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

Sonia Jerez[1*], Laura Palacios-Peña[1], Claudia Gutiérrez[2], Pedro Jiménez-Guerrero[1], Jose María López-Romero[1], Juan Pedro Montávez[1]

(1) Regional Atmospheric Modeling (MAR) group, Department of Physics, University of Murcia, 30100 Murcia, Spain
(2) Environmental Sciences Institute, University of Castilla-La Mancha, 45071 Toledo, Spain

*Correspondence to: sonia.jerez@gmail.com

Abstract

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

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1 – Introduction

Regional Climate Models (RCMs) are powerful tools providing high resolution climate information by dynamically downscalling coarser datasets, e.g. from Global Circulation Models (GCMs). Their added value is not only about the increased resolution, but also about the fact that such an increased resolution allows modeling and considering fine scale processes and features that are missed or misrepresented otherwise, e.g. local circulations and land uses (Rummukainen 2010, Jacob et al 2014, 2020, Schewe et al 2019). Still, certain phenomena need to be parametrized, e.g. the turbulence within the planetary boundary layer, the microphysics processes and all about cumulus. However, there are relevant processes that GCMs usually model dynamically, but RCMs usually do not. This is the case of the atmospheric aerosols concentration and their multiple non-linear interactions (eg. Taylor et al 2012 *vs.* Ruti et al 2016), the so-called aerosol-radiation and aerosol-cloud interactions (Boucher 2015).

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

In the current context of climatic crisis, the scientific challenge is getting twofold: (1) a good understanding of processes that occur in the atmosphere and of what will occur in the future, because this is crucial (IPCC 2013) in order to (2) advance effective measures both at global and regional scales (IPCC 2014). In particular, climate change mitigation strategies require that low-carbon energies grow very fast in the coming decades (Rohrig et al 2019, IRENA 2019). This rapid transition of the energy sector towards renewables-powered decarbonized systems makes the energy production, transmission and distribution increasingly sensitive to weather and climate variability

(Jerez et al 2013, Bloomfield et al 2016, Collins et al 2018, Kozarcanin et al 2018, Troccoli et al 2018, Germer & Kleidon 2019, Turner et al 2019, van der Wiel et al 2019, van Ruijven et al 2019). Thus, several works have been devoted to assess this issue through the use of climate modelling tools (Crook et al 2011, Gaetani et al 2014, Jerez et al 2015, Tobin et al 2015, Wild et al 2015, Tobin et al 2016, Bartók et al 2017, Tobin et al 2018, Ravestein et al 2018, Schlott et al 2018, Gil et al 2019, Jerez et al 2019, Müller et al 2019, Soares et al 2019, Solaun & Cerdá 2019, Zappa et al 2019).

From the extensive literature, we rescue here four key features that motivated the present work. First, the increasing use of RCM to perform evaluations of the renewable energy resources and their supplying potential (e.g. Jerez et al 2013, 2015, 2019, Tobin et al 2015, 2016, Gil et al 2019, Soares et al 2019). Second, the key role of aerosols regarding the accuracy of the simulated solar resource by climate models (Gaetani et al 2014, Nabat et al 2015b, Gutiérrez et al 2018, 2020, Boé et al 2020, Pavlidis et al 2020). Third, the reported discrepancies between GCMs and RCMs future projections for the solar resource (Jerez et al 2015, Bartók et al 2017), which still remain largely a mystery. And fourth, none of the previous studies has unveiled so far the non-evident role of interactively modeled atmospheric aerosol concentrations and the resulting aerosol-radiation and aerosol-cloud interactions for simulating the solar resource using regional climate models under present and future climate scenarios.

Hence, our objective here is to shed light on that. For that, we made use of a widely applied RCM, the Weather Research and Forecasting (WRF) Model (Skamarock et al 2008) and its coupled form with Chemistry (WRF-Chem; Grell et al 2005), to perform sets of present (period 1991-2010) and future (period 2031-2050) simulations over Europe in three ways: (1) without dynamic aerosol modeling, (2) with dynamic aerosols and aerosol-radiation interactions activated, and (3) with dynamic aerosols and both aerosol-radiation and aerosol-cloud interactions activated.

