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Atmospheric Chemistry and Physics Discussions

Precipitation response to Aerosol-Radiation and Aerosol-Cloud Interactions in 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.

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 ACI, 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 spatially averaged precipitation 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 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. 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 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 western 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 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.

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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). The main tool 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. 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). 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) highlight that it is necessary to use regional climate/chemical coupled models to investigate ACI interactions in more detail. 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

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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. 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 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 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 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 episodical 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)).

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.

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2 Data and Methods

2.1 Experiments

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 prescribing AOD and CCN is defined as the BASE case (WRF simulations without ARI nor ACI interactions). Two additional scenarios including ARI and ACI are simulated in order to quantify the affects of these interactions. In the BASE experiment, aerosols are not treated interactively, but using the default WRF configuration which considers 250 CCN per cm^3 and sets 0.12 AOD to calculate the radiation extinction. 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 experiment includes the aforementioned ARI and, in addition, permits the use of aerosols estimated on-line to interact with the microphysics processes. The description of ACI as implemented in the simulations can be found in Palacios-Peña et al. (2020). Summarizing, ACI in WRF-Chem were implemented by linking the simulated cloud droplet number with the Lin (Lin et al., 1983) microphysics, 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 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; Rodrıguez et al., 2001; Goudie and Middleton, 2006) that are introduced to the inner domain through boundary conditions (Palacios-Peña et al., 2019). 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 (previosly described), another important parameterizations is related to radiation. The interactions of clouds and incoming solar radiation have been implemented by linking simulated cloud droplet number with the Goddard shortwave radiation 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 gas-phase chemical mechanism used in WRF-Chem is RACM-KPP (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 Optical Depth has been already extensively evaluated in Palacios-Peña et al. (2020).

The simulated historical period 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, beginning with the direct interpolation of the soil data of the reanalysis. This period was chosen in accordance with the results of Jerez et al. (2020). The boundary conditions were updated every 6 hours. Model outputs are recorded every hour. The evolution of greenhouse gases CO_2, CH_4 and N_2O were considered in accordance with the recommendation of Jerez et al. (2018).

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 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).

The statistical significance of the differences among the climatologies reproduced by the simulations is checked by using a Bootstrap method with 1000 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 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 are met is indicated inside each element of the matrix. The total

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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 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 (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). First, an analysis of principal components (Von Storch, 1999) is made, which is applied to the correlation matrix. 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 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 to a spatial region in this study).

3 Results and discussion

The sensitivity of precipitation to the aerosol treatment in climate simulations is analyzed by comparing BASE, ARI and ACI simulations over Europe during a 20 year period. The differences between ACI-BASE in spatially-averaged total precipitation are small, around 0.5%. Figure 2a shows the differences (percentage respect BASE) in the mean annual rainfall. The results depict a great 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 Mediterranean area, with increases up to 10% (although changes are not significant, $p> 0.05$). In the rest of the domain, there are other areas, such as the Iberian Peninsula, with a strong spatial variability (e.g. increasing rainfall on the Mediterranean coast and decreasing in the northeastern areas). Overall, the role of introducing ACI interactions leads to a spatial redistribution of precipitation. The differences between ARI and BASE simulations present a similar pattern (not shown).

In order to investigate the variations in the regimes of precipitation, the changes in the number of rainy days is estimated. Figure 2b shows the relative differences in the days with precipitation $>$ 0.1mm. The patterns of differences are 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) number of days implies less (more) precipitation. The analysis of the low clouds in the domain (Figure 2c)

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shows a pattern similar to the aforementioned patterns. This may indicate that both the 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.

Regarding the added value of incorporating aerosol physics into the model has been evaluated 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). Overall, WRF-Chem (both in the BASE and ACI 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 simulations slightly reduce the differences in the spatial distribution. However, the differences between ERA5 and ACI are much larger than the differences between ACI and BASE (not shown).

Despite this, as previously noted (Figure 2a-c), the ACI 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 order to understand the contribution of the different types of aerosol the differences in precipitation 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 (AOD), as well as the spatial extension of the event.

