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 ARI+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 time-mean spatially averaged precipitation over the whole domain 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 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 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 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 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 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.

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.

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. 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 (Huang et al., 2007; Khain et al., 2008; Stevens and Feingold, 2009; 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); Pavlidis et al. (2020) highlight that it is necessary to use regional climate/chemical coupled models to investigate ACI interactions in more detail. These studies covert 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 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 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 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 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.

2 Data and Methods

2.1 Experimental setup

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. The first experiment, BASE, consist in prescribing AOD and CCN 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.

In the BASE experiment, aerosols are not treated interactively, but using the default WRF configuration which considers 250 CCN per cm^3 and 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 ARCI experiment includes the aforementioned ARI and, in addition, permits aerosols to interact with the microphysics processes. The description of ARCI as implemented in the simulations can be found in Palacios-Peña et al. (2020) as well as validation of the AOD fields. Summarizing, 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 in Figure 1). The inner domain is compliant with Euro-Cordex recommendations (Jacob et al., 2014). It covers Europe with a spatial resolution of 0.44º 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 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 micro-physics (Lin scheme), another important parameterization is related to radiation. The interactions of aerosol and clouds with incoming solar radiation have been implemented by linking simulated cloud droplet number with the 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).

As mentioned above, aerosols are treated online, i.e. the model creates the aerosols departing from antropogenic 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 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 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 (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. After removing the spinup-up period, which was chosen in accordance with the results of Jerez et al. (2020a), the model outputs are merged. This methology 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_2, CH_4 and N_2O were incorporated as recommended in Jerez et al. (2018), varying CO_2 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 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 addtion, the comparison of the annual and seasonal climatologies for other atmospherics fields such as sea level pressure (slp), geopotential (z) height and temperature (T) at 1000,750 and 500mb, maximum minimum temperatures (tasmax,tasmin), dayly 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 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 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-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 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 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 ARCI simulations over Europe during a 20 year period. The differences between ARCI-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 ARI and ACI interactions leads to a redistribution of the annual precipitation. The most remarkable difference is a reduction of annual precipitation over central Europe for ARI that os enhanced when ACI interactions are included, being more intense and extensive. This reduction of precipitation is linked mainly to a reduction of the number of days with precipitation larger than 0.1mm (N_{p01}) and clouds at low level (CLL) . In fact the most significant and widespread changes are obtained for CLL. In addition a statistical 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) the decrease of precipitation, CLL and N_{p01} in central Europe is reproduced all seasons but for summer. While the increase in Eastern mediterranean is reproduced along the whole year being stronger at winter. These changes are also related to other changes in variables. RSDS decreases in ARI and ARCI experiments mainly over the half Southern part of the domain, due to the higher AOD. However there is some parts of central Europe where rsds become larger due to the increase of clouds specially in Autum and Spring. Changes in temperature are opposite for tasmax and tasmin, reaching differences around 0.5K with spatial patterns quite similar to those CLL. The most remarkable changes are obtained for DTR with a pattern characterized by a important increase in de North (less CLL) and a decrease in the south (bigger AOD). The modification of energy fluxes also affect circulation. The SLP fields as well as geopotential heigth (Z) at several levels also shown statistical significant sensitivity to ARI and ACI effects. Here the most remarkable features are strong differences between ARI and ARCI experiment. ARCI shows a important increase of slp in central and northen part of the domain respect ACI. This behavior is also appreciated for Z. Finally, just mention that ARI and ARCI also simulate a rise in the temperature in the Northen and central Europe. This could imply that simulated changes in precipitation can also be indirectly affected by changes in atmospheric circulation. This fact could even make more difficult to relate the changes in precipitation with 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 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) 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 **??**). Overall, WRF-Chem (both in the BASE and 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, ARCI simulations slightly reduce the differences in the spatial distribution. However, the differences between ERA5 and ARCI are much larger than the differences between ARCI and BASE .

Despite this, as previously noted (Figure 2a-c), the 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 changes in the dynamics. 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 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 (ARCI-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 4b-e show these relationships for the different variables.

The lower left box of Figure 4e 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 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 case of the PMratio (Figure 4e), 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 4b), the results show that higher AOD550 values lead to a lower reduction in the number of rainy days. The changes are small (under 2%) although the relationship is clear (R = 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=0.4) 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 posible physical explanation for this behavior in this area is that the higher the PMratio (Figure **??**), the greater the concentration of small particles that change the properties of the clouds, mainly the low clouds (Figure 2, 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 (direct and semidirect effects). As noted in Figure 2 the reduction of CLL also occurs in ARI experiment, this could be explained by the atmosphere warming due to aerosol radiation absorption (black carbon) that causes the effect exposed above. The stronger signal in ARCI can be attributed to the addition of both proceses. On the other hand, a high concentration episode of PM2.5 can occur together a PM10 event, decreasing the PMratio. Therefore the better relationship with PMratio could be related to giant aerosols enhancing precipitation, and thereby opposing the effect of smaller aerosols.

