  $Z$  at several levels, also show statistically-significant sensitivity to ARI and ACI effects.  
Here the most remarkable features are the large differences between ARI and ARCI experiment. ARCI shows a noticeable  
increase of  $slp$  in central and northern part of the domain respect ACI. This behavior is also appreciated for  $Z$ . Finally, it is

225 worth highlighting that ARI and ARCI also indicate a rise in the temperature over northern and central Europe. This might imply that simulated changes in precipitation can also be indirectly affected by changes in atmospheric circulation. This fact could hamper to establish the relationship between changes in precipitation and changes in the treatment of aerosols in our experiments.

In order to investigate the variations in the regimes of precipitation, the changes in the number of rainy days ~~is-are~~ estimated. Figure 2b shows the relative differences in the number of days with precipitation > 0.1mm. The patterns of differences are 230 similar to those of averaged precipitation, implying that the reduction in precipitation is mainly caused by the decrease in the number of rainy days. However, there are some noticeable exceptions. The relationships in the two large areas mentioned above are direct; that is, higher rainfall is linked to a larger number of precipitation episodes. However, there are areas where the relationship is inverse, ~~more-(less)higher(lower)~~ number of days implies less(more) precipitation. The analysis of the low clouds in the domain (Figure 2c) shows a pattern similar to the aforementioned patterns. This ~~may-might~~ indicate that both the 235 ARI and ACI effect can play very different roles on cloud properties and therefore on precipitation depending on the target area. This issue ~~is-addressed later~~ will be addressed later in this contribution.

~~Regarding the-~~

### 3.2 Evaluation against ERA5 reanalysis

The added value of incorporating on-line aerosol interactions and complex aerosol physics into the model has been evaluated 240 by analyzing the differences in precipitation, number of rainy days and low clouds between the simulations and the re-analysis of the European center ERA5 (Figure ~~2d-f~~3). Overall, WRF-Chem (both in the BASE and ~~ACI-ARCI~~ simulations), tends to underestimate precipitation over the European Mediterranean region and along the coasts of the Nordic countries, while overestimates rainfall in the rest of the domain. These patterns are analogous for all the analyzed variables. If looking only at the areas where the differences are significant, ~~ACI-ARCI~~ simulations slightly reduce the differences in the spatial distribution. 245 However, the differences between ERA5 and ~~ACI-ARCI~~ are much larger than the differences between ~~ACI and BASE (not shown)~~ ARCI and BASE.

Despite this, as previously noted (Figure 2a-c), the ~~ACI-ARCI~~ experiment introduces significant differences with respect to the BASE simulation over central Europe. These differences reach values about the 5% in the number of rainy days. Therefore, a relationship between aerosols in these areas and the changes aforementioned might be expected ~~-in spite of the induced~~ 250 changes in the dynamics. This relation is explored in the following section of this contribution.

### 3.3 Relationship between aerosol physical properties and precipitation

In order to understand the contribution of the different types of aerosol to changes in precipitation, the differences in ~~precipitation~~ rainfall have been assessed by choosing a set of episodes. The episodes were selected attending to the value of variables representative for the aerosols size and concentration (PM10 and PM2.5), their ratio (PMratio) and their impacts on radiation 255 (AOD), as well as the spatial extension of the event.

Figure 4 shows the relative changes for the different sets of episodes for AOD at 550nm (AOD550)(b), PM10(d), PM2.5(c) and the PMratio(d). Calculations were conducted using only those points with significant differences (Figure 2b). Figure 4a shows the relative changes (~~ACI-BASE~~ARCI-BASE) in the number of rainy days for different sets of episodes, selected by choosing the extension/size of the episode (number of grid points) of the cells exceeding a value of PMratio (values from 0.2 to 0.8). In a range of intensities, quasi-linear relationships appear. Figures 4b-e show these relationships for the different variables.

The lower left box of Figure 4e ~~would indicate~~ indicates that 5970 out of 7303 days present a PMratio > 0.64 (y axis) achieved in more than 180 cells of the domain (x axis). When calculating the differences in ~~ACI-BASE~~ARCI-BASE precipitation in the 5970 days accomplishing that condition (PMratio > 0.64 in more than 180 cells of the domain), the differences in rainy days over those cells is around 4%. Thus, e.g., the number of days in which PMratio is > 0.75 in more than 280 points is 1030 and the reduction in the number of rainy days is 8%. Following with ~~the ease of the~~ PMratio (Figure 4e), the higher the intensity the ~~greater~~ larger the reduction in the number of rainy days; and the greater the extent/size of the event, the larger the reduction in rainy days (e.g. reaching the maximum reduction around 15%). In fact, the multiple regression coefficient between the different variables is  $R = 0.80$ .

For AOD550 (Figure 4b), the results show that higher AOD550 values lead to a lower reduction in the number of rainy days. ~~However, in this case the~~ The changes are small (under 2%) ~~and the relationships are not~~ although the relationship is clear ( $R = 0.40$ ,  $0.78$ ). Results are analogous for PM2.5 (Figure 4c) ~~but the relationship is less clear~~ ( $R = 0.53$ ). For PM10 the changes are higher but with less clear relationship ( $R = 0.40$ ) However, relationships with the PMratio (Figure 4e) are important and significant ( $R = 0.80$ ). Therefore, an important conclusion is that the variable with the largest impact on the number of rainy days is the PMratio in this area.

The possible physical explanation for this behavior in this area is that the higher the PMratio ~~, the greater~~ (Figure 7), the higher the concentration of small particles ~~that change~~ changing the properties of the clouds ~~, mainly the low clouds~~ (mainly low clouds) (Figure 2e, reduction of low cloudiness over Central Europe) making leading to a clearer atmosphere. This results in higher temperatures and an increase in the condensation level, leading to a reduction in the number of rainy days and therefore a decrease in the precipitation amount (direct and semidirect effects). As noted in Figure 2 the reduction of CLL also occurs in the ARI experiment. This could be explained by the atmospheric warming caused by the radiation absorption of dark atmospheric aerosols (black carbon), causing the effect exposed above. The stronger signal in ARCI can be attributed to the addition of both processes. On the other hand, a high concentration episode of PM2.5 can occur together with a PM10 event, decreasing the PMratio. Therefore, the better relationship with PMratio could be related to coarse aerosols enhancing precipitation, and thereby opposing the effect of smaller aerosols.

