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LETTER

Future evolution of surface solar radiation and photovoltaic potential in Europe: investigating the role of aerosols

C Gutiérrez, S Somot, P Nabat, M Mallet, L Corre, E van Meijgaard, O Perpiñán and M Á Gaertner

1 Environmental Sciences Institute, University of Castilla-La Mancha, Avenida Carlos III s/n, 45071, Toledo, Spain
2 Centre National de Recherches Météorologiques, CNRM, UMR 3589, Météo-France/CNRS, Toulouse, France
3 Royal Netherlands Meteorological Institute (KNMI), PO Box 3730AE, De Bilt, the Netherlands
4 ETSIDI-UPM, Departamento de Ingeniería Eléctrica, Electrónica, Automática y Física Aplicada, Ronda de Valencia 3, 28012 Madrid, Spain
5 Faculty of Environmental Science and Biochemistry, University of Castilla-La Mancha, Avenida Carlos III s/n, 45071, Toledo, Spain
6 Author to whom any correspondence should be addressed.

E-mail: claudia.gutierrez@uclm.es

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Abstract
In recent decades, trends in photovoltaic (PV) technology deployment have shown an overall increase across the world. Comprehensive knowledge of the solar resource and its future evolution is demanded by the energy sector. Solar resource and PV potential have been estimated in several studies using both the global climate model (GCM) and regional climate model (RCM), revealing a GCM–RCM discrepancy in the projected change over Europe. An increase in surface solar radiation (SSR) (and therefore in PV potential production) is projected by GCMs, whereas most RCM simulations project a decrease in SSR over Europe. In this work, we investigate the role of aerosol forcing in RCMs as a key explaining factor of this inconsistency. The results show that RCM simulations including evolving aerosols agree with GCMs in the sign and amplitude of the SSR change over Europe for mid-21st century projections (2021–2050 compared to 1971–2000 for representative concentration pathway climate change scenario RCP8.5). The opposite signal is projected by the rest of the RCMs. The amplitude of the changes likely depends on the RCM and on its aerosol forcing choice. In terms of PV potential, RCMs including evolving aerosols simulate an increase, especially in summer for Central and Eastern Europe, with maximum values reaching +10% in some cases. This study illustrates the key role of the often-neglected aerosol forcing evolution in RCMs. It also suggests that it is important to be very careful when using the multi-model Coordinated Regional Climate Downscaling Experiment (CORDEX) projections for solar radiation and related variables, and argues for the inclusion of aerosol forcing evolution in the next generation of CORDEX simulations.

1. Introduction
The generalized increase in photovoltaic (PV) installed capacity in recent decades demands a detailed study of the spatiotemporal features of the solar resource. Due to the link between solar energy production and atmospheric variables, there is increased interest in the availability of climate change projections for the solar resource [1]. Climate modeling is a key tool in evaluating future energy potential, despite constraints such as its low spatial resolution or known biases in the representation of cloudiness.

Although the variability of solar radiation is mainly due to changes in cloudiness, other constituents of the atmosphere, mostly aerosols, also decrease the amount of energy reaching a PV generator’s surface. These become, in highly polluted areas, as important as clouds [2] and cause economic losses due to the lack of an accurate prediction [3]. Because of its geographical situation, the Euro-Mediterranean area is one of the areas most influenced by natural and anthropogenic aerosols from different sources, affecting the spatiotemporal distribution of the solar resource and hence the PV potential [4–8].
Different simulations with different general circulation models (GCMs) have been evaluated to assess the impact of future climate change on PV potential and variability [9–11], and have projected an increase over Europe during the 21st century. However, more recent studies using the regional climate models (RCMs) of the European branch of the Coordinated Regional Climate Downscaling Experiment (EURO-CORDEX) at higher resolution have shown an opposite behavior: a limited but overall decrease in surface solar radiation (SSR) and PV potential in the same area [12–14]. These results constitute one of the few illustrations so far of GCM–RCM inconsistency in the projection of a climate change signal [13, 15]. In addition, it is worth underlining that this current inconsistency may lead to diverging messages being delivered to PV production stakeholders depending on the climate information source. So far, this inconsistency has been attributed to an added value of RCMs with respect to GCMs, due to the improved cloud representation in RCMs leading to an improved related climate change response in these models [13].

