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P. Nabat[1], S. Somot[1], J. Boé[2], L. Corre[3], E. Katragkou[4], S. Li[5,6], M. Mallet[1], E. van Meijgaard[7], V. Pavlidis[4], J.-P. Pietikäinen[8], S. Sørland[5,9]and F. Solmon[10]

[1]CNRM, Université de Toulouse, Météo-France, CNRS, Toulouse, France
[2]CECI, Université de Toulouse, CERFACS/CNRS, Toulouse, France
[3]Météo-France, Toulouse, France
[4]Department of Meteorology and Climatology, School of Geology, Aristotle University of Thessaloniki, Thessaloniki, Greece
[5]Institute for Atmospheric and Climate Science, ETH Zurich, Switzerland
[6]College of Hydraulic Science and Engineering, Yangzhou University, Yangzhou, China
[7]Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands
[8]Climate Service Center Germany (GERICS), Helmholtz-Zentrum Hereon, Hamburg, Germany
[9]Sweco, Bergen, Norway
[10]Laboratoire d'Aérologie, CNRS, Toulouse, France

Key Points:

- (1) The role of anthropogenic aerosols in European summertime climate change is assessed using a set of multi-model regional climate simulations
- (2) Reduced concentrations of anthropogenic aerosols in Europe lead to an increase in surface solar radiation and an extra warming near surface
- (3) Current differences in aerosol representation explain a part of inconsistencies between global and regional climate projections in Europe

Corresponding author: Pierre Nabat, `pierre.nabat@meteo.fr`

Abstract

Global and regional climate models (respectively GCMs and RCMs) are delivering conflicting messages about summertime climate change in Europe, revealing notably a weaker warming in RCMs. A dedicated multimodel ensemble of nine GCM-RCM pairs is analyzed to assess the role of anthropogenic aerosols in these inconsistencies. The expected decrease of anthropogenic aerosol concentrations is found both to modify the future evolution of shortwave radiation and to generate an extra warming. For every tenth in aerosol optical depth drop in Central Europe, shortwave radiation is increased at the surface by 6.3 Wm^{-2} and decreased at the top of the atmosphere by 5.6 Wm^{-2}, while near-surface temperature is increased by 0.3°C. The consideration of time-varying anthropogenic aerosols in RCMs thus contributes to improving GCM/RCM consistency in Europe for these three variables, but not for water cycle. The results obtained underline the necessity to better consider aerosols in upcoming regional climate simulations.

Plain Language Summary

As far as summertime climate change in Europe is concerned, global and regional climate models do not provide exactly the same information, insofar as the warming simulated by regional models is notably lower than in global models. The decrease of anthropogenic aerosol concentrations, not always taken into account in regional models, could be one possible explanation of these inconsistencies. This hypothesis is analyzed here with the help of a dedicated multimodel ensemble of simulations with constant and evolving aerosols. This evolution of aerosols is shown to increase surface solar radiation and near-surface temperature in Europe. The consideration of time-varying anthropogenic aerosols in regional climate models thus contributes to reducing the differences between global and regional climate simulations.

1 Introduction

Reliable and robust regional climate change information is becoming central for taking the right decisions in adapting the human society to a rapidly changing climate. Nowadays, this information is mostly based on Global and Regional Climate Models (respectively GCMs and RCMs) regardless of the processing subsequently applied (bias correction, statistical downscaling). GCMs and RCMs are usually considered as complementary and consistent, the former being the forcing of the latter. GCMs are supposed to provide the large scale information whereas RCMs produce more detailed dynamically downscaled climate information for a given large scale (Laprise et al., 2008).

However, several studies (described below) have recently underlined strong inconsistencies at the large scale between the climate change signal derived from GCM-based and RCM-based ensembles, such as the fifth version of the Coupled Model Intercomparison Project (CMIP5, Taylor et al., 2012) and the associated Coordinated Regional Climate Downscaling Experiment (CORDEX, Jones et al., 2011) respectively. While GCM-RCM conflicting messages at regional and local scales (e.g. for European subregions, or mountain areas) can be interpreted as the signature of the RCM added-value in future climate projections (Giorgi et al., 2016; Torma & Giorgi, 2020), they are not expected to occur systematically at the large scale (e.g. at the European scale). Such conflicting messages may create confusion for climate model data users such as impact communities, stakeholders and operational climate services. Not understanding or trying to solve these problems could lead to downgrade the confidence in the capacity of climate models to provide reliable information on climate change at regional level.