Figure 3 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 3a shows the relative changes (ACI-BASE) in the number of rainy days for different sets of episodes, selected by choosing the extension (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 3b-e show these relationships for the different variables.

The lower left box of Figure 3e would indicate 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 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 case of the PMratio (Figure 3e), the higher the intensity the greater the reduction in the number of rainy days; and the greater the extent 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 3b), the results show that higher AOD550 values lead to a lower reduction in the number of rainy days. However, in this case the changes are small (under 2%) and the relationships are not clear (R = 0.40). Results are analogous for PM2.5 (Figure 3c). However, relationships with the PMratio (Figure 3e) are important and significant. 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 physical explanation for this behavior in this area is that the higher the PMratio, the greater the concentration of small particles that change the properties of the clouds, mainly the low clouds (Figure 2c, reduction of low cloudiness over Central

Europe) making 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.

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 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 4. The regions are listed attending to the number of grid cells of each group, being the most numerous and also the most dispersed the Region 1. The centroid series (average series of regions) are represented in Figure 5. The filled circles (green) indicate that the relative differences between the ACI and BASE experiments are significant.

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, 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%, the differences for small 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).

Regions 3 and 4 have a different behavior. In these regions an increase in precipitation occurs when including ACI. Region 3 does not have a clear spatial pattern, with points scattered along the entire domain. For low thresholds there are hardly any 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%. Finally, Region 4 shows a clear spatial pattern, with most of the points concentrated in the Eastern Mediterranean. In 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 in a different manner. Over regions 2 and 5, which cover northern, central and eastern Europe, 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 Mediterranean, rainfall increases with the introduction of ACI, 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.

In order to better understand the processes involved in each of the areas, the differences between ACI and ARI are analyzed. This will permit discriminate which, aerosol-radiation or aerosol-cloud interactions, processes are most relevant. Figure 6a-c shows the differences in ACI-BASE, ARI-BASE and ACI-ARI analyzing precipitations surpassing 1 mm/day. In the case of

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Region 5, both simulations give us 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 6d). This inhibits convection and therefore, a reduction in cloudiness. On the other hand, the higher concentration of small particles modifies 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 6d), 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, 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 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 6c).

Finally, Figure 6f shows the relative differences between PM10 concentrations between ACI and ARI. The spatial pattern shows an area of positive differences over Central Europe and the western Mediterranean, except for the western Iberian Peninsula. Conversely, negative differences prevail in the rest of the domain; that is, the ARI simulation has lower concentrations of PM10. Therefore, in Region 4 the increase in precipitation and cloudiness is associated with a decrease in PM10. In order to clarify this analysis, Figure 6g shows the relative difference in the concentration of PM10 between ACI 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 changes in precipitation and a decrease in the PM10. If focusing only on Zone 5, Eastern Mediterranean (yellow points) the relationship 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 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 counted in PM10 since of in-cloud scavenging. Therefore, a decrease in PM10 occurs 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 6e & 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.

4 Conclusions

The effect of aerosols on regional climate simulations still presents many uncertainties due to their complex and non-linear interactions that depends on a wide variety of factors. The quantity, size and color of aerosols modify the radiative balance and, therefore, many other derived variables such as local temperature, cloudiness or precipitation. In addition, the amount of moisture available will determine the size of the water droplets based on the amount and type of aerosols available. The size and color of the clouds will be affected, which will once again affect the radiative budget. In addition, this can spatially redistribute precipitation regimes, allowing it to rain in different areas or provoking rainfall intensity to change. However, there

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is a lack of contributions that have studied these problems and the large increase in computational time needed to include ACI and ARI interactions in regional climate simulations have traditionally hampered the works covering this analysis from a climatic perspective.

In order to address these issues, a set of regional climate simulations have been conducted for the period 1991-2010 without aerosol-atmosphere interactions (BASE), with ARI and with ACI parameterizations 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.

When introducing the ACI and ARI interactions, the spatial average of the total rainfall does not vary too much from the BASE scenario. However, there is a spatial redistribution of such precipitation. Although there are changes in many places in the domain, the largest occur in the area of central Europe, where a decrease in precipitation is found as a result of activating the aerosol–radiation and aerosol-cloud interactions. Conversely, the behavior is the opposite in the eastern Mediterranean. 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.