### 3.4 Regional role of aerosols on precipitation

As noted previously, the relationships among changes in precipitation, number of rainy days and cloudiness, are different in different regions of our domain. Therefore, the role of aerosols, analyzed either considering their nature or their concentration, causes different changes in precipitation regimes. In order to quantify this effect, the series of relative changes in the number of

290 rainy days have been constructed at each point for different thresholds ranging from 0.1 to 20mm/day. The grouping method described in the methodology section has been applied to this series, obtaining 5 different regions ~~.-Showed in-~~ (Figure 5). The regions are listed attending to the number of grid cells of each group, being Region 1 the most numerous and also the most dispersed~~the Region 1.-~~. The centroid series (average series of regions) are represented in Figure 6. The filled circles (green) indicate that the relative differences between the ~~ACI-ARCI~~ and BASE experiments are significant.

295 Region 1 does not present a clear pattern, covering most of the points the Atlantic Ocean and southern Europe. This area has ~~no significant differences and these are~~ very low, non-significant differences, with values between 0.5% and -2.5%. Therefore, the effect of including aerosol-cloud interactions in this area practically does not affect precipitation. Region 2 and Region 5 have a similar behavior. In both zones there is a decrease in precipitation for almost all thresholds except the most extreme rainfall events where precipitation increases. In Region 2 changes range from -2% to -4%, with the differences for ~~small-low~~ thresholds being significant ~~,-~~ (up to 2mm/day). In the case of ~~the~~-Region 5, the differences are always significant and much larger. The maximum reduction is obtained for episodes of precipitation above 14mm/day, reaching relative changes in the precipitation of the entire area around 12%. Note that ~~the~~-Region 5 is almost coincident with the area previously analyzed (significant differences Figure 2).

Regions 3 and 4 have a different behavior. In these regions an increase in precipitation occurs when including ~~ACI-ARCI~~.  
305 Region 3 does not have a clear spatial pattern, with points scattered along the entire domain. For low thresholds there are ~~hardly any-no significant~~ changes, while for high thresholds it presents a very significant increase in precipitation with significant relative changes (e.g. 5% for a threshold of 8mm/day). For higher thresholds the relative changes are close to 20%. However this result should be analyzed with caution since the lack of spatial structure, although from the statistical point of view there is a coherent increase of moderate and intense precipitation events that can be supported by some physical processes presented in the literature (Khain et al., 2008).

310 Finally, Region 4 shows a clear spatial pattern, with most of the points concentrated in the ~~Eastern Mediterranean. In eastern Mediterranean. Over~~ this area, the range of thresholds between 1 mm/day and 5 mm/day presents significant differences; however, for thresholds > 5mm/day, the series remain constant around 4.5% and the statistical significance disappears.

Therefore, the role of the aerosols on precipitations shows a clear spatial dependence, affecting strong and weak precipitation  
315 ~~in a different manner. Over regions differently. Over Regions~~ 2 and 5, which cover northern, central and eastern Europe, ARI and ACI interactions tend to reduce precipitation. This reduction is significant for almost all events below 15mm/day. In the Mediterranean area and especially in the ~~Eastern-eastern~~ Mediterranean, rainfall increases ~~with the introduction of ACI~~in the ARCI experiment, mainly due to the increase in the number of days with rainfall below 5mm/day. Meanwhile, in Region 3 the total rainfall undergoes very variable changes, but fundamentally an increase in moderate and strong rainfall events.

### 320 3.5 ARI vs. ARCI relevance for modifying precipitation

In order to better understand the processes involved in each of the areas, the ~~differences between ACI-absolute annual values and differences between ARCI~~ and ARI are analyzed in terms of the concentrations of PM10, PM2.5 and PMratio (Figure 7). This will ~~permit discriminate which~~ allow to discriminate which processes (aerosol-radiation or aerosol-cloud interactions;

processes) are most relevant. ~~Figure 8a-c~~ As commented above, Figure 4 shows the differences in ~~ACI-BASE~~ ~~ARCI-BASE~~,  
325 ~~ARI-BASE~~ and ~~ACI-ARI~~ analyzing precipitations surpassing 1 ~~ARCI-ARI~~ analyzing precipitation (number of days exceeding  
0.1 mm/day and total amount) as well as the cloud cover at low level. In the case of Region 5, both simulations ~~give us~~ provide  
a reduction in the number of days of precipitation. Therefore, both ARI and ACI affect precipitation in the same direction.  
ARI causes ~~less radiation to reach the surface (Figure 8d). This inhibits convection and therefore, a reduction in cloudiness. On~~  
~~the other hand, an increase of temperature at low levels (see temperature at 850 hPa in the Supplementary Material), specially~~  
330 ~~during autumn and springtime, leading to a reduction of clouds and precipitation. ARCI experiment enhances this effect by~~ the  
higher concentration of small particles ~~modifies~~ modifying the properties of the clouds, inhibiting precipitation processes again  
~~. Moreover, in the area of the Eastern Mediterranean ARI have hardly any impact on cloudiness (Figure 8d), but on the number~~  
~~of rainy days. Therefore, the effects in that area will be mainly due to the interaction of aerosols with clouds when acting as~~  
~~CCN. This effect can be clearly seen in other areas of Region 4, such as the Atlantic Coast of Scandinavia. Finally~~ by reducing  
335 clouds due to microphysical processes, since over this area there is a prevalence of small aerosols (see PMratio in Figure 7 and  
Supplementary Material).