So far, most of the detected conflicting messages have been revealed for summertime climate change in Europe for surface solar radiation (Bartók et al., 2017; Boé et al., 2020; Gutiérrez et al., 2020; Coppola et al., 2021; Chen, 2021), cloud cover (Bartók et al., 2017; Cherif et al., 2020), near-surface temperature (Boberg & Christensen, 2012;

Sørland et al., 2018; Schwingshackl et al., 2019; Boé et al., 2020; Coppola et al., 2021; Ribes et al., 2022) and precipitation (Sørland et al., 2018; Boé et al., 2020). In this region, RCMs show a weaker warming and a weaker drying than their driving GCM in summer. Value differences can reach up to -30 Wm^{-2} and -4.5°C at the end of the 21st century under the Representative Concentration Pathway RCP8.5 scenario (Boé et al., 2020), order of magnitude of the climate change signal. For some variables, the inconsistency can even lead to a reversal of the sign of climate change, with GCMs showing for example a clear increase in the surface solar radiation at the end of the 21st century whereas the RCMs show a decrease or only a small increase (Bartók et al., 2017; Boé et al., 2020; Gutiérrez et al., 2020). The identification of the inconsistencies is robust through various analysing approaches, large multi-model ensembles and clean GCM-RCM pairs (Boé et al., 2020; Coppola et al., 2021; Taranu et al., 2022). Moreover it is verified for various temporal horizons and socio-economic scenarios (Boé et al., 2020; Gutiérrez et al., 2020; Coppola et al., 2021). It is noteworthy that the inconsistency level strongly depends on the choice of the GCM-RCM pair (Bartók et al., 2017; Boé et al., 2020; Gutiérrez et al., 2020; Taranu et al., 2022), which tends to invalidate the conclusion about the predominance of the role of the increased horizontal resolution in explaining these inconsistencies.

Various hypotheses have been proposed to explain these GCM-RCM conflicting messages: different behaviours in the simulated cloud cover (Bartók et al., 2017), missing aerosol forcing in RCMs (Boé et al., 2020; Gutiérrez et al., 2020; Chen, 2021; Schumacher et al., 2024), missing air-sea coupling in RCMs (Boé et al., 2020), smaller present-climate biases in RCMs (Sørland et al., 2018), missing plant physiological CO_2 effect in RCMs (Schwingshackl et al., 2019), and GCM-RCM inconsistencies in physical parameterizations (Taranu et al., 2022). Those competing and often contradictory arguments have so far failed to firmly establish the main factors explaining the GCM-RCM inconsistencies in Europe, partly because these studies use either one single model or simulation ensembles without dedicated sensitivity tests. Similar GCM-RCM inconsistencies have also been reported over other regions such as North America (Chen, 2021).

Antagonistic effects between, on one side, greenhouse gases which induce a positive radiative forcing and strongly contribute to global warming and, on the other, anthropogenic aerosols which induce a negative radiative forcing and whose emissions evolution in the 20th century explain the dimming/brightening phenomenon (Wild, 2009), have long been identified (Ramanathan & Feng, 2009). The evolution of greenhouse gases and anthropogenic aerosols is generally included in GCMs, but not systematically for aerosols in most RCMs up to now (Gutiérrez et al., 2020). Anthropogenic aerosols are therefore a good candidate to explain the identified conflicts, given the main role of this specific forcing in past European climate change through the dimming effect since the 1980s (Wild, 2009; Philipona et al., 2009; Nabat et al., 2014; Wild et al., 2021; Schumacher et al., 2024), their tendency to decrease in 21st century scenarios over the area (Gutiérrez et al., 2020; Drugé et al., 2021), and more generally the complexity and the large regional variations in aerosol climate effects (Persad et al., 2023).

In this study, we intend for the first time to use a dedicated multi-model sensitivity study to pursue the two following complementary objectives: (1) specifically assess the role of anthropogenic aerosols in explaining the GCM-RCM conflicting messages in summertime climate change in Europe and (2) quantify the role of the aerosol change in future climate change projections over Europe. The simulation ensembles used for this purpose covers a large RCM and GCM diversity, consisting in sensitivity runs with and without evolving aerosols in near-future projections. The following analyses focus on climate change signal in the near future (2021-2050), regarding radiation, near-surface (at 2m) temperature and water cycle.