When the results are compared with ERA5, BASE simulation tends to overestimate rainfall across the domain except in 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 this improvement is small.

The results obtained for the number of precipitation days > 0.1mm 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 Europe, in the linear regime, the intensity and size of the PMratio events have a direct relationship with the increase in the differences in the number of rainy days.

The previous conclusion is limited to the number of days of precipitation greater than 0. 1mm and it is interesting to check the relationship for other thresholds. Analyzing several precipitation thresholds, five types of behavior throughout the target domain were identified: aerosols contribute positively or negatively to precipitation depending on the area and intensity of precipitation. The available humidity, the competence of the CCN and the type of aerosol (size, color, shape) are the most important factors conditioning one type of behavior or another. In the experiments conducted, the inclusion of ACI 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 < 5mm/day. For Region 3, which is a very dispersed area, there are also positive changes for moderate and strong rainfall regimes. There rest of areas are almost not 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 with respect to the ARI experiment because of in-cloud scavenging.

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Concluding, the effect of aerosols on climatic variables is varied and complex and more studies on this topic are needed to reduce the uncertainty associated with the inclusion of aerosols in regional climate experiments as well as a best understanding of the physical processes leading changes in precipitation.

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.

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

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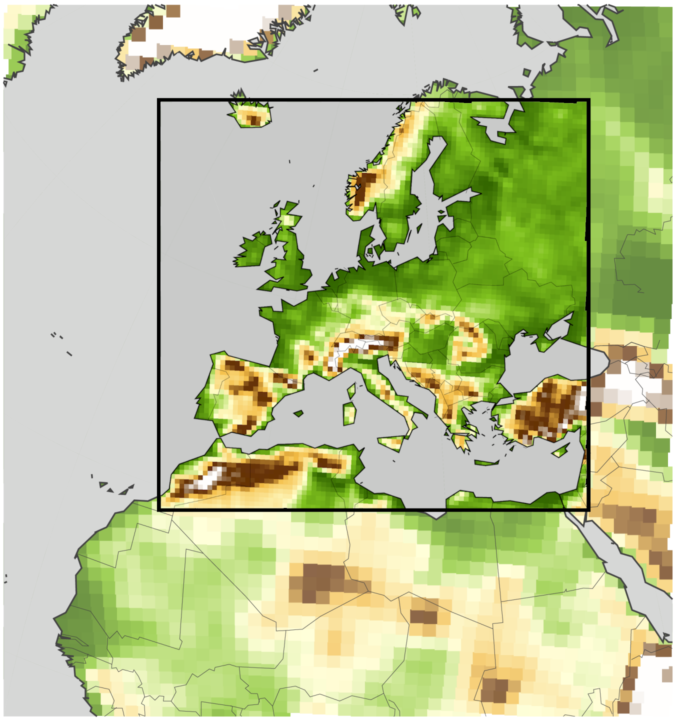

Figure 1. Simulation domains covered in the experiments. The inner Euro-CORDEX domain is boxed in the Figure.