On the other hand, there are areas where the effects of ARI and ACI tend to cancel each other, or have different effects on  
small or large rainfall. ~~For example, in~~ This is the case of the ~~southern Iberian Peninsula, the inclusion of aerosols leads to a~~  
~~reduction in the number of days of precipitation > 1 mm due to purely radiative effects (Figure 8c).~~

340 ~~Finally, Figure 8f shows the relative differences between~~ area of Balkans, where the ARI effect tends to decrease precipitation,  
while ACI tend to increase rainfall, being the net effect (ARCI) negligible (Figure 2). This behavior can be attributed to the  
different role of small and big aerosols. While small particles inhibit the formation of clouds by semidirect effects, large  
aerosols ease cloud formation and precipitation by indirect effects. Note that over that area there is an increase of large particles  
(PM10 concentrations between ACI and ARI. The spatial pattern shows an area of positive differences over Central Europe and  
345 the western Mediterranean, except for the western Iberian Peninsula) and a statistical significant increase of AOD (Figure 8).  
Conversely, negative differences prevail in the rest of the domain; that is, the ARI simulation has lower concentrations of PM10.  
~~Therefore, in Region 4~~

Finally, the increase in precipitation and cloudiness ~~is associated with a decrease in~~ in Region 4 could be associated with  
larger values of PM10. In order to clarify this analysis, (big condensation nuclei). In this case, ARI effects are almost negligible  
350 along the year. However, the ARCI experiment shows a clear positive difference with respect to the BASE case and ARI.  
Figure 8 ~~g~~ shows the relative difference in the concentration of PM10 between ~~ACI~~ ARCI and ARI, and the differences in the  
number of rainy days with precipitation > 1mm/day. The points are distributed in a quasi-random way with respect to 0. The  
cells of the whole Region 4 show a bias towards positive values ~~in the for~~ changes in precipitation and a decrease ~~in the for~~  
PM10. If focusing only on ~~Zone 5, Eastern Mediterranean~~ Eastern Mediterranean of cluster 4 (yellow points) the relationship  
355 is clear. Most of the points showing an increase in precipitation undergo a decrease in PM10. A plausible explanation is that,  
in these areas, the PM10 load is high due to the intrusion of desert dust and sea-salt aerosols. The difference between the ~~ACI~~  
ARCI and ARI simulation is the activation of the aerosol-cloud interaction mechanism, using the aerosols calculated online  
as CCN to form clouds while in ARI, the CCN are a prescribed at a fixed value. The PM10 used to form clouds in ~~ACI will~~

~~no longer be~~ ARCI will be no longer counted in PM10 since of in-cloud scavenging. Therefore, a decrease in PM10 occurs  
360 and this decrease coincides with an increase in cloudiness. In addition, the increase of precipitation will also decrease PM10  
due to wet deposition. Note that the patterns are not completely coincident, with the precipitation pattern shifted slightly to  
the north (see the comparison in Figures 8e & f). This can be attributed to the displacement of the cloud masses in such area,  
~~which under conditions of heavy PM10 loads can have an important southern component.~~ This behaviour can be attributed of  
the role of giant aerosol particles in warm rain initiation (Johnson, 1982), increased precipitation in stratiform precipitation by  
365 dust through deposition growth (Gong et al., 2010) or the enhanced drizzle formation in stratocumulus (Feingold et al., 1999).

#### 4 Conclusions

The effect of atmospheric aerosols on regional climate simulations ~~still presents~~ presents nowadays many uncertainties due  
to ~~their~~ complex and non-linear ~~interactions that depends~~ processes represented, which depend on a wide variety of factors.  
The quantity, size and ~~color of aerosols modify the radiative balance~~ optical properties of aerosols condition the modification  
370 of the radiative budget and, therefore, many other derived variables such as local temperature, cloudiness or precipitation. In  
addition, the amount of moisture available ~~will determine~~ determines the size of the water droplets based on the amount and  
type of aerosols available. ~~The size and color~~ Atmospheric aerosols also affect the size and optical properties of the clouds ~~will~~  
~~be affected, which will once again affect,~~ which also modify the radiative budget. ~~In addition, this~~ Moreover, these processes  
can spatially redistribute the precipitation regimes, allowing it to rain rainfall in different areas or provoking rainfall intensity to  
375 change. However changes in its intensity. Despite the importance of the problem from a climatological point of view, there is  
a lack of scientific contributions that have studied these problems ~~and the~~. The large increase in computational time needed  
to include ACI and ARI interactions in regional climate simulations ~~have~~ has traditionally hampered the works covering this  
analysis from a climatic perspective.

In order to address ~~these~~ the aforementioned issues, a set of regional climate simulations have been conducted for the period  
380 1991-2010 without on-line aerosol-atmosphere interactions (BASE), with ARI and with ~~ACI~~ ARI+ACI (ARCI) parameteriza-  
tions in an on-line coupled model. All simulations cover the domain of Europe defined by the Euro-CORDEX initiative. This  
analysis has focused on average precipitation, number of precipitation days larger than a certain threshold and cloudiness. In  
addition, the effects on other variables such as temperature at different levels, geopotential height, radiation at surface, and sea  
level pressure are presented as Supplementary Material (SM).

385 When introducing the ACI and ARI interactions, the spatial average of the total rainfall does not ~~vary too much~~ differ  
from the BASE scenario. However, there is a spatial redistribution of such precipitation. Although there are changes in ~~many~~  
~~places in several places throughout~~ the domain, the largest ~~occur~~ modification occurs in the area of central Europe, where a  
decrease in precipitation is found as a result of activating the ~~aerosol-radiation~~ aerosol-radiation and aerosol-cloud interactions.  
Conversely, the behavior is the opposite in the eastern Mediterranean, where the effects of aerosol-cloud interactions prevails.  
390 These results are reproduced by analyzing the number of days of precipitation > 0.1mm, with very similar patterns. However,  
there are areas where the relationship between precipitation and number of rainy days is ~~the opposite~~ not straightforward.