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 5. 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 6. The filled circles (green) indicate that the relative differences between the ARCI 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 Figure 2).

Regions 3 and 4 have a different behavior. In these regions an increase in precipitation occurs when including ARCI. 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%. However this result should be interpreted 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).

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, 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 Mediterranean, rainfall increases with the introduction of ARCI, 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 ARCI and ARI are analyzed in terms of the concentrations of PM10 PM2.5 and PMratio (Figure 7). This will permit discriminate which, aerosol-radiation or aerosol-cloud interactions, processes are most relevant. As comennted above Figure 4 shows the differences in ARCI-BASE, ARI-BASE and ARCI-ARI analyzing precipitation (number of days surpassing 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 a reduction in the number of days of precipitation. Therefore, both ARI and ACI affect precipitation in the same direction. ARI causes an increase of temperature at low levels (see SM T850) specially at Autum and Spring that leads a reduction on clouds and precipitation. The effect of ARCI is to enhance this effect by the higher concentration of small particles that modifies the properties of the clouds, inhibiting precipitation processes again by reducting clouds due to microphysis processes, since this area there is a prevalence of small aerosols (see PMratio in Figure 7 and SS).

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. This is case of the area of Balkans where whole ARI effect tends to decrease precipitation, ACI tend to increase, being the net effect (ARCI) almost nule (see Figure 2) . This behavior can be attributted to the different role of small and big aerosols. While small particles inhibit the formation of clouds by semidirect effecs, large aerosols ease the cloud formation and precipitation by indirect effects. Note that over that area there is an increase of large particles (PM10) and a statistical significant increase of AOD (see Figure 8. Conversely, negative differences prevail in the rest of the domain; that is, the ARI simulation has lower concentrations of PM10.

Finnally, the increase in precipitation and cloudiness in Region 4 could be associated with larger values of PM10 (big condentation nuclei). In this case ARI effects are almost negligible along the year. However ARCI experiment shows a clear positive difference respect the Base case and ARI. Figure 7 shows the relative difference in the concentration of PM10 between 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 changes in precipitation and a decrease in the PM10. If focusing only on Eastern Mediterranean of cluster 4(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 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 ARCI 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 8). This can be attributed to the displacement of the cloud masses in such area. This behaviour can be attributed of the role of giant aerosol particles in warm rain initiation Johnson (1982), increased precipitation in stratiform precipitation by dust through deposition growth Gong et al. (2010) or the enhnaced drizzle formation in stratocumulus Feingold et al. (1999).

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 optical properties 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 optical properties 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 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 ARI+ACI (ARCI) 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. 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 suplementary material.

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 where that the aerosol-cloud interactions prevails. 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 not clear.

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 quantitatively 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 efficiency of the CCN and the type of aerosol (size, optical propèrties, shape) are the most important factors conditioning one type of behavior or another. In the experiments conducted, the inclusion of ARCI 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. Also we found that some areas (Region 3, which is a very dispersed area) there are also positive changes for moderate and strong rainfall regimes. Although this finding can be identified with some studies some times named the deepening effect Stevens and Feingold (2009) that relate the role of aerosols with an increase of precipitation for some convective events, it should be taken with caution because of the lack of spatial structure of this cluster. The rest of areas are almost not affected.

Some of the obtained changes can be explained as direct, semidirect and indirect effecs of aerosols on clouds. The reduction of precipitation could be linked to both; atmosphere warming and excess of CNN. The radiative processes have the ability to change the thermodinamic environment, due to the radiation abosorption by small particles (mainly black carbon), stabilizing the environment or increasing de condensation level. The excess of CNN leads to small drops producing a precipitation depletion. In principle this would increase the lifetime effect, however our experiments show a extra depletion of cloudness, probably related to a faster evaporation of water drops. All these processes are associated with a high small particles concentration respect big ones. On the other hand, the effects of large aerosols (PM10, giant condensation nuclei) seems to be totally opposite. These particles seems to enhance the precipitation proceses, specially increasing light precipitation events Feingold et al. (1999) or anticipating precipitation development. Sometimes both processes (semidirect and indirect) overlap being the net effect null.