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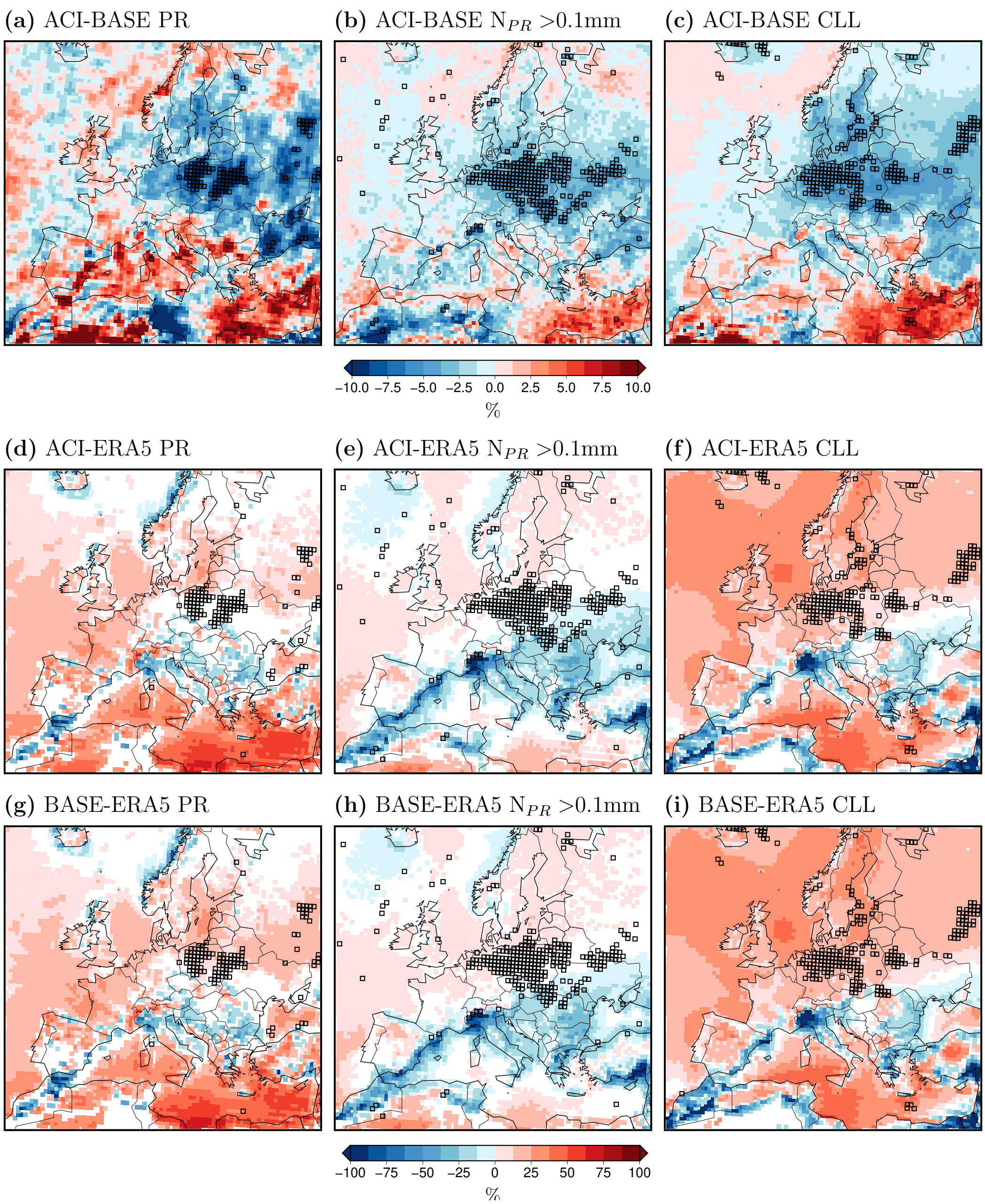

Figure 2. (Top row) Relative differences for precipitation between ACI and BASE experiments (a); number of days of precipitation > 0.1mm (b); and low clouds (c). Squares indicate points whose differences are significant for a p-value of 0.05. (Second row) Significant relative differences (colors) between ACI and ERA5. (Third row) Id. second row for BASE-ERA5. In both rows, the squares indicate $p < 0.05$ for the ACI-BASE difference (top row). The analysis has been conducted for the mean values of the period 1991-2010.