When the results are compared with ERA5, BASE simulation tends to overestimate rainfall across the domain except in some areas of Mediterranean and Nordic countries. When ACI interactions are incorporated into the modeling setup, these differences are reduced, although ~~the order of magnitude of quantitatively~~ this improvement is small/limited.

395 The results obtained for the number of precipitation days  $> 0.1\text{mm}$  were related with different aerosol variables (AOD550, PM2.5, PM10 and PMratio). That relationship shows a highly non-linear behaviour, although a regime where the linear approximation is acceptable was also identified. For ~~Central-central~~ Europe, in the linear regime, the intensity and size-extension (size) of the PMratio events have a direct relationship with the increase in of the differences in the number of rainy days.

~~The Albeit the~~ previous conclusion is limited to the number of days of precipitation ~~greater than 0.1mm and it is~~  $> 0.1\text{mm}$ ,  
400 it becomes interesting to check the relationship for other thresholds. ~~Analyzing several precipitation thresholds, five~~ Five types of behavior throughout the target domain were identified ~~:- aerosols by analyzing several precipitation thresholds. Aerosols~~ contribute positively or negatively to precipitation depending on the area and the intensity of precipitation. The available humidity, the ~~competence efficiency~~ of the CCN and the type of aerosol (size, ~~color~~ optical properties, shape) are the most important factors conditioning ~~one the~~ type of behavior ~~or another~~. In the experiments conducted, the inclusion of ~~ACI-ARCI~~  
405 leads to a reduction of precipitation in all regimes in ~~the~~ northern-central and eastern parts of Europe. However, in the eastern Mediterranean, precipitation increases due to the increase of days with rainfall  $< 5\text{mm/day}$ . ~~For~~ Also positive changes for moderate and strong rainfall regimes are found over some areas (Region 3, which is a very dispersed area, ~~there are also positive changes for moderate and strong rainfall regimes. There~~). Although this finding can be identified with the so-called deepening effect (Stevens and Feingold, 2009), relating aerosols with an increase of precipitation for some convective events,  
410 this statement should be considered with caution because of the lack of spatial structure of this cluster. The rest of areas are ~~almost not barely~~ affected.

~~These conclusions are valid for both simulations, ARI and ACI. However, for the eastern Mediterranean area, aerosol-cloud interactions have the largest impact on cloudiness and, therefore, on the number of rainy days. The aerosols that mainly influence that change are large particles (PM10) with a natural origin. In this area there is an important load of sea salt and frequent dust outbreaks that, in the case of the ACI experiment, are used as CCN, resulting in a decrease in PM10-~~  
415

Some of the changes obtained can be related to the direct, semidirect and indirect effects of aerosols on clouds. The reduction of precipitation over some areas could be linked to both atmosphere warming and excess of CNN. The radiative processes have the ability to change the thermodynamic environment due to the absorption of radiation by fine dark particles (mainly black carbon), stabilizing the environment or increasing the condensation level. The excess of CNN leads to small drops producing a precipitation depletion. In principle this would increase the lifetime effect; however the experiments presented here show an extra depletion of cloudiness, likely related to a faster evaporation of water drops. All these processes are associated with a high concentration of fine aerosols with respect to the ARI experiment because of in-cloud scavenging coarse particles. On the other hand, the effects of coarse aerosols (PM10, giant condensation nuclei) seem to be totally the opposite. These particles seem to enhance precipitation processes, specially increasing light precipitation events (Feingold et al., 1999) or anticipating precipitation development. Sometimes both processes (semidirect and indirect) overlap, being the net effect negligible.  
420  
425

Concluding, the effect of aerosols on climatic variables is varied and complex and ~~more~~ further studies on this topic are needed ~~to in order to~~ (1) reduce the uncertainty associated with the inclusion of aerosols in regional climate experiments ~~as well as a best understanding of the physical~~; and (2) better understand the physical and microphysical processes leading changes in precipitation. This contribution demonstrates from a modeling approach that changes in the concentration, extension and type of aerosols alter the precipitation regimes and amount in different ways. These changes are spatial- and seasonal-dependent and are in agreement with other works (e.g. Li et al. (2019)). The inclusion in regional climate experiments of on-line aerosols, as well as cloud-aerosol interactions, alter precipitation patterns as well as other surface and upper air variables (Pavlidis et al., 2020; Jerez et al., 2020b) and could differ from other approximations such as using AOD climatologies or prescribed CCN (Nabat et al., 2015). In addition, future research aimed at disentangling the effects of aerosols on regional climate simulations should be devoted to understand the role of regional and large scale circulation (regimes), possible feedbacks and overlapping processes.

*Author contributions.* JML-R, JPM and PJ-G designed the research. JML-R performed the experiments. JML-R, JPM, SJ and RL-P analyzed the outputs from experiments. LP-P contributed to the design of the numerical experiments. JMLR and JPM wrote the paper with inputs from all coauthors.

440 *Competing interests.* The authors declare that they have no conflict of interest.