Section 2 provides experimental details. Section 3 presents the results. Conclusions are drawn and discussed in Section 4.

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2 – Experiments and data

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

The three experiments consisted of, and are named as:

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

ARI: aerosols are treated interactively (see bellow) and aerosol-radiation interactions are activated in the model.

ACI: aerosols are treated interactively, as in ARI experiments, and both aerosol-radiation and aerosol-cloud interactions are activated in the model.

The WRF spatial configuration consisted of two one-way nested domains (Supp Fig 1). The inner one (target domain) is an Euro-Cordex (https://www.euro-cordex.net/; Jacob et al 2014, 2020) compliant domain covering Europe with an horizontal resolution of 0.44º in latitude and longitude. The outer one has a horizontal resolution of 1.32º and covers the most important areas of Saharan dust emission as in Palacios-Peña et al 2019a. This configuration was necessary to generate and include the information of the Saharan dust intrusions through the boundaries of our target domain for the ARI and ACI experiments, because the boundary conditions from the GCM do not provide

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this information. In the vertical dimension, 29 unevenly spaced eta levels were specified in the two domains, with more levels near the surface than upward, and the model top was set to 50 hPa. The physics configuration of the WRF model consisted of the Lin microphysics scheme (Lin et al. 1983), the RRTM radiative scheme (Iacono et al. 2008), the Grell 3D ensemble cumulus scheme (Grell 1993, Grell and Dévényi 2002), the University of Yonsei boundary layer scheme (Hong et al. 2006) and the Noah land surface model (Chen & Dudhia 2001, Tewari et al. 2004). Boundary conditions from the GCM were updated every 6 hours, including the low boundary condition for the sea surface temperature. Nudging was applied to the outer domain, but not to the target domain.

To perform ARI and ACI experiments, we used the WRF model coupled with Chemistry (WRF-Chem) version 3.6.1 (Grell et al 2005, Chin et al 2002). WRF-Chem runs with GOCART aerosol module (Ginoux et al 2001). This scheme was coupled with RACM-KPP (Stockwell et al 1997, Geiger et al 2003) as chemistry option. The Fast-J module (Wild et al 2000) was used as photolysis option. Biogenic emissions were calculated using the Guenther scheme (Guenther et al 2006). The simulated aerosols included five species, namely sulphate, mineral dust, sea salt aerosol, organic matter and black carbon. Anthropogenic emissions coming from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP; Lamarque et al 2010) were kept unchanged in the simulation periods (we considered the 2010 monthly values). Natural emissions depend on ambient conditions and varied accordingly in our simulations following Ginoux et al 2001 for dust and Chin et al 2002 for sea salt.

The inclusion of aerosol-radiation and aerosol-cloud interactions in ARI and ACI simulations are extensively described in Palacios-Peña et al 2020. However, a brief summary is included here. The former (aerosol-radiation) are included following Fast et al 2006 and Chapman et al 2009. The overall refractive index for a given size bin was determined by volume averaging associating each chemical constituent of aerosol with a complex index of refraction. The Mie theory and the summation over all size bins were used to determine the composite aerosol optical properties assuming wet particle diameters. Finally, aerosol optical properties are transferred to the shortwave radiation scheme. Aerosol-cloud interactions were implemented by linking the simulated cloud droplet number with the microphysics schemes (Chapman et al 2009) affecting both the calculated droplet mean radius and the cloud optical depth. Although this WRF-Chem version (3.6.1) does not allow a full coupling with aerosol-cloud interactions, the microphysics implemented here is a single moment scheme that turns into a two moments scheme in the simulations denoted as ACI.

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

3 - Results

We focus on the summer season (JJA), when solar energy provides its most, AOD tipically reaches the highest values and the aerosol radiative effect has been proven to be strongest (Pavlidis et al 2020). As a first test, Supp Fig 2a-d provides the GCM, BASE, ARI and ACI JJA climatologies of RSDS in the present period. Although the four patterns depict similar structures, a closer look to the deviations of the climatologies from the WRF experiments with respect to the GCM (Supp Fig 2e-g) reveals significant differences through resembling patterns: positive values (higher RSDS values in the RCM experiments) south and northward (up to 20 and 30% respectively), and negative values in between (10-15%, eventually up to 25%). Nonetheless, there still exist significant differences within the set of WRF experiments (Fig 1a-c), in which this research puts the focus.