2 Methodology

2.1 The coordinated multi-model experimental protocol

This study has been designed in the framework of the CORDEX Flagship Pilot Study on aerosols (FPS-aerosol, Solmon & Mallet, 2021), and relies on a protocol of coordinated multi-model simulations addressing both of the above objectives (Protocol 1B, Somot et al., 2021). This protocol can be seen as a sensitivity experiment to assess current practices in CORDEX RCMs with regards to considering the evolution of aerosols. Indeed, the aerosol forcing and its evolution in historical and scenario runs was not specified in the CORDEX experimental protocol aiming at downscaling CMIP5 GCMs, which may lead to GCM/RCM inconsistencies, with potential impacts on the simulated climate change signal.

The current protocol relies on existing Med- and EURO-CORDEX baseline simulations downscaling CMIP5 GCMs, and new RCM sensitivity simulations, as follows: (1) one simulation covering the historical period 1971-2000, (2) a second simulation covering the period 2021-2050 for the RCP8.5 run, and (3) an additional future scenario that is a perfect twin of the CORDEX standard run (2021-2050), but with respectively evolving (constant) aerosols if the aerosols were constant (evolving) in the official CORDEX simulation. These simulations are respectively named RCMhis, RCMevol and RCMcst thereafter.

2.2 Description of multi-model simulations

The ensemble of regional simulations consists in nine GCM-RCM pairs, performing the three simulations listed above. The GCM-RCM pairs combine six different RCMs (whose horizontal resolution ranges from 12 to 50 km), driven at their lateral boundaries by six different CMIP5 GCMs (Table 1).

Aerosols are considered through monthly means of aerosol optical depth (AOD) fields given the absence of full tropospheric chemistry in these simulations. These AOD fields evolve over time in RCMevol, but remain annually constant in RCMcst. They come either from the driving GCM if possible, or from an aerosol climatology in which the temporal evolution has been added (Szopa et al., 2013). This temporal evolution of aerosols was originally included only in the official EURO-CORDEX simulations of ALADIN63 and RACMO22E, while for COSMO-crCLIM, REMO2015 and RegCM, aerosols were constant. Aerosol-radiation interactions are considered in all simulations (aerosol direct effect). Regarding aerosol-cloud interactions, only ALADIN63 includes the cloud-albedo effect (only involved in the radiative code and not in the cloud parameterization), while none of these RCMs incorporates the other aerosol indirect effects on cloud microphysics.

This ensemble of simulations is highly diversified, all at once in terms of GCMs, RCMs, aerosol datasets, and in the representation of the radiative effects of aerosols. To our knowledge, this is the first time that such a large and diverse ensemble has been used to estimate the effects of aerosols on climate at the regional scale, and their impact on the GCM-RCM inconsistencies.

3 Impact of evolving aerosols on regional climate projections

Anthropogenic aerosol emissions in Europe have been decreasing since the 1980s (Streets et al., 2006), and are projected to decrease further in the coming decades, resulting in a large reduction in aerosol concentrations over Europe, in particular scattering sulfate particles (Gutiérrez et al., 2020). AOD is consequently largely reduced over Europe in 2021-2050 compared to 1971-2000 (Figure 1), with values ranging from -0.10 to -0.33 on average over Central Europe (CEU, as defined in Seneviratne et al., 2012, shown in Figure 1), and from -0.05 to -0.14 over the Mediterranean (MED). The threefold difference between the various simulations (Figure S1) is similar to the uncertainty found in the whole CMIP5 ensemble: Cherif et al. (2020) showed a decrease in MED AOD

Table 1. Characteristics of GCM-RCM pairs used in this study.

Institute	RCM	Grid	Driving GCM	Aerosols
AUTH	WRF[a]	50 km	CCSM4 (r6i1p1)	From GCM[g]
CNRM	ALADIN63[b]	12.5 km	CNRM-CM5 (r1i1p1)	From GCM[h]
CNRM	ALADIN63[b]	12.5 km	HadGEM2-ES (r1i1p1)	From GCM[g]
CNRM	ALADIN63[b]	12.5 km	NorESM1-M (r1i1p1)	From GCM[g]
CNRM	ALADIN63[b]	12.5 km	MPI-ESM-LR (r1i1p1)	From GCM[i]
ETH	COSMO-crCLIM[c]	12 km	MPI-ESM-LR (r1i1p1)	Clim[j]+trend[i]
GERICS	REMO2015[d]	12 km	EC-Earth (r12i1p1)	Clim[k]+trend[h]
KNMI	RACMO22E[e]	12 km	EC-Earth (r3i1p1)	From GCM[g]
LAERO	RegCM[f]	50 km	EC-Earth (r12i1p1)	Clim[i]+trend[i]