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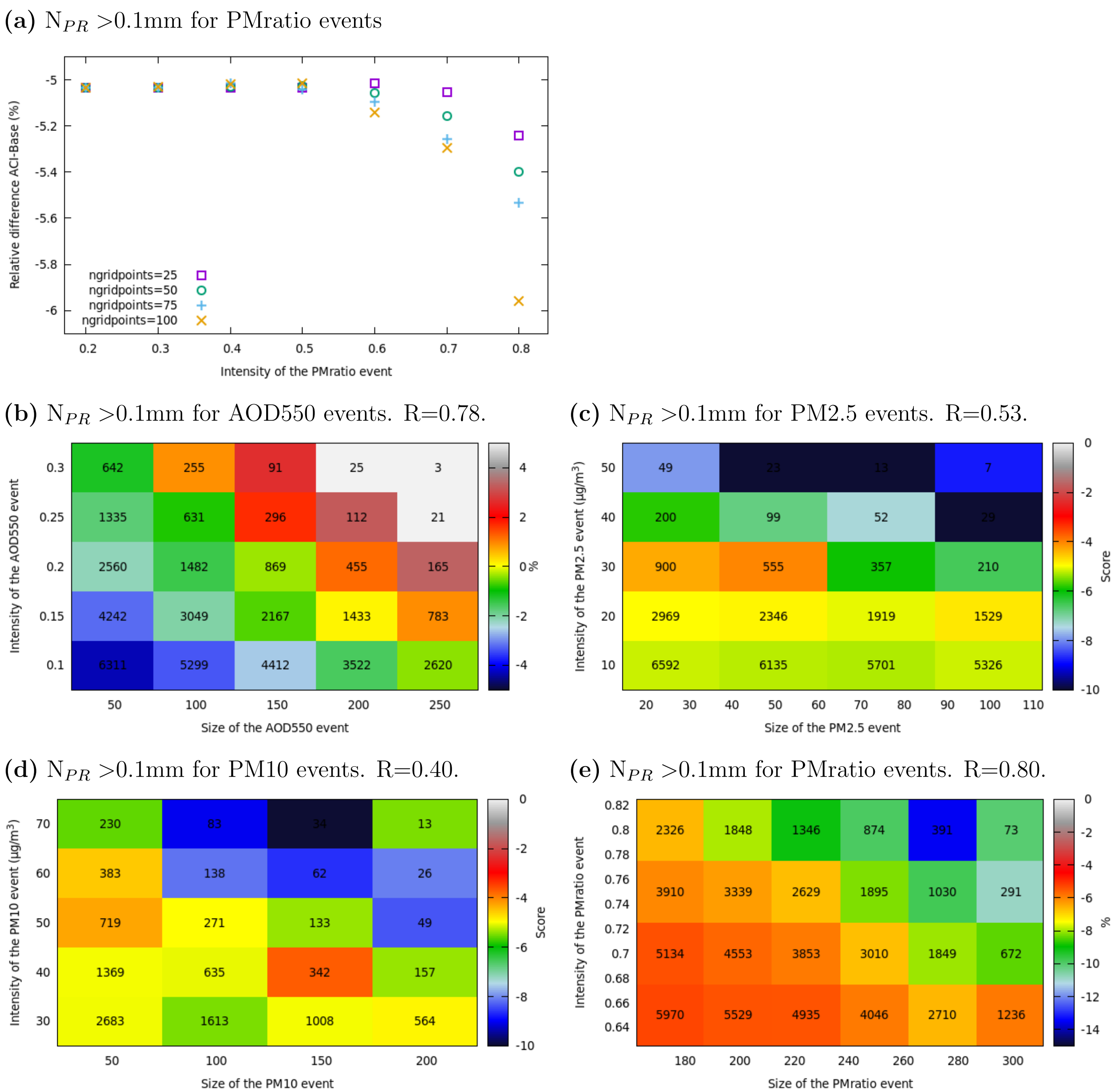

Figure 3. Relative difference (colors) in the ACI–BASE simulations for the 1991-2010 period based on (b) the intensity and size of AOD550 events, (c) the intensity and size of PM2.5 events, (d)for events of PM10 and (e) for those of PMratio. The calculation is made for the domain cells with significant ACI-BASE 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 3a (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 adjustment of those values.