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. This work demostrates 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 some of the are in agrement with other works Li et al. (2019) The inclusion in regional climate experiments of online aerosols simulations 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 aproximations 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 increse efforts to understand the role of regional and large scale circulation (regimes), possible feedbacks and overlapping proceses.

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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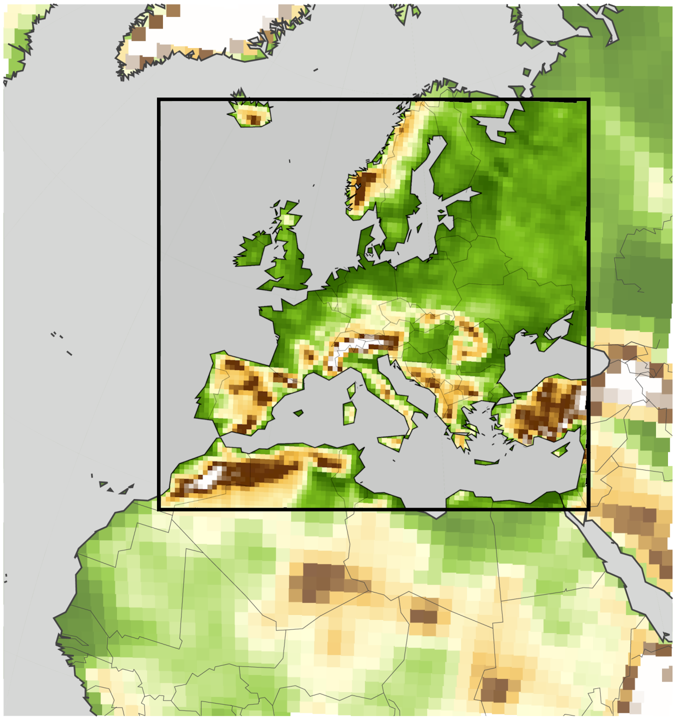

Figure 1. Simulation domains covered in the experiments. The inner Euro-CORDEX domain is boxed in the Figure.