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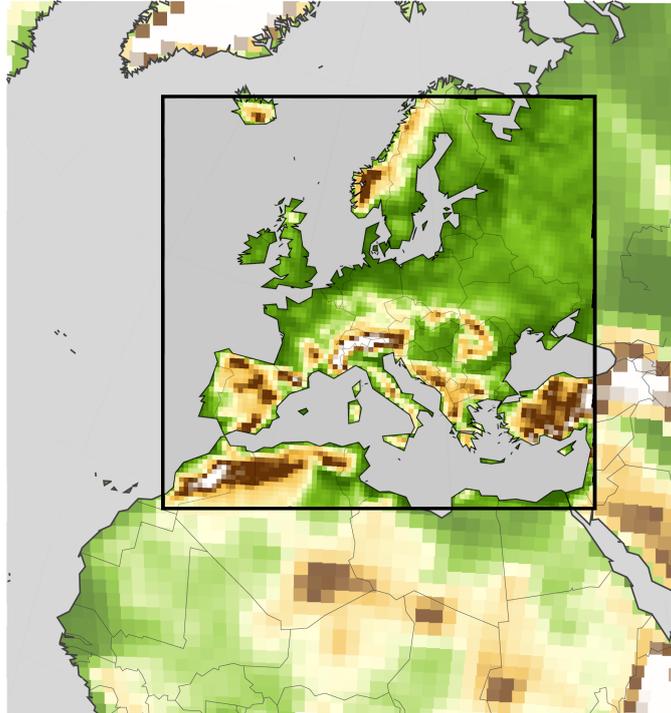
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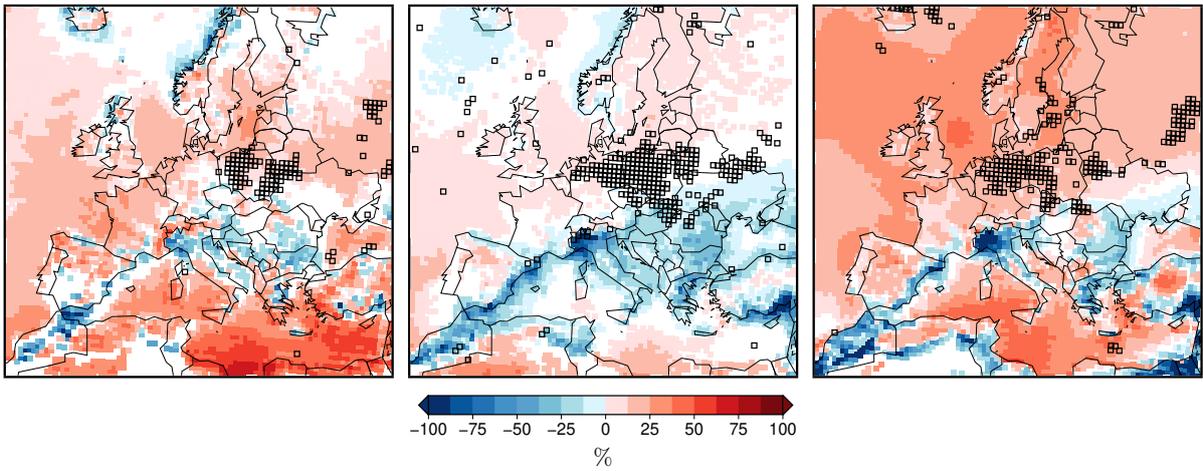
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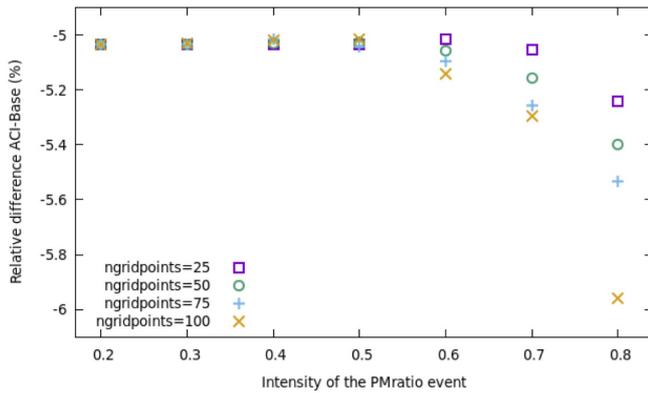
**Figure 1.** Simulation domains covered in the experiments. The inner Euro-CORDEX domain is boxed in the Figure.



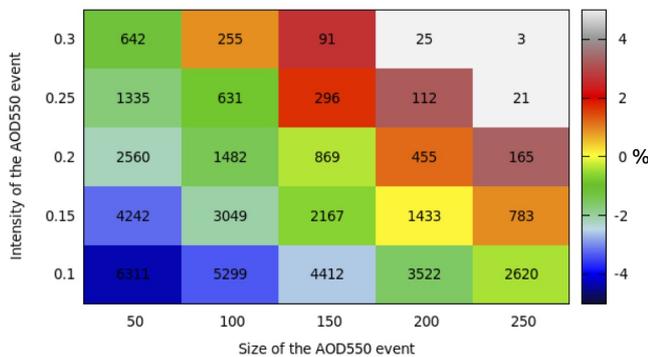


**Figure 3.** Significant relative differences (colors) between ARCI and ERA5. Squares indicate statistical significant differences ( $p < 0.05$ ). The analysis has been conducted for the mean values of the period 1991-2010.

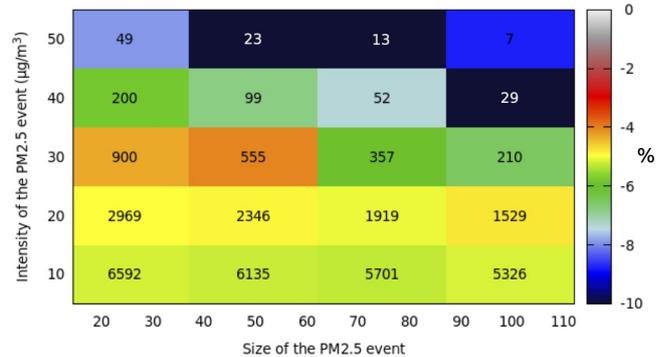
**(a) NDP >0.1mm for PMratio events**



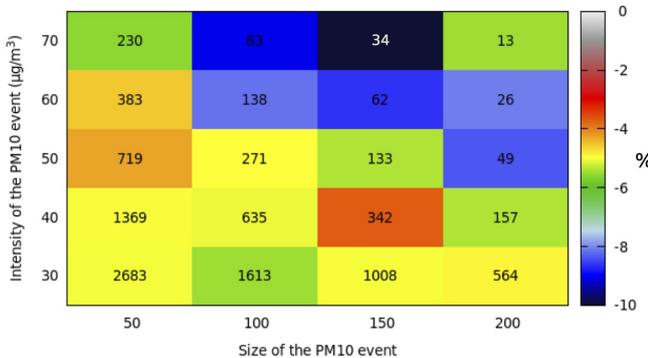
**(b) NDP >0.1mm for AOD550 events. R=0.78.**