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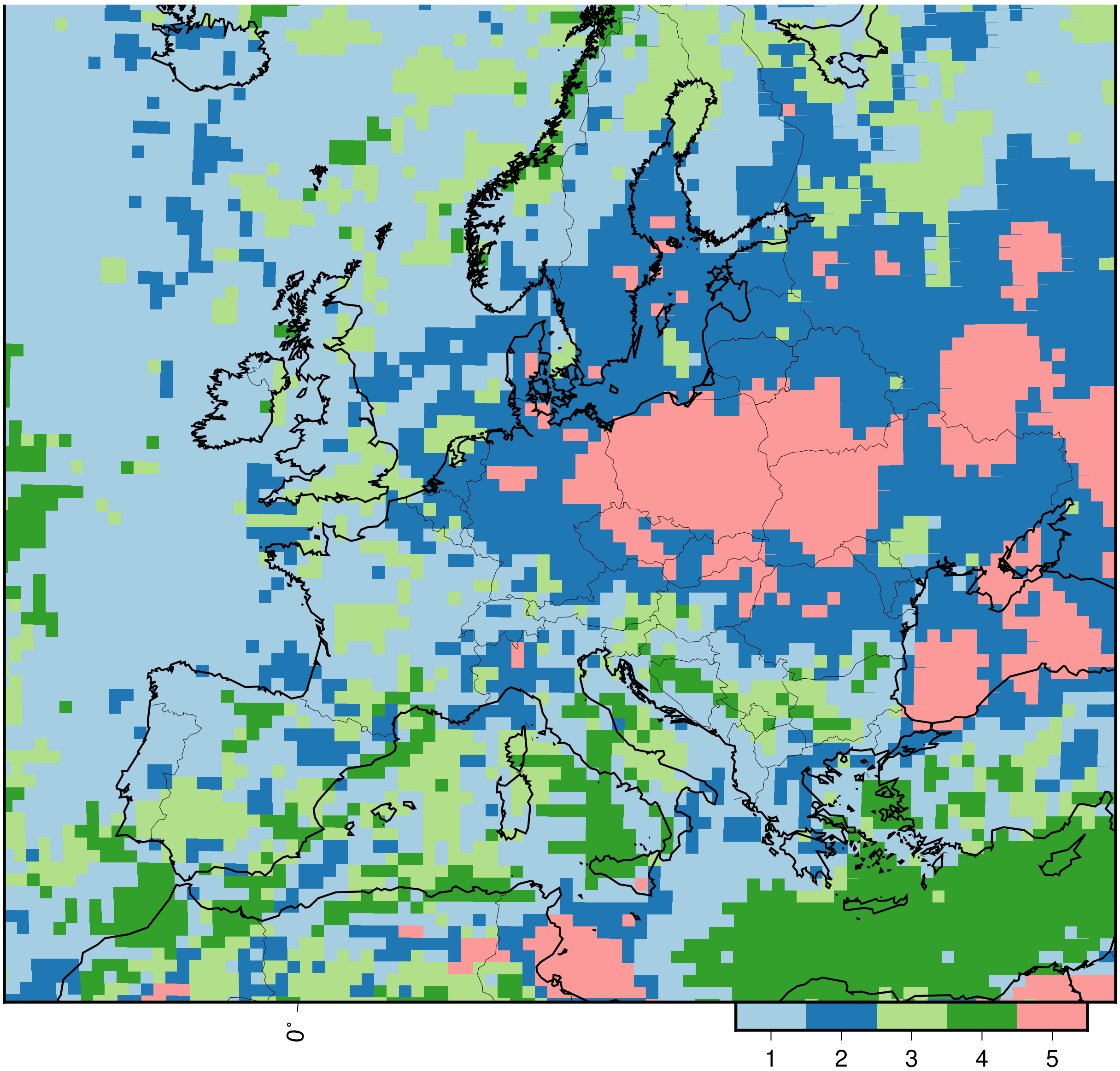

Figure 4. Cluster analysis of rainy days: each color depicts a cluster with different temporal variability for the time series of the relative difference (ACI-BASE) in number of days of precipitation over a threshold running from 0.1mm to 20mm/day for the period 1991-2010.