RCM references: [a]Pavlidis et al. (2020), [b]Nabat et al. (2020), [c]Leutwyler et al. (2017), [d]Jacob et al. (2012), [e]van Meijgaard et al. (2012), [f]Giorgi et al. (2012)
Aerosol references: [g]Lamarque et al. (2011), [h]Szopa et al. (2013), [i]Kinne (2019) [j]Kinne et al. (2006), [k]Tanré et al. (1984)

ranging from -0.03 to -0.14 between the 1980-1999 and 2020-2039 periods. Therefore, our ensemble well represents the range of possible futures in terms of anthropogenic aerosols.

In this section we will present and discuss the impact of this evolution of aerosols on the relevant climate variables (shortwave (SW) radiation, near-surface temperature, precipitation, evapotranspiration and cloud cover) in terms of future summer (June-July-August, JJA) changes (2021-2050 minus 1971-2000).

3.1 Radiative budget

At the top of the atmosphere (TOA), the decrease of the concentrations of scattering particles leads to a decrease of all-sky outgoing SW radiation in GCMs and RCMevol simulations (Figure 1), respectively -7.7 Wm^{-2} and -5.2 Wm^{-2} in the multi-model average in CEU. This decrease is highest in RCMs with the highest decrease in AOD: ALADIN-CNRM-CM5, ALADIN-NorESM1-M and ALADIN-HadGEM2-ES (Figures 2 and S2). On the contrary, in RCMcst, TOA SW radiation is not substantially reduced (-1.2 Wm^{-2} on average).

In parallel, the surface SW incoming radiation is distinctly increased over Europe in GCMs and RCMevol simulations (Figure 1), respectively 11.3 and 10.9 Wm^{-2} in CEU, while slightly decreased in RCMcst (-1.8 Wm^{-2}). In other words, regional models that do not include evolving aerosols would be mistaken in the sign of the future evolution of surface SW incoming radiation. In RCMevol, the future changes in both surface and TOA SW radiation are spatially similar to the future changes in AOD.

Overall, the evolution of aerosols strongly impacts SW radiation. A significant linear relationship between SW radiation and AOD future changes has been found (Figure 2): +6.3 Wm^{-2} at the surface and -5.6 Wm^{-2} at TOA per -0.1 in AOD in CEU. Similar relationships can be established for the MED domain (Figure S8): +6.7 Wm^{-2} at the surface and -6.3 Wm^{-2} at TOA per -0.1 in AOD.

3.2 Near-surface temperature

As for SW radiation, Figure 1 shows large differences in continental near-surface temperature future summer changes between GCMs and RCMs. Over Europe, the warming between 1971-2000 and 2021-2050 is higher in GCMs (+2.0°C in CEU) than in RCMcst (+1.4°C). Nonetheless, RCMs with evolving aerosols (RCMevol) have a stronger warming in Europe (+1.7°C) than RCMcst, consistently with surface SW radiation variations.