The inclusion of interactive aerosols (ARI and ACI experiments) reduce the JJA mean values of RSDS in central and northern parts of our domain by a few percents as compared to the BASE experiment (Fig 1a,b). This reduction is generally stronger in ARI than in ACI. Consequently, the ACI minus ARI pattern (Fig 1c) depicts mostly positive values over central and southern regions. In order to try to understand these patterns, Fig 1 also provides differences in the CCT and AOD summer climatologies between experiments and the spatial correlations (*s_corr*) between these patterns and those of RSDS differences (panels d to f and g to i, respectively). Compared to BASE,

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both ARI and ACI lead to more cloudiness in central and northern regions and less cloudiness southward, specially in ACI (Fig 1d-f), which is well correlated with the spatial distribution of the differences between experiments in RSDS. Also, the dynamic treatment of aerosols lead to noticeable differences (up to 10%) in the AOD values between ACI and ARI (Fig 1i), and the AOD climatologies from these two experiments provides a consistently non-nule picture (Fig 1g,h; nule values can be considered for BASE). However, the paterns for AOD do not correlate with those for RSDS. In fact, the temporal correlation at the grid point level between the series of differences in RSDS and in CTT is above 0.8 (negative) in most of the domain, while differences in AOD hardly correlates in time with differences in RSDS (Supp Fig 3a-f). Hence, the CTT differences prevail over the AOD differences in driving the RSDS differences between pairs of experiments in the present-day climate simulations. This also holds under future conditions, while the patterns of differnces in the analyzed varables show different structures (Supp Fig 4 and 5a-f).

Therefore, there is an overall a direct and predominant link between the aerosols effect on cloudiness and its impact on the amount of solar radiation reaching the surface. Contrary, the effect of interactive aerosols schemes on AOD seems to play a minor and more local role in certain locations, where it eventually can help to straightly explain the differences in RSDS between ACI and ARI as the matching between the RSDS and CCT differences devanishes. For instance, a closer look to local differences between ARI/ACI and BASE reveals regions (in central and eastern Mediterranean Europe) where, in spite of the less CCT simulated in experiments with interactive aerosols (Fig 1d,e), they also simulate less RSDS than BASE (Fig 1a,b). This could be explained by the differences in AOD and its locally relevant impact on RSDS over thse regions, as pointed out by Supp Fig 3d. Also, over areas of central Europe, while differences between ACI and ARI in CTT are small (Fig 1f), ACI provides higher values of RSDS than ARI (Fig 1c), which could be explained by the larger AOD values in the ARI simulation (Fig 1i).

Under clear-sky conditions (Fig 2), both the spatial correlations between patterns of AOD and RSDS differnces, and the temporal correlations between the respective series computed at the grid point level (Supp Fig 3g-i, 5g-i and 6), support the relevant role of the AOD_{cs} variable for the simulation of $RSDS_{cs}$. Nonetheless, differences in $RSDS_{cs}$ are lower than differences in RSDS, basically nule between ACI and ARI. It is important to note that this analysis considers coincident clear-sky dates between the pairs of experiment being faced (the percentage of days retained under this approach can be seen in Supp Fig 7). Without this restriction (see the percentage of days retained in Supp Fig 8) the match between both variables devanishes both in the present and the future periods (Supp Fig 9 and 10), may indicating the masking effect of Earth orbit related issues, of large scale climate drivers and/or local forcings such as water vapor content.