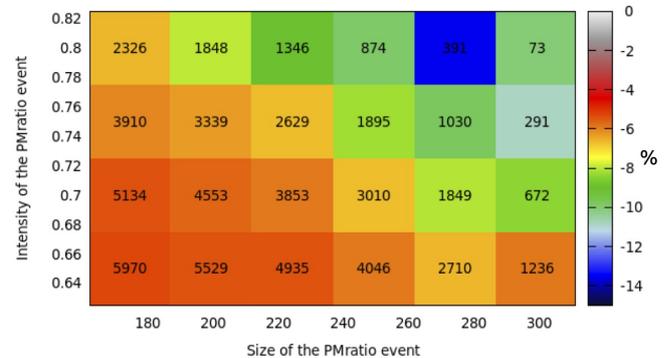
**(c) NDP >0.1mm for PM2.5 events. R=0.53.**



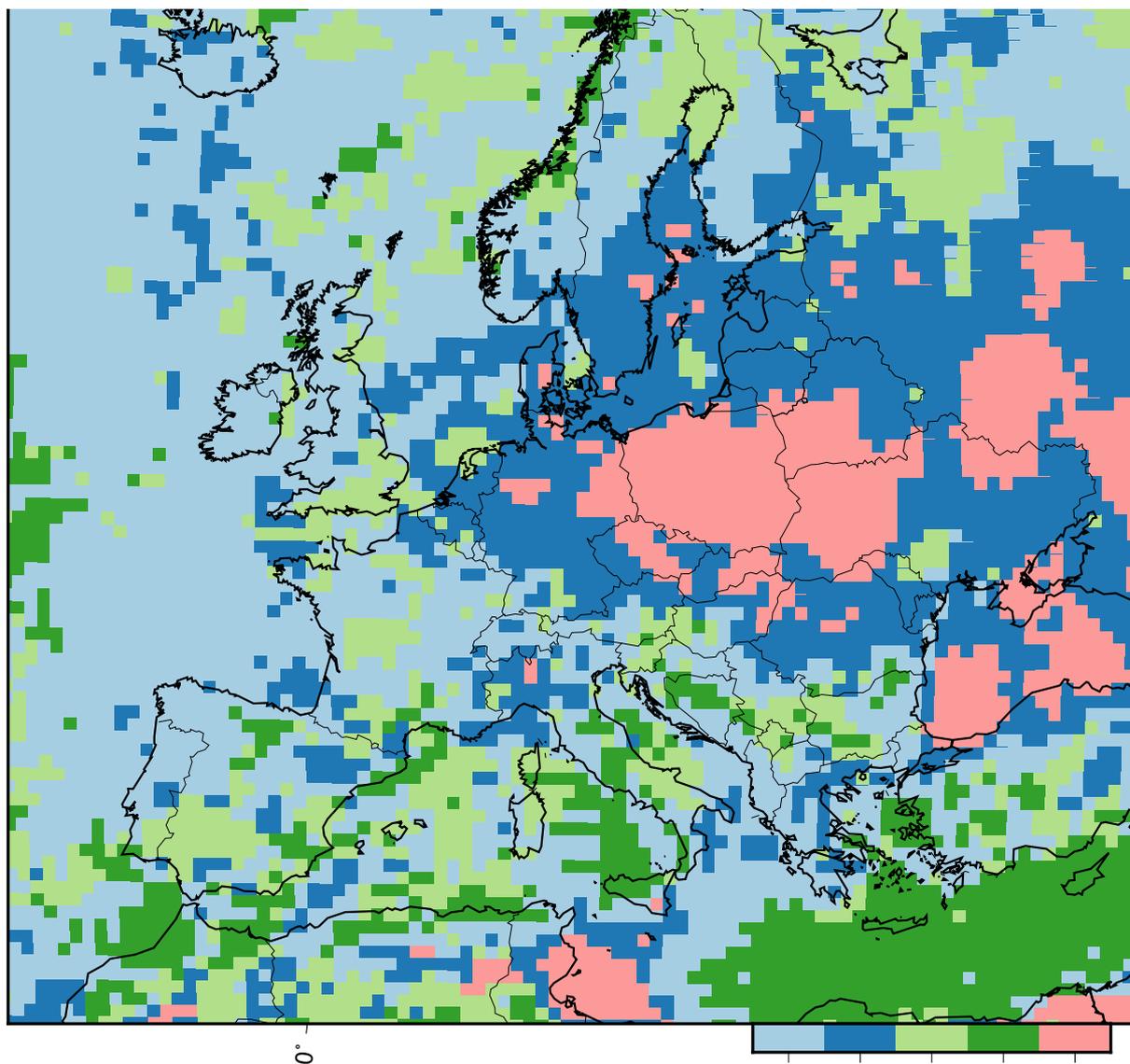
**(d) NDP >0.1mm for PM10 events. R=0.40.**



**(e) NDP >0.1mm for PMratio events. R=0.80.**

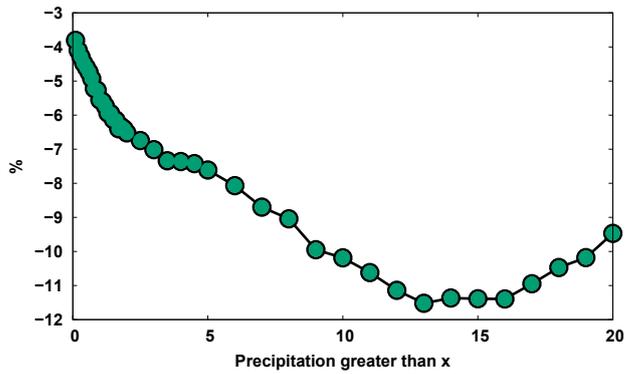


**Figure 4.** Relative difference (colors) in the ~~ACI-BASE-ARCI-BASE~~ simulations for the 1991-2010 period based on (b) the intensity and size of AOD550 events, (c) the intensity and size of PM2.5 events, (d) for events of PM10 and (e) for those of PMratio. The calculation is made for the domain cells with significant ~~ACI-BASE-ARCI-BASE~~ differences for the number of days with precipitation > 0.1mm (Figure 2b) and only for the zone where the non-constant linear behavior begins (>0.6) in Figure 4a (id. to the other variables). The number inside the boxes indicates the number of days meeting the corresponding criteria of intensity and extent of events. R denotes the multiple regression coefficient resulting from a ~~multilinear-multi-linear~~ adjustment of those values.