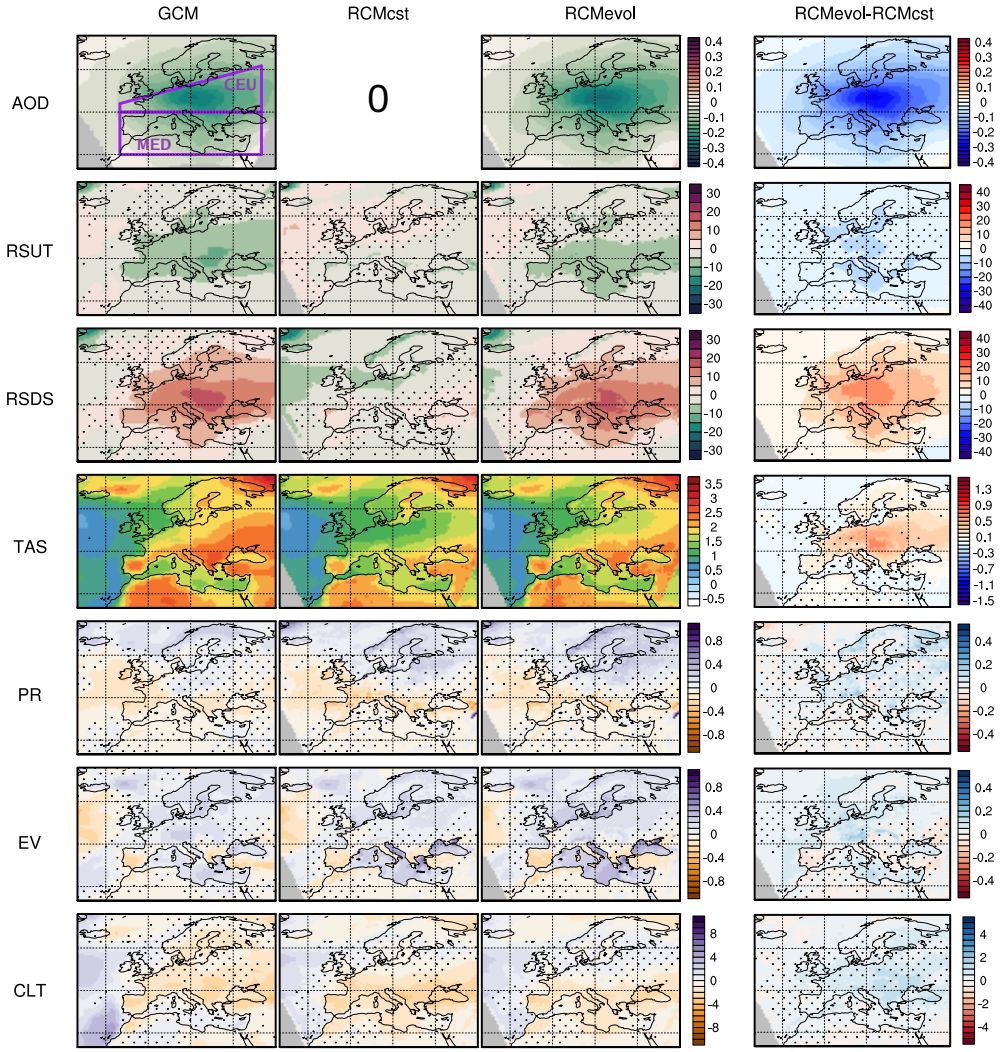

Figure 1. Multi-model averaged future changes (JJA, 2021-2050 minus 1971-2000) for the GCM, RCMcst and RCMevol ensembles. The last column gives the difference between RCMevol and RCMcst. Averages are presented for aerosol optical depth (AOD), TOA outgoing SW radiation (RSUT, Wm^{-2}), surface downwelling SW radiation (RSDS, Wm^{-2}), near-surface temperature (TAS, °C), precipitation (PR, mm/day), evapotranspiration (EV, mm/day) and cloud fraction (CLT, %). The CEU and MED regions are shown in the top left-hand map. By construction, AOD future change for RCMcst is equal to zero. Black dots indicate areas where more than 20% of models disagree about the sign of the change.

The differences are maximal over Central Europe, as for AOD. Therefore, aerosols explain a significant part of the simulated warming over this period in Europe, on all RCMs 19% on average (up to 34% in ALADIN-NorESM1-M). Figure 2 also shows a significant relationship ($R^2 = 0.55$) between near-surface temperature and AOD future summer changes: +0.3°C in near-surface temperature per -0.1 in AOD in CEU. Given the unavoidable decline of anthropogenic aerosols in Europe, these results imply that not considering changes in aerosols would lead to underestimate warming in this region.

However, there are contrasts between the different RCMs regarding the aerosol effects on temperature. On the one hand, the models with a high aerosol trend are also