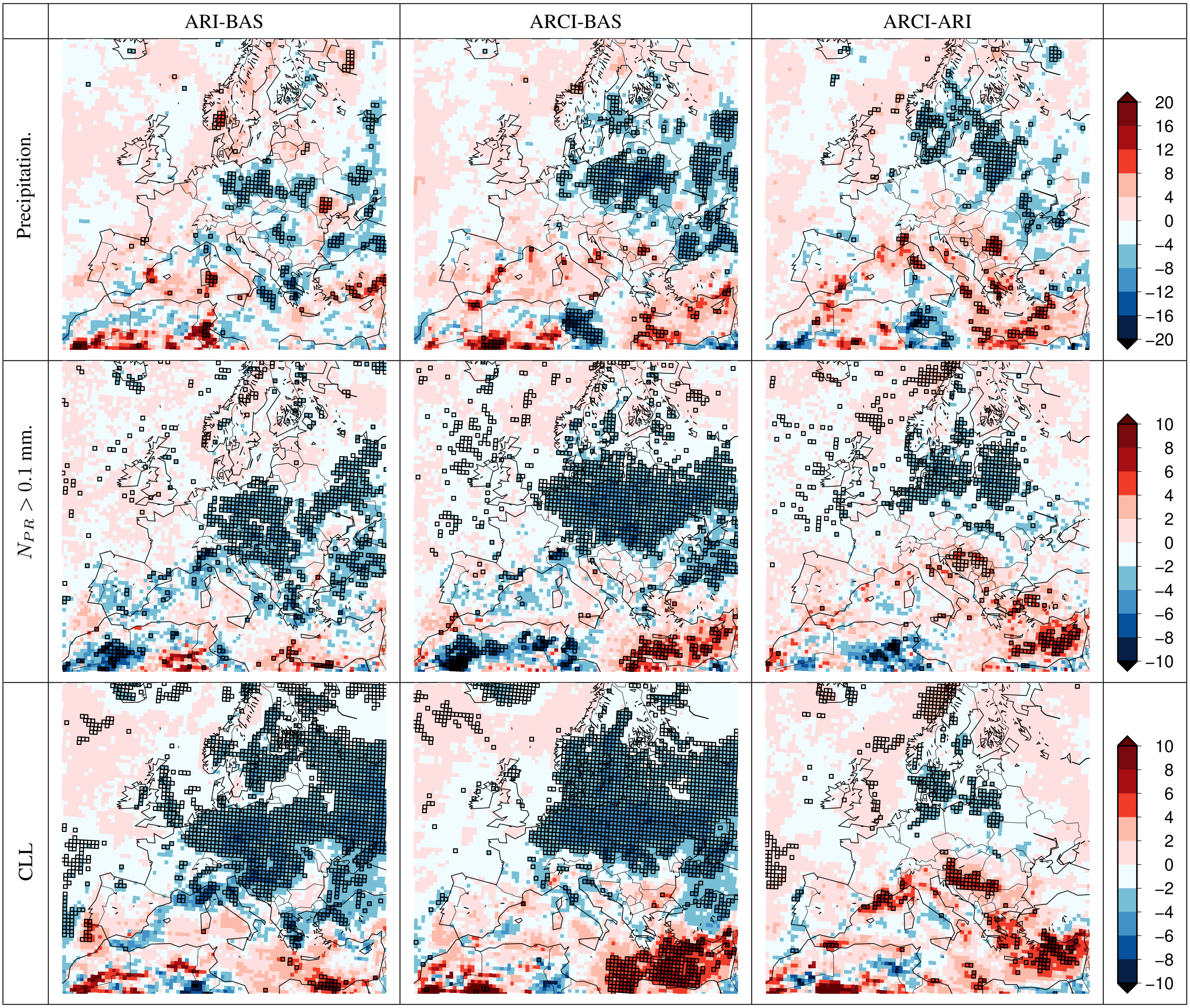

Figure 2. Relative differences for precipitation between ARI and BASE (first column), ARCI and BASE (second column) and ARCI and ARI (third column), total precipitation (first row) number of days of precipitation > 0.1mm (second row) and low clouds (Third row). Squares indicate points whose differences are significant for a p-value of 0.05.The analysis has been conducted for the mean values of the period 1991-2010

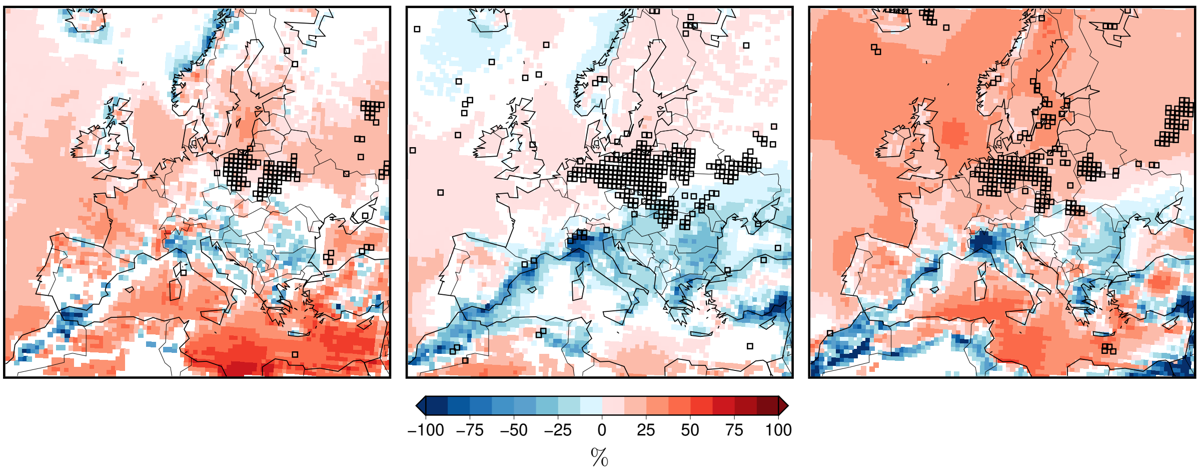

Figure 3. Significant relative differences (colors) between ARCI and ERA5. Squares indicate statistical significant differences ($p < 0.05$). The analysis has been conducted for the mean values of the period 1991-2010.