Cloudiness also seems to lead the future projections for the RSDS summer climatologies (Fig 3). BASE and ARI change patterns for RSDS (Fig 3b,c) resemble each other, with negative signals (up to 10%) appearing in northernmost regions while positive signals (up to 5%) appear southward within our target domain. These latter are more widespread in ARI than in BASE, which makes the ARI pattern the most similar to the change pattern from the GCM (Fig 3a). However, when aerosols-cloud interactions are included in the WRF runs, such a positive RSDS change signals mostly disappear while the northern negative ones reinforce in some parts as compared to the ARI pattern (Fig 3d). All this is in quite good agreement with the corresponding change patterns for CCT (Fig 3e-h) – including the fact that the negative change signals for CCT appearing southward in the GCM, BASE and ARI experiments are way less evident in ACI – and occurs in spite of two constraining facts regarding the AOD simulation approaches in our WRF experiments: (1) AOD remains unchanged in the BASE experiment (as illustrated by Fig 3j), and (2) AOD changes from the ARI and ACI experiments are hardly realistic because their anthropogenic component is disregarded (as specified in Section 2), and thus depict patterns (Fig 3k,l) that have nothing to do with the GCM projection in Fig 3i (which does consider time evolving anthropogenic aerosols). In fact, the spatial correlation between the patterns of AOD and RSDS changes is lower than between the patterns of CTT and RSDS changes, specially in ACI, the experiment in which aerosols also act on clouds.

The change signals for $RSDS_{cs}$ and AOD_{cs} (Fig 4) depict softer and with a different spatial structure to those for RSDS and AOD in the ARI and ACI experiments, turning mostly negative southward and positive northward for $RSDS_{cs}$, which occurs similarly in the three experiments (BASE, ARI and ACI). There is no clear relation between AOD_{cs} change patterns and $RSDS_{cs}$ changes (low spatial correlation), except for some local signals in areas at the North-East. However, as discussed above, the role of retaining, or not, coincident clear-sky dates between pairs of experiments is important to filter out the true role of AOD_{cs} on $RSDS_{cs}$. Thus, the fact that change patterns are constructed over different dates may partially explain the apparently negligible role of AOD_{cs} on $RSDS_{cs}$ in this case. But only partially, as the BASE change pattern for $RSDS_{cs}$ (simulated on the ground of nule AOD_{cs} change) resemble the respective patterns from ARI and ACI experiments.

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4 - Discussion and conclusions

We presented here a research on the role of dynamically modeled atmospheric aerosols in regional climate simulations with a focus on impacts on the solar resource during the summer season from a climatic perspective, including projected changes to a medium-range horizon and analysis under clear-sky conditions. For that we evaluated a set of 20-yr long runs (spanning both present and future periods) with resolved aerosol-radiation and aerosol-radiation-cloud interactive (two-way) interactions, on the ground of which we drew original conclusions.

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

Regarding the future projections, the patterns for RSDS and those for CCT show again high spatial correlations in all the GCM and RCM (BASE, ARI and ACI) projections. Although lower, still high spatial correlations define the matching between the RSDS change patterns and those for AOD in the GCM and the ARI experiment. GCM, BASE and ARI experiments agree in projecting positive RSDS change signals in southern and eastern areas (around 5%), while clear differences are found between the GCM and the BASE or ARI RSDS change patterns (with these two latter being very similar) in central and northeastern areas, where the positive signals from the GCM turns notably negative both in BASE and ARI. ACI provides the most singular and negative picture of RSDS changes among all shown, with widespread decreasing signals of a few percent points, apparently unlinked to the changes projected in AOD.

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Previous works (Jerez et al 2015) had already detected inconsistencies in the change signals between RCM projections and those from their driving GCM, which had been related to the way aerosols had been represented in the RCM through its impact on the simulated AOD (Bartók et al 2017, Gutiérrez et al 2020, Boé et al 2020), and in particular to the time-evolving aerosols in scenarios. Our results constitute an example of the impact of cloudiness and AOD in RSDS through aerosol-related physical mechanisms while keeping unchanged the anthropogenic aerosol emissions through the simulation period, revealing in this case the prevailing role of CCT changes to explain RSDS changes, and the capacity of the aerosol-radiation-cloud interactions to significantly alter the RSDS change patterns (more than what aerosol-radiation interactions alone do). Although change patterns for RSDS look much more uniform among experiments under clear-sky conditions, the results presented here may indicate that action-oriented messages from modelling experimts that did not consider the role of aerosols, in particular in a dynamic way, could be potentially misleading, thus calling for future research efforts in this line.