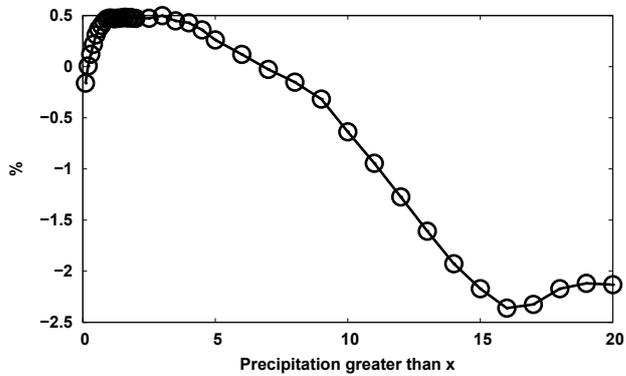


**Figure 5.** Cluster analysis of rainy days: each color depicts a cluster with different **temporal variability for the time-series behaviour** of the **relative-ARCI-BASE** difference (**ACI-BASE**) in number of days of precipitation over a threshold running from 0.1mm to 20mm/day for the period 1991-2010.

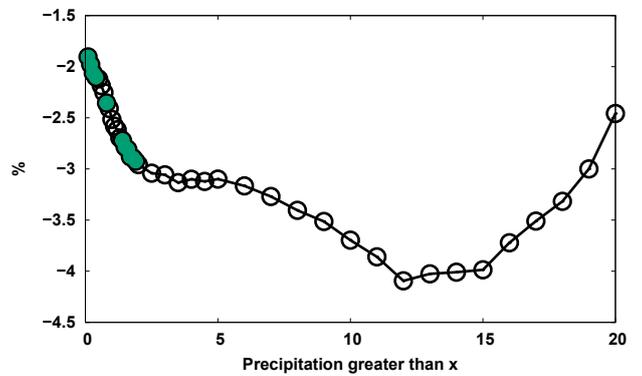
(a) Cluster 5



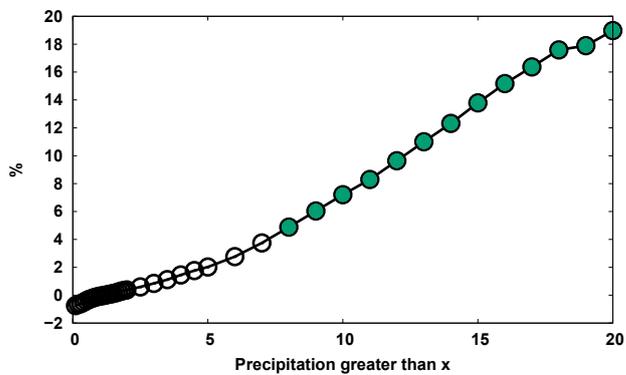
(b) Cluster 1



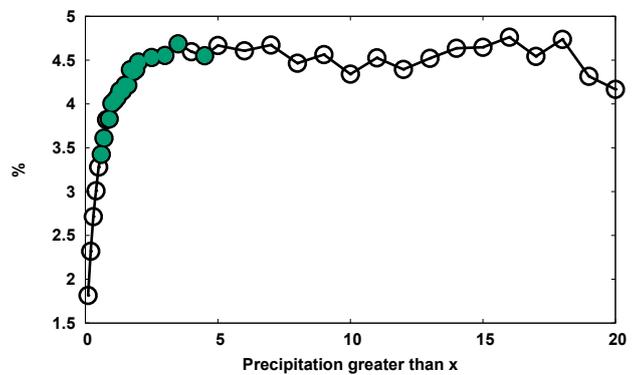
(c) Cluster 2



(d) Cluster 3



(e) Cluster 4



(clusters)

Figure 6.

Series of relative differences between ACI-ARCI and BASE based on different thresholds in rainy days for the different regions (Figure 5).

Green circles denote the thresholds for which the differences are significant (p-value < 0.05).

Relative differences for the number of precipitation days greater than 1mm and low cloudiness between ACI-BASE (only for the number of days of pr), ARI-BASE, ACI-ARI (also for PM10) Relative differences for the number of days with precipitation > 1mm between: (a) ACI and BASE, (b) ARI and BASE, (c) ACI and ARI. Relative difference for low clouds between ARI and BASE (d) and ACI and ARI (e) (The ACI-BASE difference presented in Figure 2c). Panel (f) shows the relative differences between ACI and ARI for PM10. Panel (g) shows the number of days of precipitation > 1mm compared to PM10 for all the cells of the domain (black), for Region 4 (violet) and Region 4 but only in the Mediterranean