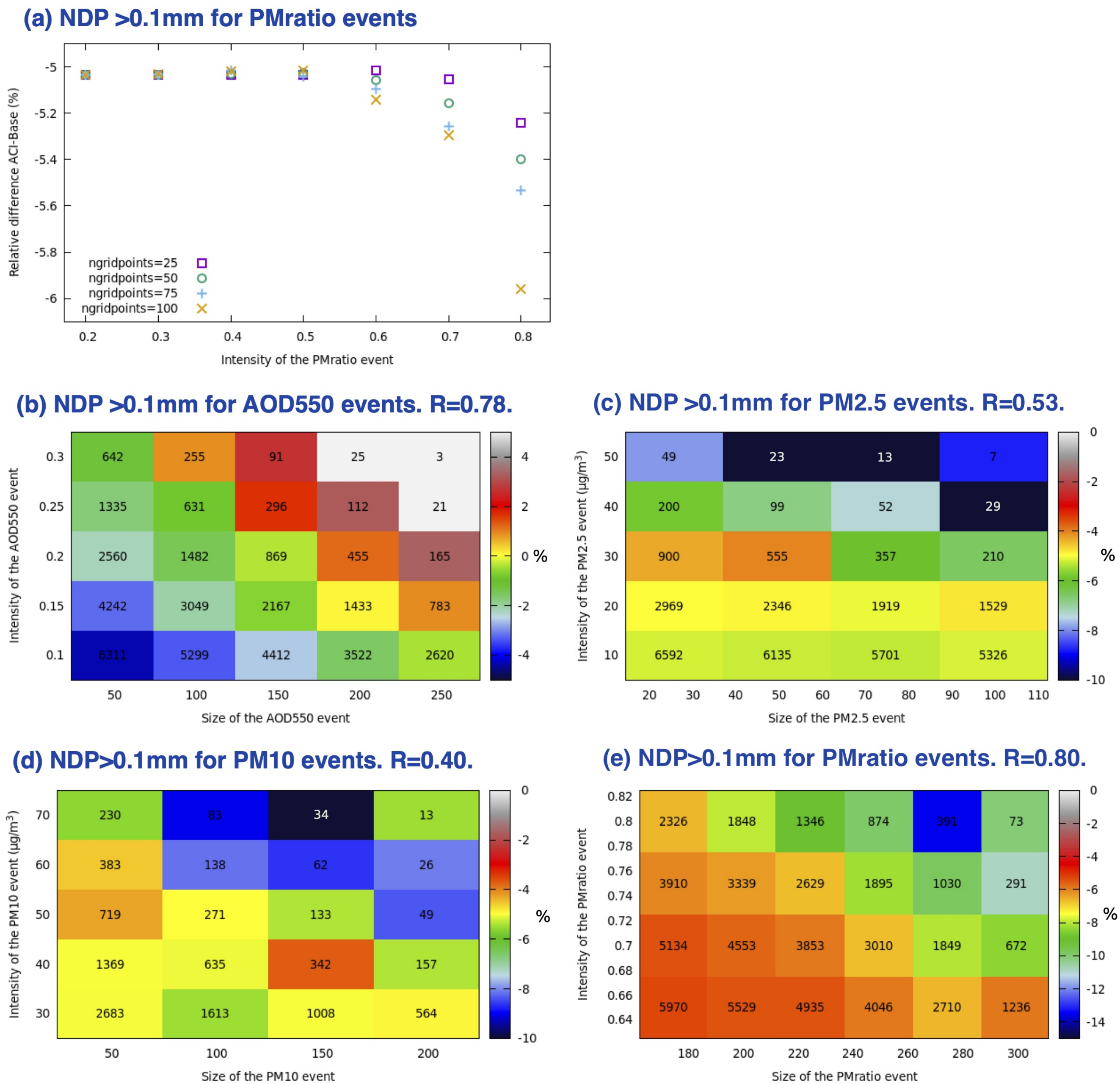

Figure 4. Relative difference (colors) in the ARCI–BASE simulations for the 1991-2010 period based on (b) the intensity and size of AOD550 events, (c) the intensity and size of PM2.5 events, (d)for events of PM10 and (e) for those of PMratio. The calculation is made for the domain cells with significant 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 adjustment of those values.