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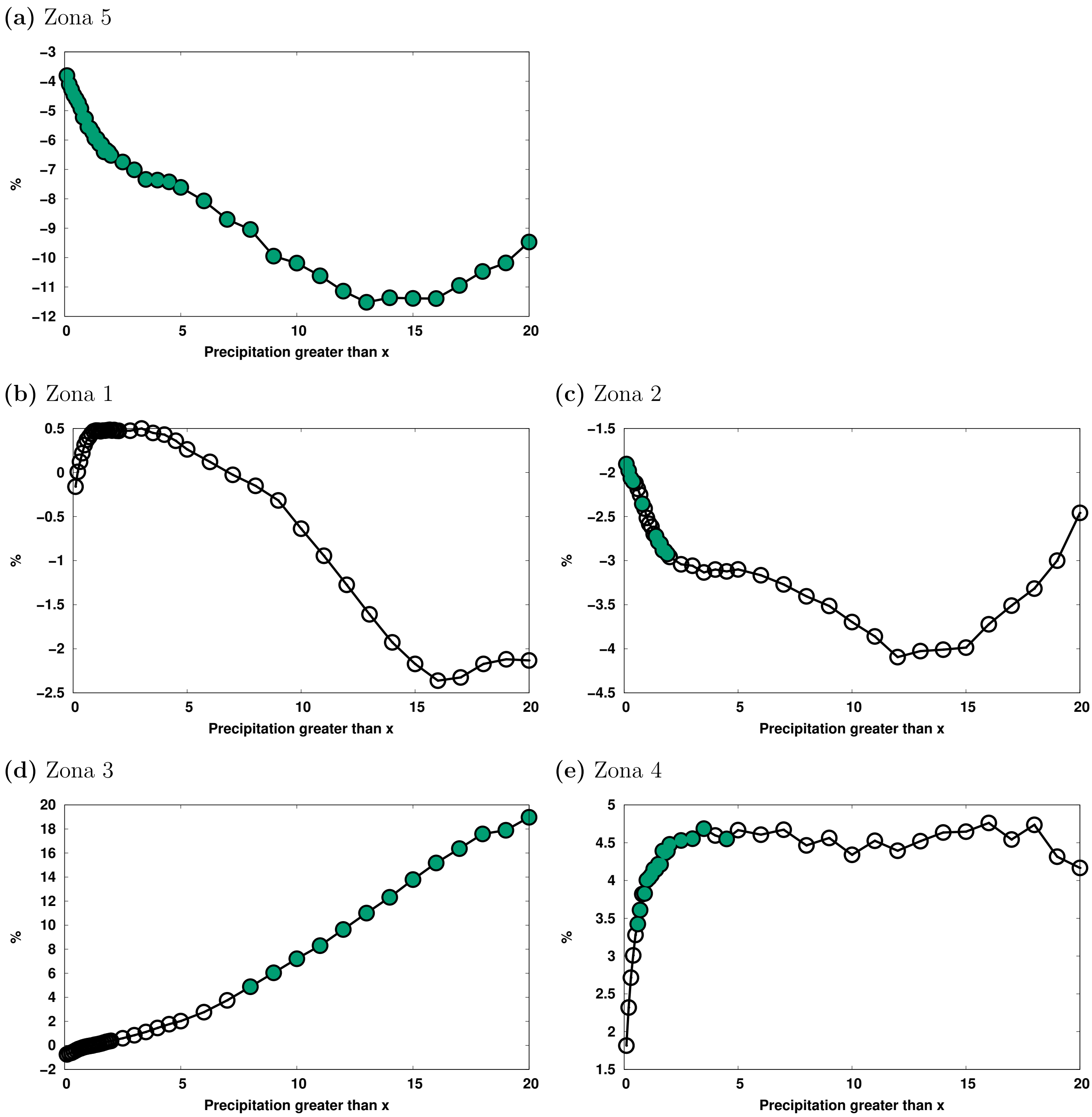

Figure 5. Series of relative differences between ACI and BASE based on different thresholds in rainy days for the different regions (Figure 4). Green circles denote the thresholds for which the differences are significant (p-value < 0.05).