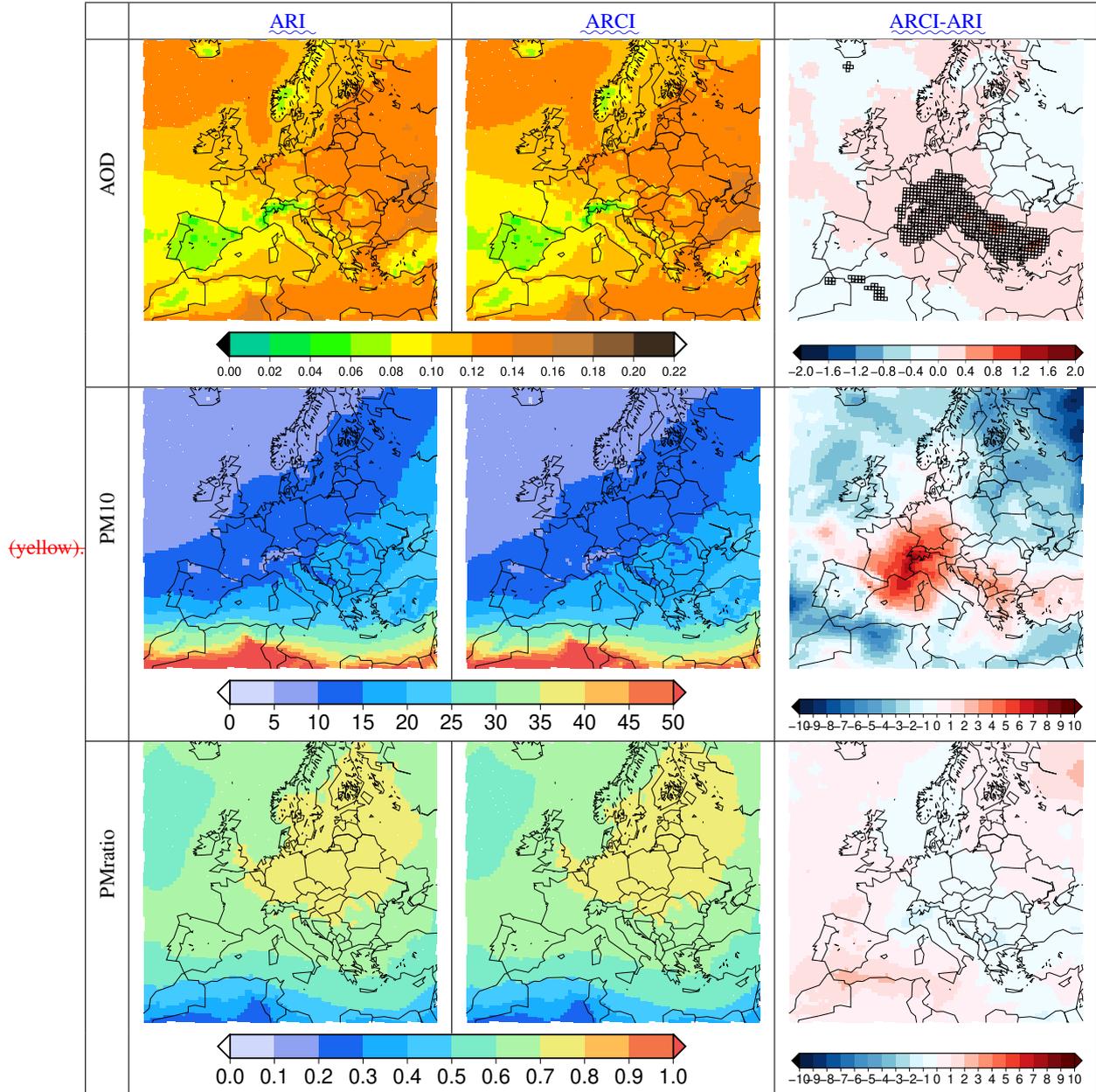
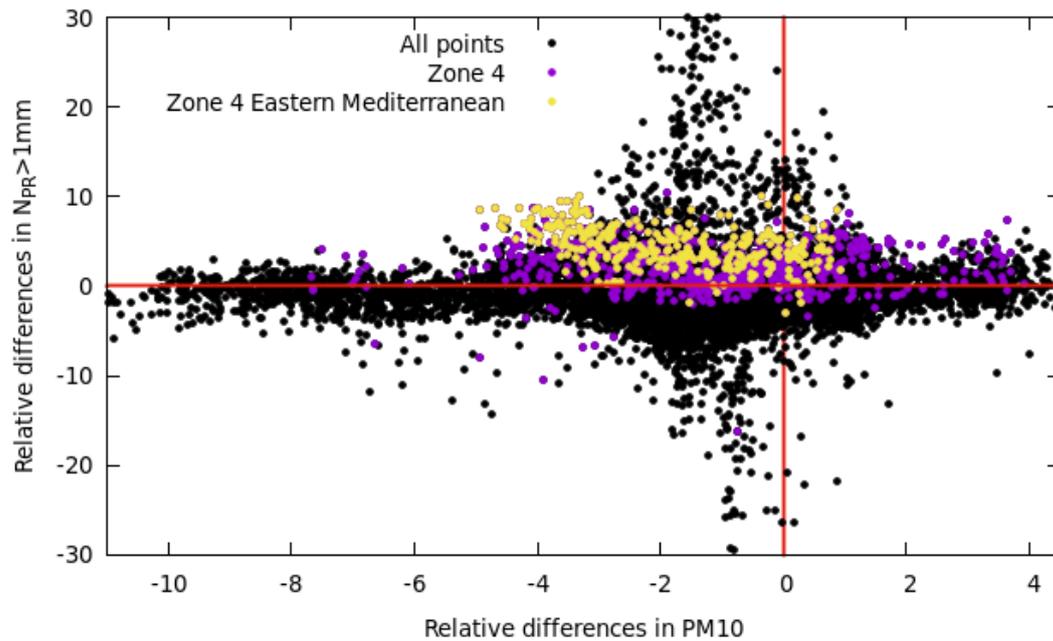


Figure 7. AOD, PM10 ( $\mu\text{g}/\text{m}^3$ ) and PMratio mean annual values for ARI and ARCI and their differences (%).



**Figure 8.** Number of days of precipitation > 1mm versus PM10 for all the cells of the domain (black), for Region 4 (violet) and Region 4 but only in the Mediterranean (yellow).