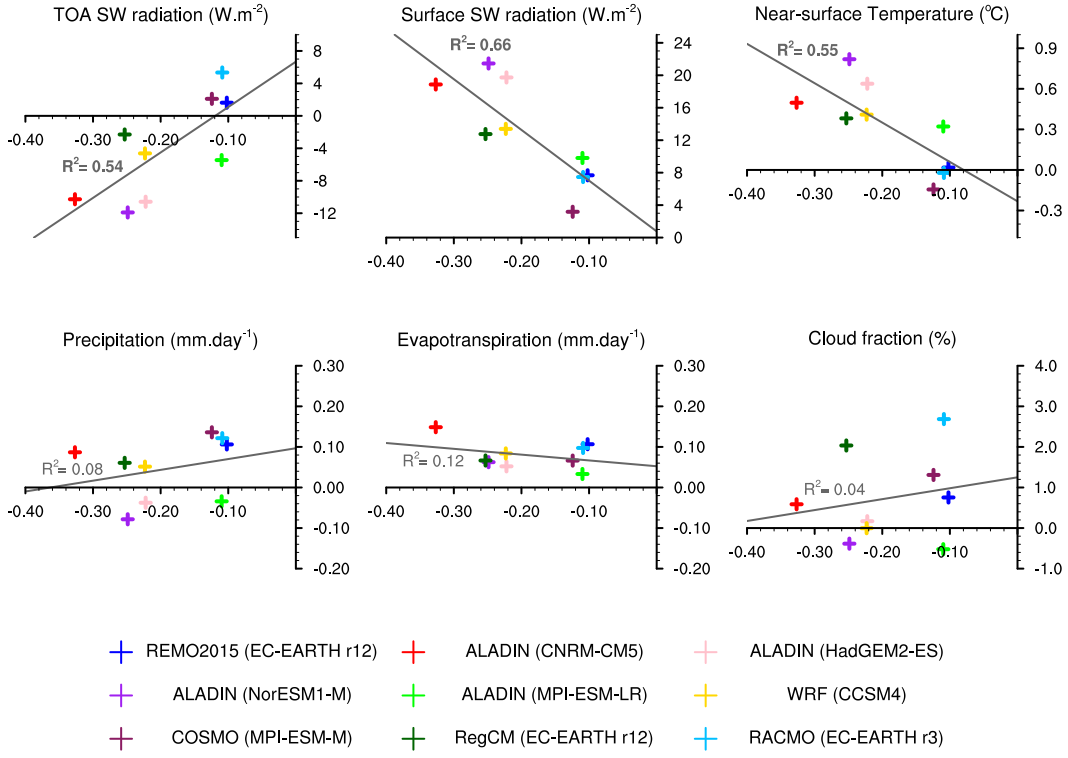

Figure 2. Averaged aerosol impact (RCMevol - RCMcst) on different parameters (TOA outgoing and surface downwelling SW radiation, near-surface temperature, precipitation, evapotranspiration and cloud fraction, y-axis for each plot) against AOD (x-axis). Averages are calculated for JJA, 2021-2050 minus 1971-2000, over the CEU domain. The black lines show the linear regression between the aerosol impact on the different parameters and AOD. Significant values of the square of the correlation coefficient (R^2) at level 0.05 are in bold characters.

those which have a larger warming (up to 0.8°C on average in CEU, reaching locally more than 1°C, Figure S4). On the other hand, three RCMs (REMO2015, RACMO and COSMO) show very little difference with and without evolving aerosols. The aerosol vertical distribution, which is not identical in each RCM (Figure S10), could contribute to these contrasts. For example, aerosols are maintained at lower altitudes in COSMO than in the other RCMs. Moreover, the evolution of near-surface temperature may be influenced by many other factors such as evapotranspiration response, cloud feedbacks.

In addition, no difference is seen over the ocean given that sea surface temperatures in RCMs are prescribed from their driving GCM. Therefore, the potential effect of aerosols on sea surface temperature (Nabat et al., 2015a) and associated feedbacks (slow adjustment, Liu et al., 2018) could not be studied here.

3.3 Water cycle

The additional surface heating due to aerosol changes could modify the climate projections of regional water cycle. GCMs show here a drying of the Mediterranean basin for the period 2021-2050 (Figure 1), with a decrease of summer precipitation in Southern Europe (extending to France and British Isles), and an increase of evapotranspiration over the Mediterranean Sea (extending to Central and Northern Europe), accompanied by a decrease of cloud cover all over Europe. This pattern is also present in the multi-model average of both RCMcst and RCMevol but with some differences. Indeed

evapotranspiration increases more in RCMevol in CEU (0.15 mm/day in multi-model average against 0.07mm/day in RCMcst), likely due to the increase of incoming SW radiation at the surface. Even if there is no statistically significant relationship between the changes in AOD and evapotranspiration, this additional increase in evapotranspiration in CEU is noted in all RCMs (Figures 2 and S6), implying that the aerosol evolution might contribute to the drying of this region.

With regards to clouds, cloud fraction decreases less in RCMevol (-0.5 %) than in RCMcst (-1.2 %). In contrast, precipitation future summer changes are quite similar in RCMevol and RCMcst multi-model averages. However, these multi-model averages hide some discrepancies between the different RCMs (Figures S5 and S7). Indeed, the sign of the change of precipitation and cloud fraction between simulations with and without aerosols is not the same in all RCMs (Figure 2). Like evapotranspiration, no significant relationship between AOD changes and precipitation/cloud cover changes can be established in CEU. Since the RCMs used here do not consider any aerosol effect on cloud microphysics (other than the cloud-albedo effect in the ALADIN63 radiative code), these changes in cloud cover and precipitation must come from semi-direct aerosol effects, namely changes in atmospheric dynamics or temperature profiles due to the absorption of solar radiation by aerosols.