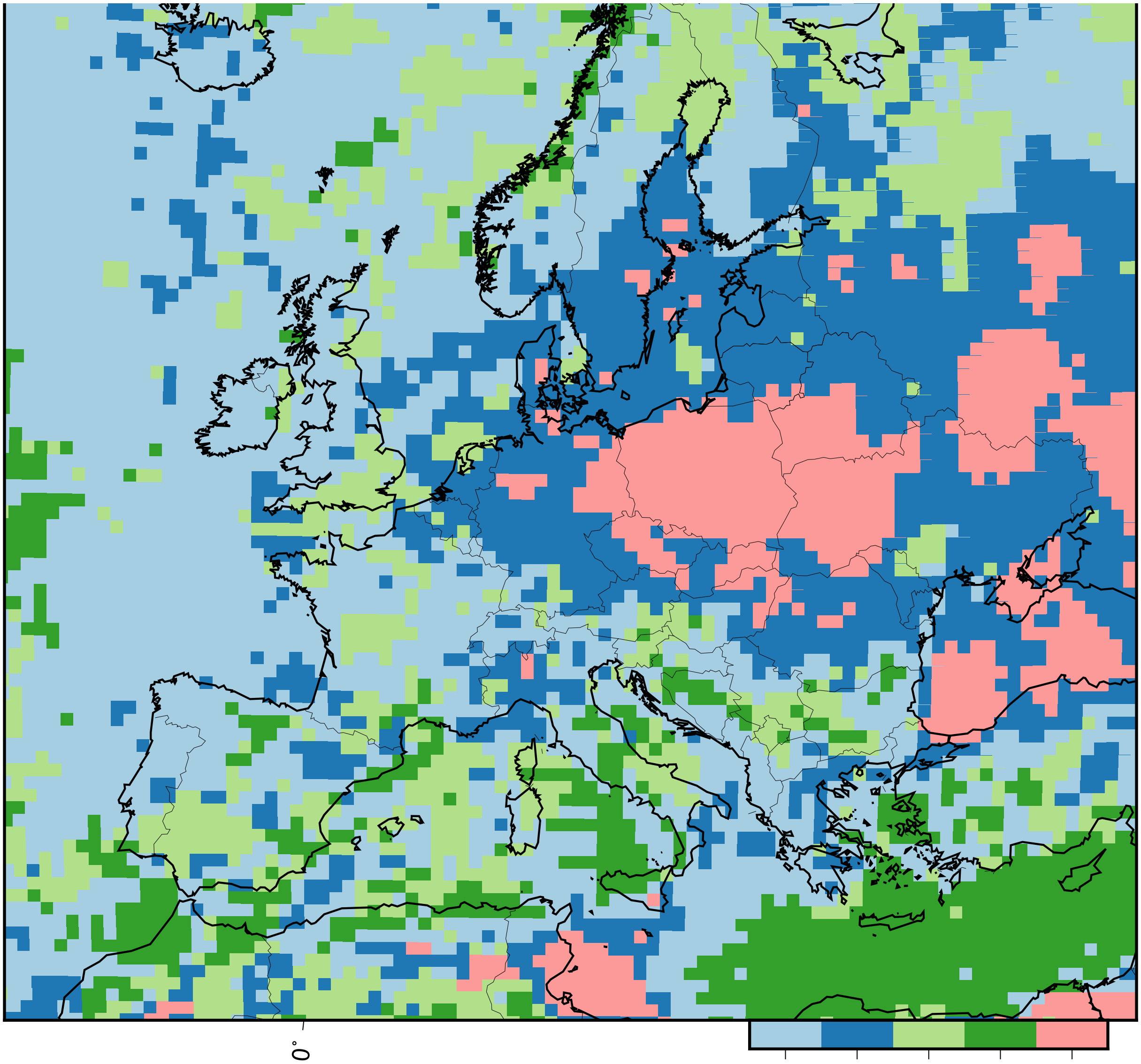

Figure 5. Cluster analysis of rainy days: each color depicts a cluster with different behaviour of the ARCI-BASE difference in number of days of precipitation over a threshold running from 0.1mm to 20mm/day for the period 1991-2010.