Usually, the added value of RCMs compared with GCMs lies in their better representation of regional features (such as small-scale climate phenomena and local forcings such as topography or coastal lines) that can only be solved at high resolution. However, the increase in resolution has led to a simplification of other processes in order not to compromise computational time and resources. Many regional climate simulations have been performed using a simplified representation of aerosol content, usually aerosol optical depth (AOD) climatologies without variations in time [6, 7], and without considering their evolution in time for future projections [13] (see table B2).

In this context, the goals of our study are (1) to further illustrate this GCM–RCM inconsistency by using well-chosen GCM–RCM pairs within the EURO-CORDEX ensemble, (2) to attribute this inconsistency to the missing evolution of aerosol forcing in CORDEX RCMs and (3) to deliver future projections of climate-related potential PV production in Europe.

In this work, we analyze the SSR and the PV potential over Europe for the mid-21st century and the RCP8.5 scenario (one of the strongest IPCC-AR5 (fifth assessment report of the intergovernmental panel on climate change) representative concentration pathways (RCPs) in terms of greenhouse gasses (GHG) concentration increase for the end of the 21st century) using GCM–RCM simulation pairs from the EURO-CORDEX initiative. We classify different RCM simulations depending on their aerosol representation in the model and their driving GCM. A modeling chain approach is used: the climate model outputs (SSR, surface temperature) are used as inputs for the PV parametric model, which is then used to calculate PV productivity. The results are shown for summer, since that is the season when both aerosol loads and solar energy are maximal in Europe.

The manuscript is organized as follows: section 2 describes the regional models and simulations used in the study, as well as the aerosol datasets for those with evolving scenarios. In section 3 the methodology and in particular the PV model used is explained. Section 4 presents the main results and a discussion before the conclusions are given.

2. Climate simulations

2.1. EURO-CORDEX

Within the Coordinated Regional Climate Downscaling Experiment (CORDEX), EURO-CORDEX [16] develops climate projections focused on the European continent at different horizontal resolutions (0.44°, 0.11°). In scenario mode, these simulations are driven by different GCMs [17] within climate model inter-comparison project phase 5 (CMIP5) and provide multi-decadal simulations over the Euro-Mediterranean area, typically from 1950 to 2100 following various IPCC-AR5 scenarios (RCP8.5, RCP4.5, RCP2.6).

Among the whole list of simulations included in the EURO-CORDEX database, aerosols are described very differently depending on the RCM (see tables B1 and B2 in the appendix). RCMs use different aerosol datasets, different levels of complexity for their representation and different temporal evolutions. In particular, it is worth noting that most of the EURO-CORDEX RCMs do not present evolving aerosols in the future projections. Only a few RCMs (namely RACMO22E, the ARPEGE-ALADIN family HadGem3 and WRF3.5/WRF331) include an aerosol dataset that evolves depending on the year, following the chosen RCP scenarios and the driving GCM.

For the purpose of this work, we use the EURO-CORDEX whole list of 0.11° simulations, available at the time of the study, under the RCP8.5 hypothesis and then a relevant six-member ensemble, which is a subsampling of the whole list, is selected. For this selection we choose two driving GCMs (EC-EARTH and CNRM-CM5) and four RCMs (RACMO22E, ALADIN53, CCLM4-8-17 and RCA4). Each GCM drives three RCM simulations, one with evolving aerosols and two with constant aerosols (see table 1 for a detailed description of the GCM–RCM pairs). In the following, a group of three RCM simulations driven by the same GCM will be referred to as a ‘family’. This sample of the EURO-CORDEX ensemble illustrates the different kinds of aerosol representation in the RCMs, facilitating comparison among them and showing some of the effects that could be masked in a larger ensemble.