4 Discussion: The role of anthropogenic aerosols on GCM-RCM inconsistencies

Given the strong impact of anthropogenic aerosols on climate change simulated by RCMs, the question is whether this will reduce inconsistencies with global simulations. Figure 3a presents the averaged future summer changes of each RCM against the changes in the driving GCM.

Both for TOA and surface SW radiation, RCM simulations with evolving aerosols are irrefutably much closer to their driving GCM than to the respective RCM simulations with constant aerosols. Results are more subtle for near-surface temperature. A better GCM-RCM consistency is noted for six GCM-RCM pairs (the four ALADIN63 simulations, WRF and RegCM), but little impact from the evolution of aerosols is found for COSMO, REMO2015 and RACMO. These discrepancies in near-surface temperature could be explained by changes in water cycle (Boé et al., 2020). All models show an increase of evapotranspiration in their simulations with evolving aerosols compared to their simulations with constant aerosols, which does not always go along with a better GCM-RCM consistency. It is probably due largely to the increased SW radiation. Nor do changes in precipitation and cloud cover systematically improve GCM/RCM consistency. The GCM-RCM inconsistencies in evapotranspiration could also be explained by other processes independently of aerosols such as the impact of the physiological effect of CO2 on changes in evapotranspiration (Boé et al., 2020), not considered in RCMs.

All these changes between RCMcst and RCMevol and their consequences on GCM-RCM consistency are summarized in Figure 3b, represented as polygons, joining the multi-model future summer changes for each variable in CEU, respectively for GCMs, RCMcst and RCMevol. Aerosols are thus shown to improve GCM-RCM consistency for near-surface temperature, TOA and surface SW radiation. It is all the more important for surface SW radiation, as the sign of the change was different between GCMs and RCMcst, while this parameter is increased in GCMs and RCMevol. Similar improvement has been found for radiation over the Mediterranean (Figure S9). With regards to near-surface temperature, the range of simulations showing the strongest warming in CEU (more than 2°C between 2021-2050 and 1971-2000) is only covered by GCMs and RCMs with evolving aerosols (blue crosses in Figure 3b). No simulation with constant aerosol (green crosses in Figure 3b) significantly exceeds the 2°C warming value in CEU, and the average of RCMcst itself is out of the range of the different driving GCMs.

However, our results also suggest that for the three other variables (precipitation, cloud cover and evapotranspiration), aerosol radiative forcing trends are not directly linked