Author contribution

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

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Code and data availability

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

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Figure caption

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

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

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

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

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

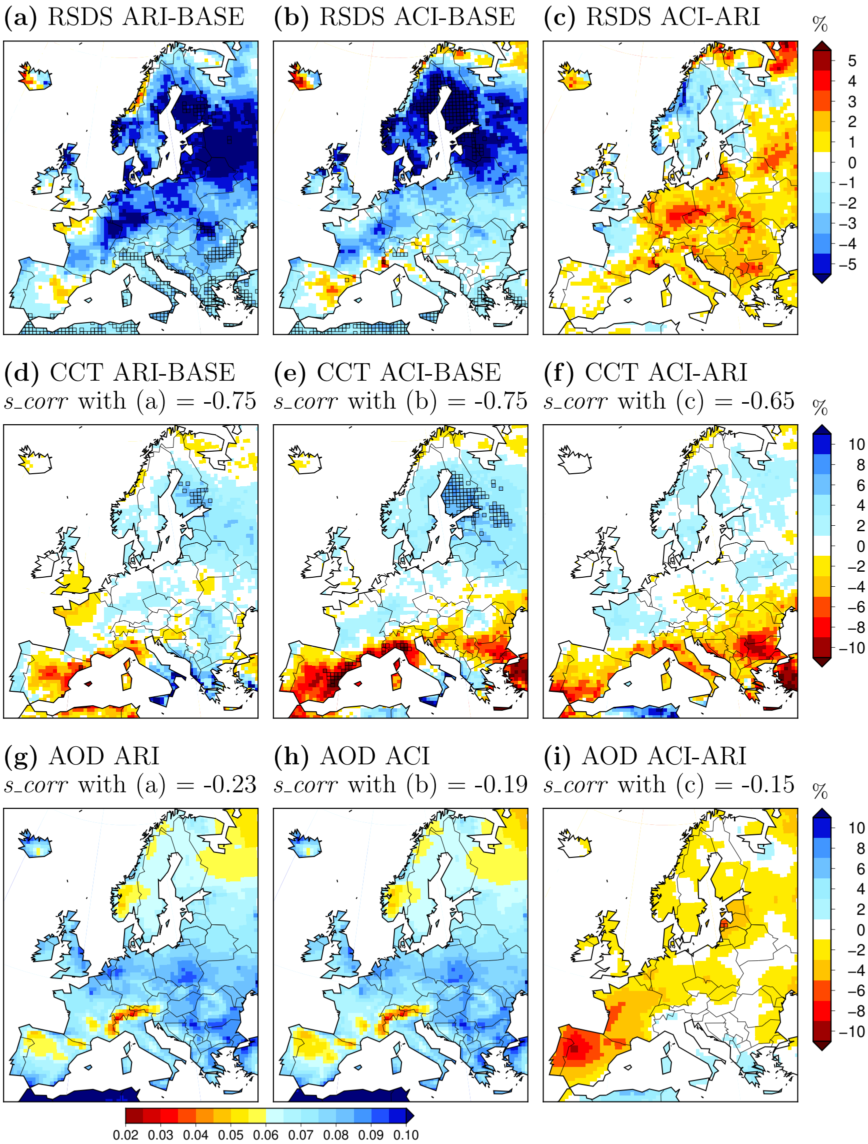

Figure 1

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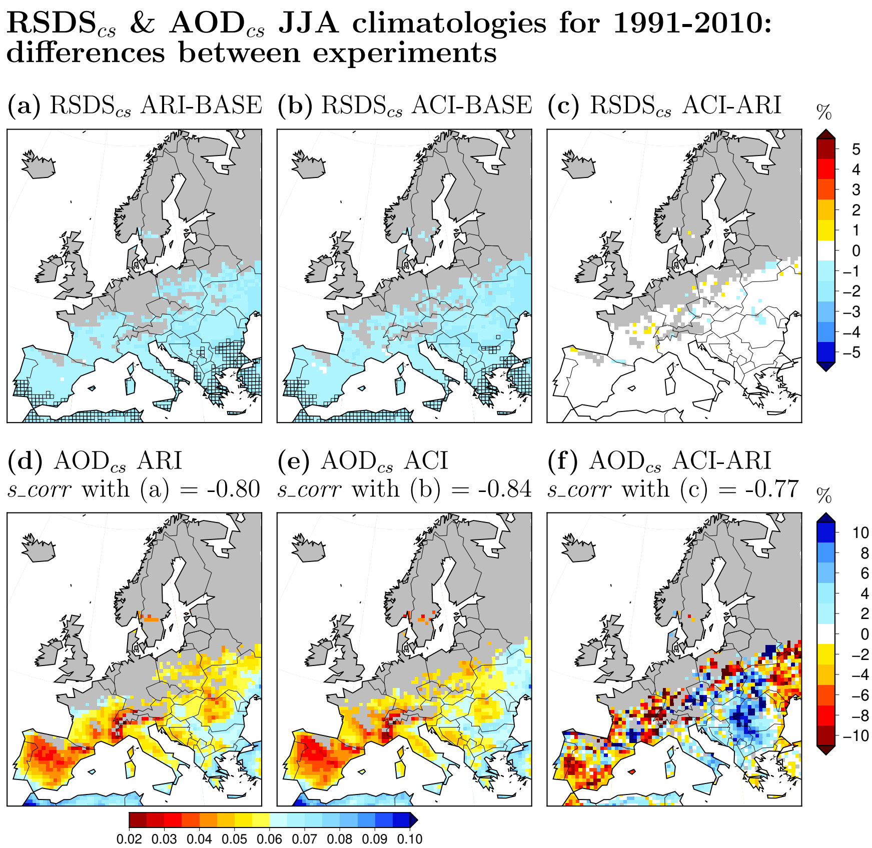

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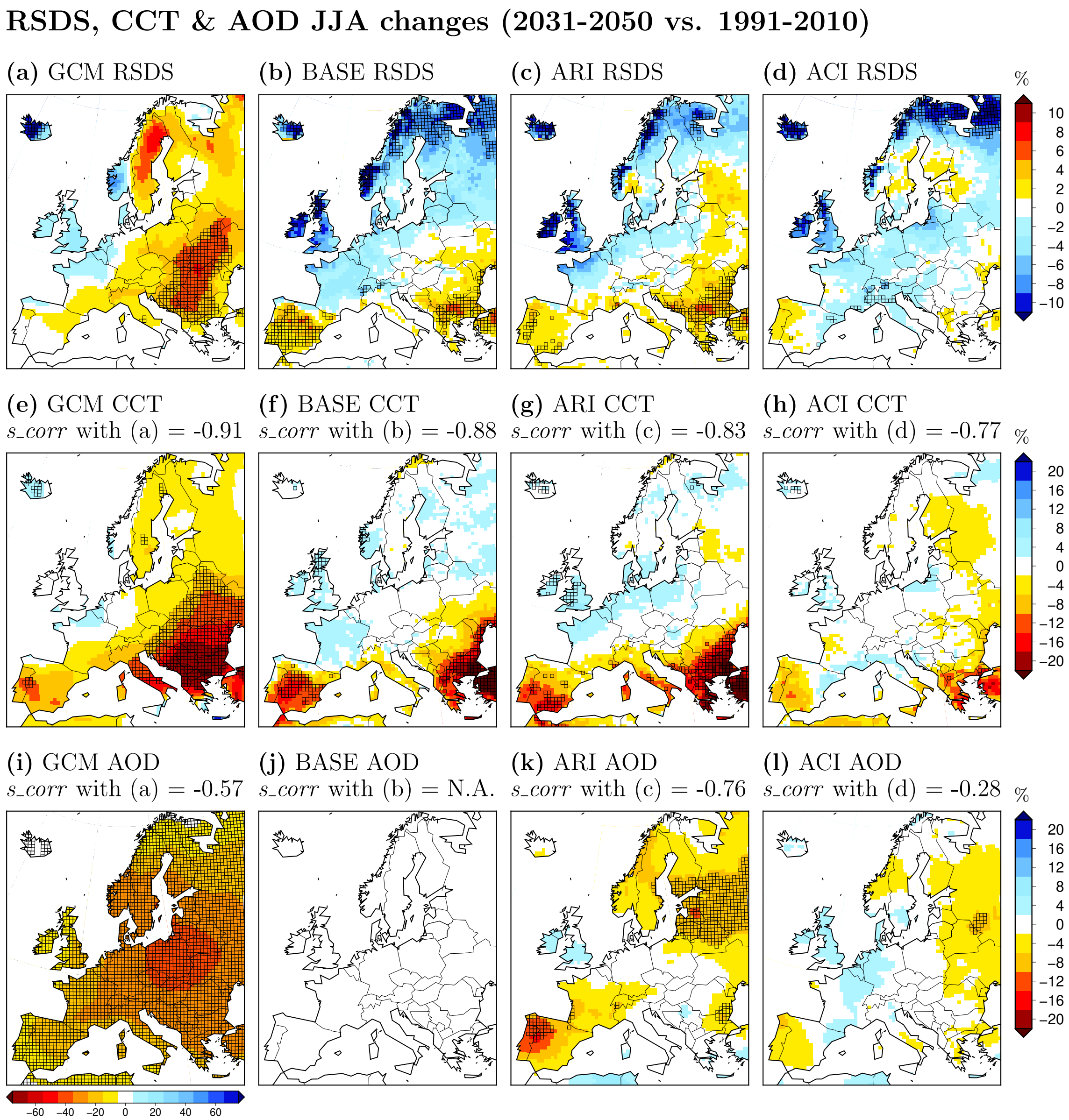