To measure the climate change signal, we decided to contrast a 30-year near-future period (2021–2050) to a similar period at the end of the 20th century (1971–2000). The focus on the near-future allows our results to be nearly independent of the chosen socio-economic scenario (here RCP8.5) and to maximize the aerosol effect with respect to the GHG effect. The choice of 30-year long periods makes it possible to minimize the uncertainty related to the natural
Table 1. RCMs from EURO-CORDEX used in the analysis and aerosol description grouped by the CMIP5 GCMs drivers. The institution’s name corresponds to the abbreviation used for the EURO-CORDEX dataset for the center that performs the climate simulations.

| Institution | CMIP5 GCM | Institution       | RCM           | Member | Aerosol description                                                                 | Classes                                                                 | Scenarios       |
|-------------|-----------|-------------------|---------------|--------|--------------------------------------------------------------------------------------|------------------------------------------------------------------------|-----------------|
| CNRM-CERFACS| CNRM-CM5  | CNRM              | ALADIN53      | r1ip1  | Climatology: Szopa 2013 [20]                                                        | Sea salt, sulfate, black carbon, desert dust, organic carbon           | Evolve with RCP |
|             |           | CLMcom            | CCLM4-8-17    | r1ip1  | Climatology: Tanré 1984 [18]                                                        | Sea, land, desert, urban                                               | No evolution    |
|             |           | SMHI              | RCA4          | r1ip1  | Parametrization in radiation fluxes                                                  | Single integrated class                                                | No evolution    |
|             |           |                   |               |        |                                                                                     |                                                                        |                 |
| ICHEC       | EC-EARTH  | KNMI              | RACMO22E      | r12ip1 | CAM inventory, Lamarque 2011 [21]                                                     | Sulfate, organic matter, desert dust, sea salt, stratospheric aerosols, volcanic | Evolve with RCP [22] |
|             |           | CLMcom            | CCLM4-8-17    | r12ip1 | Climatology: Tanré 1984 [18]                                                        | Sea, land, desert, urban                                               | No evolution    |
|             |           | SMHI              | RCA4          | r12ip1 | Parametrization in radiation fluxes                                                  | Single integrated class                                                | No evolution    |
|             |           |                   |               |        |                                                                                     |                                                                        |                 |
climate variability as only one realization of each GCM–RCM pair is usually computed in EURO-CORDEX. In addition, the PV power plants operating during 2021–2050 are the ones that will be planned shortly, so the results are timely for the industry.

### 2.2. Aerosol datasets

In table 1 the information about the aerosol datasets included in the EURO-CORDEX RCMs used in the study is presented (in table B1 and B2 of the appendix, information about the whole list of EURO-CORDEX models is presented). It can be observed that only two RCMs include time-evolving aerosols: RACMO22E and ALADIN53. Each of these RCMs has a different dataset of aerosols for future projections. The two other models do not have a realistic representation of aerosols in terms of AOD, as CCLM4-8-17 uses the climatology of Tanré et al (1984) [18], which is known to strongly overestimate AOD over Europe [19], and RCA4 has only a single integrated class for aerosols.

**Aerosol description in ALADIN53**

The aerosol dataset used in ALADIN53 runs is based on AOD fields for five different species: black carbon, organic carbon, dust, sea salt, and sulfate. It is described in Szopa et al (2013) [20] and built from the global LMDz-OR-INCA climate-chemistry coupled model. For the historical period it accounts for reference aerosol emissions, including seasonal cycles for each species and trends for the anthropogenic aerosol species (sulfate, black carbon, and organic carbon). The future simulations include the same temporal variations but follow the corresponding RCP8.5 scenario emissions. It is worth noting that this aerosol dataset has been used in two CMIP5 GCMs (IPSL-CM5 and CNRM-CM5) and in all the ARPEGE-ALADIN historical and scenario simulations performed in CORDEX whatever the domain, resolution, scenario, or running institute. In particular ALADIN53 and its driving GCM, CNRM-CM5, share the same aerosol forcing.

**Aerosol description in RACMO22E**

A spatial and vertically distributed dataset derived from the CAM inventory [21] is used in RACMO22E simulations. It accounts for six species (see table 1). The historical run also follows the reference emissions [21] and from 2006 it evolves in time with the RCP [22]. As well as for ALADIN53, the same aerosol implementation is used in RACMO22E and EC-EARTH. The same aerosol datasets based on historical and RCP-scenario CMIP emissions has been used in all simulations of EC-EARTH and RACMO22E.

### 3. Methods

The spatial behavior of SSR is analyzed by computing the yearly mean change for the period 2021–2050 with respect to the reference period 1971–2000. Additionally, the summer change is obtained by averaging the months June, July, and August (JJA), which correspond to the season when the AOD is higher over the Euro-Mediterranean area [23].