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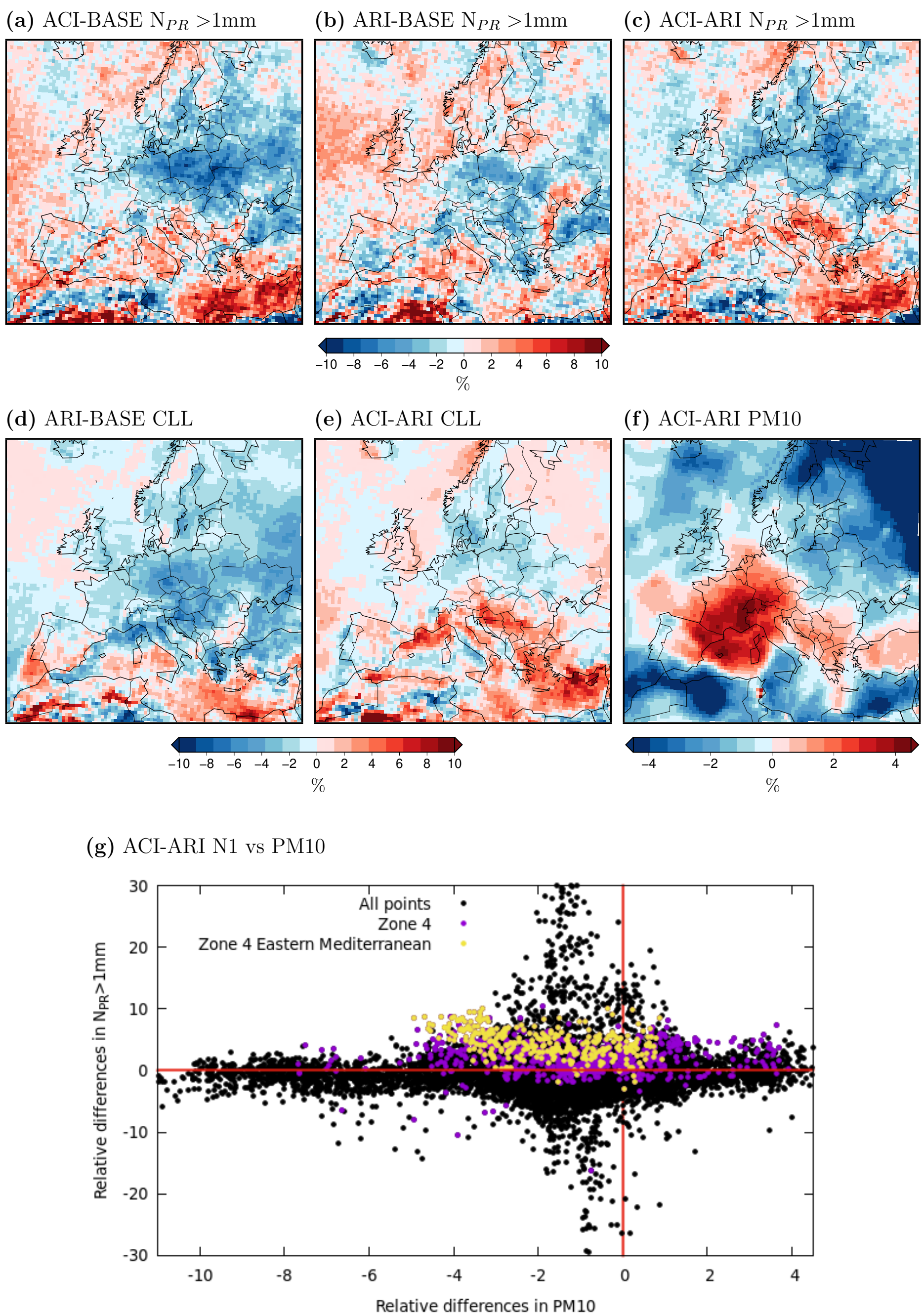

Figure 6. Relative differences for the number of days with precipitation > 1mm between: (a) ACI and BASE, (b) ARI and BASE, (c) ACI and ARI. Relative difference for low clouds between ARI and BASE (d) and ACI and ARI (e) (The ACI-BASE difference presented in Figure 2c). Panel (f) shows the relative differences 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 (yellow).