Figure 3

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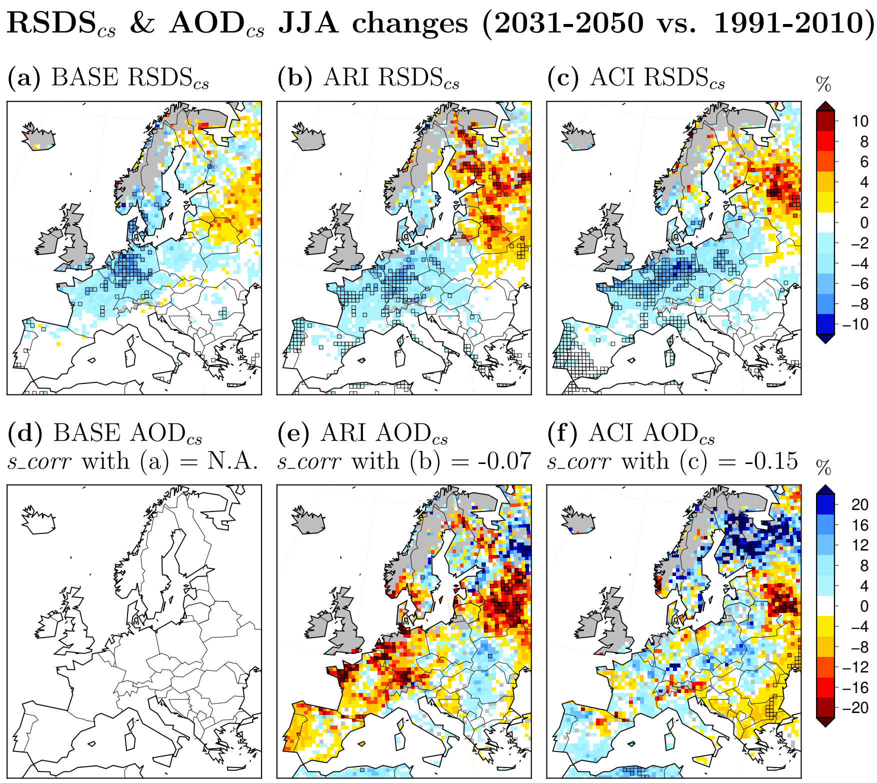

Figure 4