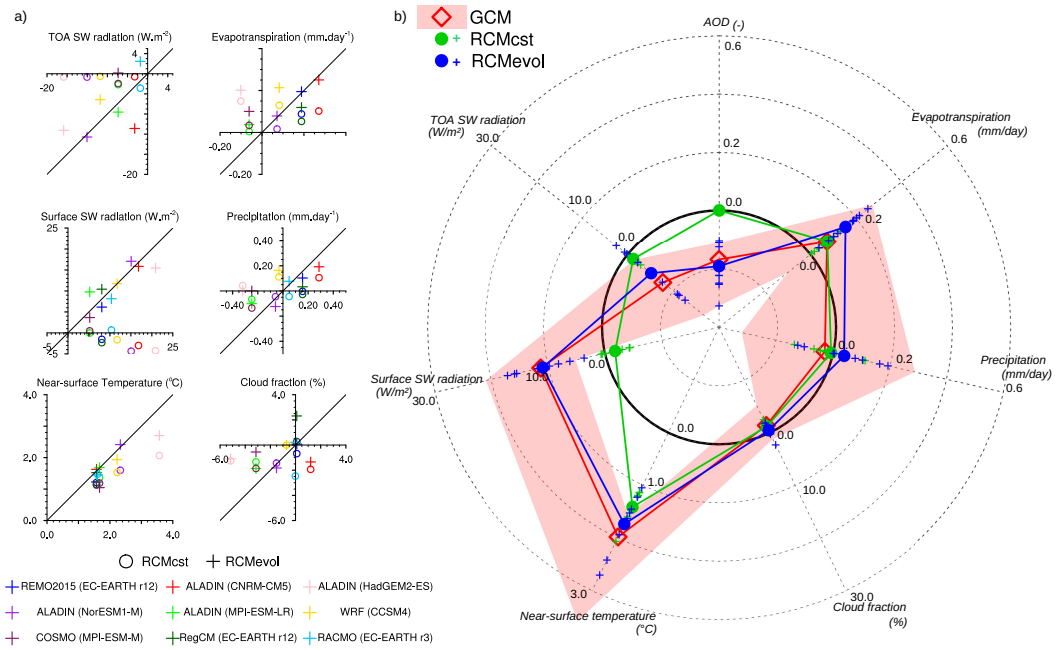

Figure 3. GCM/RCM consistency in climate change (JJA, 2021-2050 minus 1971-2000, CEU domain). a) Averaged changes in RCM simulations (y-axis) against their driving GCM simulation (x-axis), for the same parameters as in Figure 2. The black diagonal lines indicate the y=x line. b) Multi-model averaged changes. A radius is assigned to each variable, for which the change is derived respectively for the multi-model averages of GCM (red square), RCMcst (green point) and RCMevol (blue point). Individual models for RCMcst and RCMevol are noted in green and blue crosses respectively, while the red shaded area shows the range of all GCM simulations (min/max). The bold black circle indicates no change, and each dotted circle is separated by 10 Wm^{-2} for TOA and surface SW radiation, 1.0°C for near-surface temperature, 0.2 mm/day for evapotranspiration and precipitation, 0.2 for AOD and 10 % for cloud fraction.

to GCM-RCM inconsistencies. Figure 3b confirms that the respective RCMevol and RCMcst ensembles cannot be distinguished from the ensemble of their driving GCM for these three variables. This result must be qualified by the fact that aerosol-cloud interactions are poorly represented in the simulations used here. These microphysical processes are complex, depending both on aerosol and cloud properties, and need to be better understood and then properly integrated into models to assess their impact on climate (Seinfeld et al., 2016).

These results highlight the fact that GCM-RCM conflicting signals need to be documented, understood and solved to improve the robustness of future regional climate information. Disentangling the origin of the conflict is possible although not always easy. The spatio-temporal variability of aerosol radiative forcing is one of the drivers of climate change, and needs therefore to be better considered in upcoming regional climate simulations, notably in the next generation of CORDEX runs driven by CMIP6 GCMs. Besides Europe, the role of the regional aerosol forcing could be relevant for other areas, such as China, India, North America, or South Africa.

5 Conclusions

The present study uses a diversified multi-model ensemble of GCM-RCM simulations to disentangle the role of aerosols in climate change over Europe, and their possible contribution to GCM-RCM inconsistencies. Regional future simulations (2021-2050) with and without the evolution of anthropogenic aerosols, with respect to equivalent historical simulations (1971-2000), are compared and analysed. Results show that aerosols play an essential role in the future evolution of SW radiation, insofar as the decrease of their concentrations due to reduced anthropogenic emissions is responsible for an increase of surface incoming SW radiation and an associated decrease of outgoing SW radiation at TOA. This change in aerosols also induces an extra surface warming in Europe in most of the simulations presented here. The future summer changes in both SW radiation and near-surface temperature have a significant response to anthropogenic aerosol changes. However, no clear response to the evolution of aerosols has been found for cloud cover and precipitation future changes, even if all models show a slight increase of evapotranspiration.

Besides, this study provides some answers to the question of GCM/RCM inconsistencies. Time-varying anthropogenic aerosols have been shown to increase GCM/RCM consistency in SW radiation (both for the surface and TOA) and, to a lesser extent, near-surface temperature, but not for water cycle (precipitation, evapotranspiration, cloud cover). These results motivate an improved representation of aerosols in the next generation of CORDEX for past and future runs, as well as a closer collaboration between GCM and RCM developers and users. It is indeed important to motivate climate modelling communities to more systematically look for GCM-RCM conflicting messages in order to document them, to try to understand their origin and even better to solve the conflict either by correcting the source of the inconsistency or by deciding what is the most reliable information source. It is also worth mentioning that although aerosols play an important role in climate change, the future evolution of aerosols itself remains highly uncertain, whatever the scenario and the type of modelling (RCMs, GCMs).

Open Research Section

The CMIP5 and CORDEX simulations used in this study are available on the Earth System Grid Federation portal (https://esgf-node.ipsl.upmc.fr/projects/esgf-ipsl/). The dedicated FPS-Aerosol simulations for the nine GCM-RCM pairs (Nabat et al., 2024) are available at `https://doi.org/10.5281/zenodo.13736588`.

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