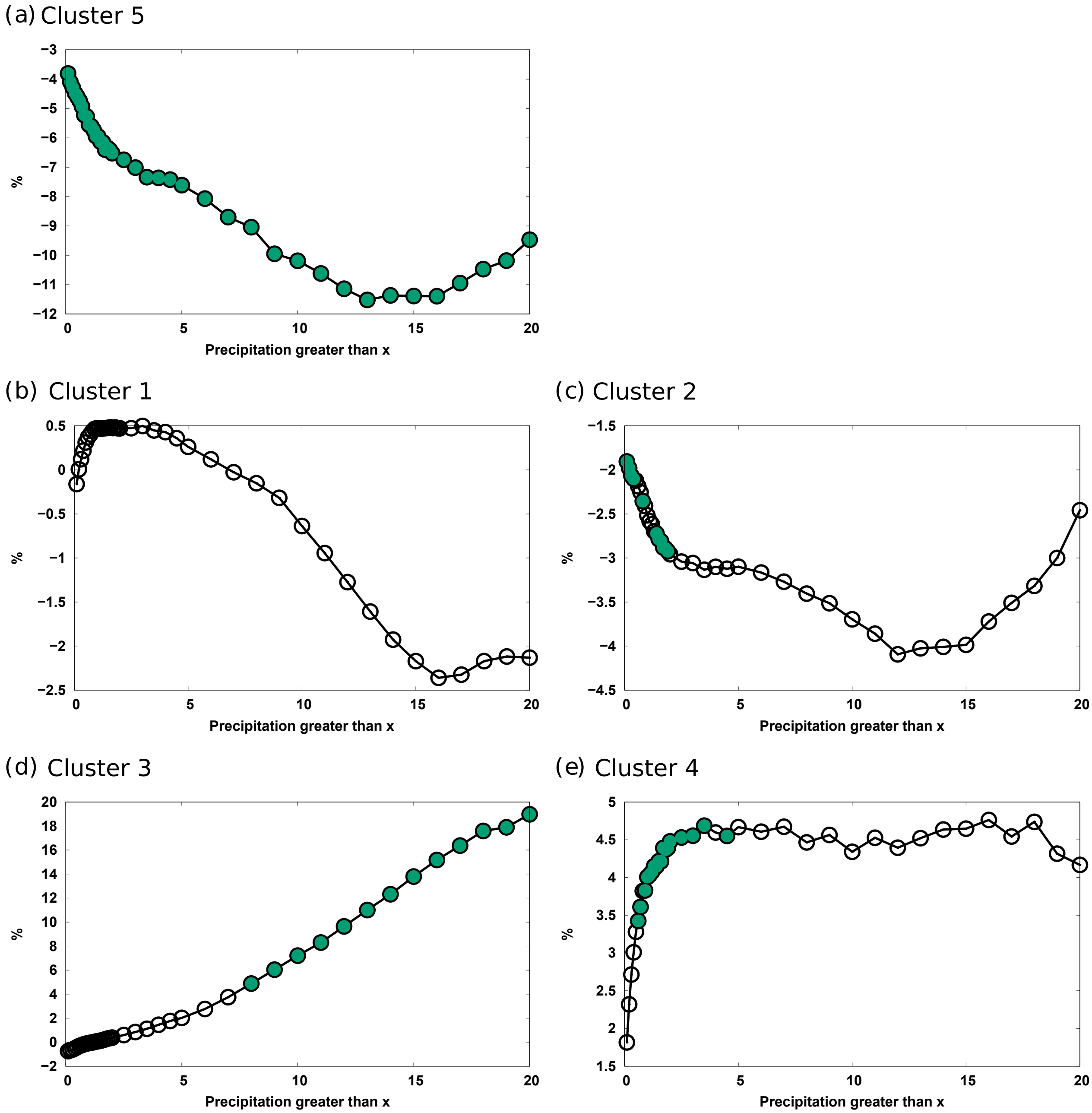

Figure 6. Series of relative differences between ARCI and BASE based on different thresholds in rainy days for the different regions (Figure 5). Green circles denote the thresholds for which the differences are significant (p-value < 0.05).

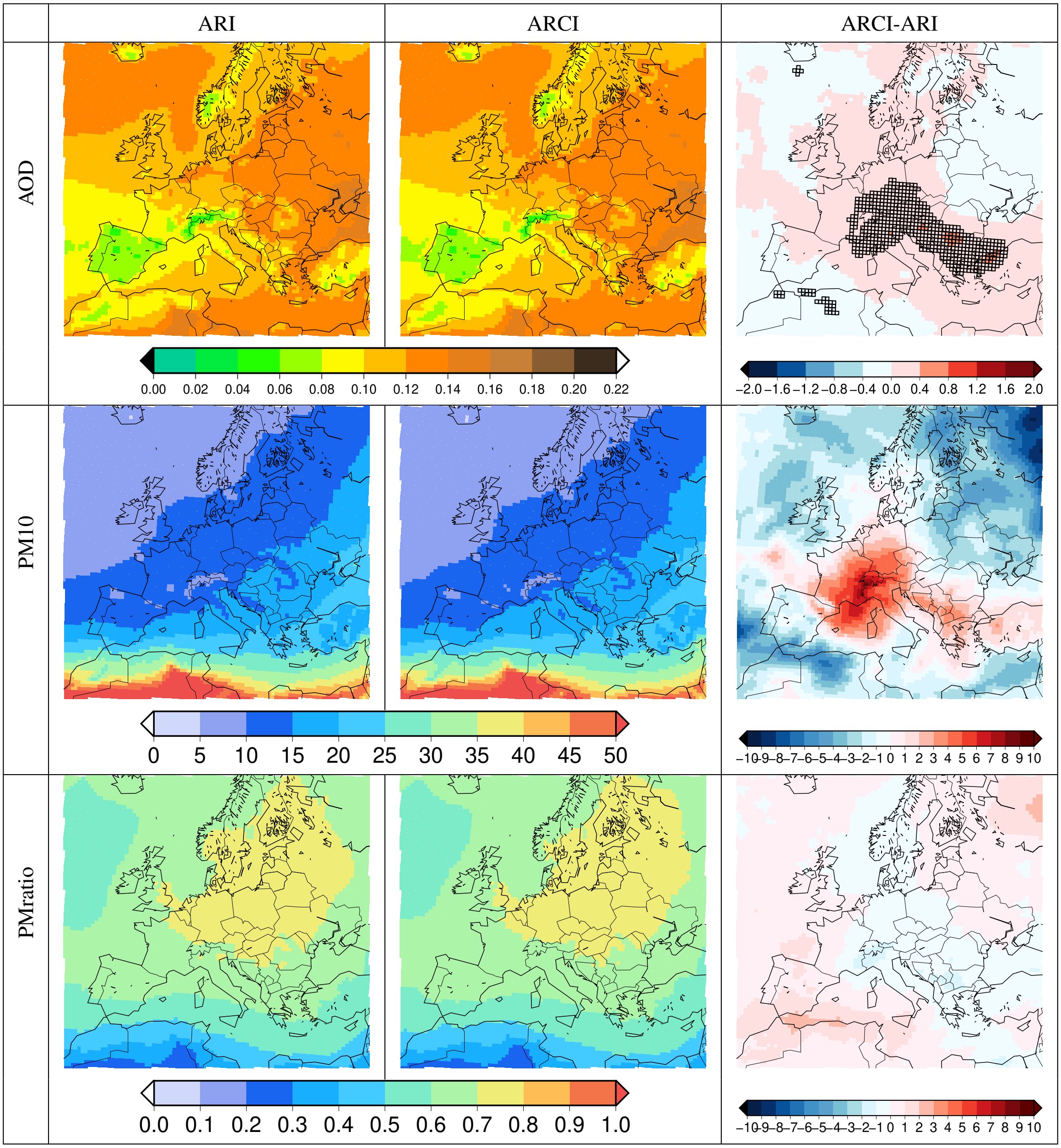

Figure 7. AOD, PM10 ($\nu g/m^3$) and PMratio mean annual values for ARI and ARCI and their differences (%).

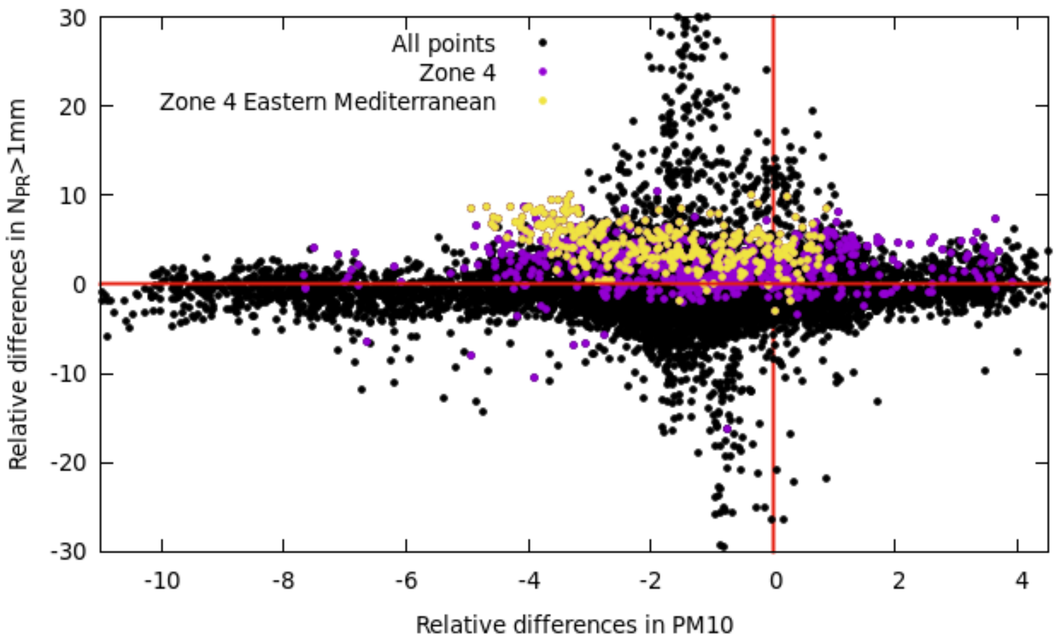

Figure 8. Number of days of precipitation > 1mm versus PM10 for all the cells of the domain (black), for Region 4 (violet) and Region 4 but only in the Mediterranean (yellow).