As an important driver of the variability of SSR, the total cloud cover variable (CLT) is also analyzed. This allows us to know if a correlation exists between the two variables and how this correlation is modified for models with or without evolving aerosols.

The so-called European averaged values presented in the text, in figure 2 and in table A1, are made for the latitude–longitude box (land and sea points): −15°W, 45°E, 30°N, and 65°N. It is important to note that for figure 2, we used all the 12 km scenario projections under the RCP8.5 scenario available at the time of the study.

### 3.1. PV potential

In order to obtain a projection of the PV productivity over Europe under climate change scenarios, a modeling chain approach is considered, which means that a sequence of models is applied to obtain different outputs. Short-wave solar radiation and temperatures from different climate simulations are used as inputs of a parametric PV model that gives an estimation of the power output.

The PV modeling process can be summarized in two steps: first, incident solar irradiation that reaches solar cells inside the panels is obtained through the decomposition of global solar irradiation and the transposition to the plane of array (POA). After that, the electrical performance of the system is modeled. Surface solar irradiation from climate models is equivalent to global horizontal plane irradiation (GHI).

Monthly means of SSR from climate models are decomposed first into the diffuse and direct beam components. The decomposition is made through a regression between the clearness index [24] (which represents the relationship between global irradiation at the horizontal plane and the extra-terrestrial irradiation) and the diffuse fraction (relationships between the diffuse component and GHI) [25].

The average daily irradiance (W m$^{-2}$) is obtained for each month [26], which enables different components to be obtained in the plane of the array. Direct irradiance in the tilted plane is obtained straightforwardly from geometrical criteria. The diffuse component is obtained using the Hay and McKay model [27].

The effective irradiation is then obtained from the consideration of optical losses due to the incident angle and dust accumulation [28]. Only a moderate dust accumulation degree is considered.

The second step transforms the ‘effective’ irradiation into power (productivity) (kWh/kWp) output considering the electrical performance of the system, where the productivity is the energy produced (kWh) divided by the power capacity (kWp) of the modeled PV plant. The system includes characteristics of a general PV module and inverter, the arrangement of the generator and some efficiency losses. The characteristics of the general PV system are the same as the ones
described in [29, 30]. Power from the PV generator also depends on the cell’s temperature. Mean temperature from climate models is also used to compute the cell’s temperature using the procedure explained in [30]. The whole process and the R package, solaR, used for the computation are described in detail in [31].

4. Results

4.1. Changes in AOD

The AOD changes for the two RCMs of the subsampling with evolving aerosols are presented in figure 1 and in table A1. The magnitude of the change in ALADIN53 is higher, with a maximum in the decrease of $-0.46$ whereas the maximum decrease for RACMO22E is $-0.36$. On average over Europe, RACMO (ALADIN) has an AOD decrease of $-0.1$ ($-0.2$). The spatial pattern for both is similar, with the maximum decrease over Central Europe. This AOD decrease is mostly due to the large decrease in sulfate aerosols [20, 32].

4.2. Changes in SSR and CLT

The mean summer (JJA) change for the period 2021–2050 with respect to the reference period 1971–2000 for SSR is represented in figure 2 for the whole list of EURO-CORDEX 12 km RCP8.5 simulations available.

Only ten simulations have a non-negligible positive mean change (above 2 W m$^{-2}$) and they are all carried out either with ALADIN (53 and 63) or RACMO22E. ALADIN in its two versions is the one with an average value above 10 W m$^{-2}$, followed by RACMO, which has a positive increase between 4 and 7 W m$^{-2}$ for all the runs and different driving GCMs. The multi-model mean change for the whole list of simulations is close to zero. Most of the models present an average change of around $-3$ W m$^{-2}$.

The spatial mean (JJA) changes in SSR and CLT for the six-member ensemble models are presented in figures 3 and 4.

The summer mean change for SSR shows an increase in Europe, more relevant in Central Europe and the Central Mediterranean, for both RCMs with evolving aerosols in scenarios (ALADIN53 and RACMO22E), although there are differences in the magnitude of the changes (see figure 3).

ALADIN53 presents the highest change over the European area (see values in table A1), as shown in figures 2 and 4. Both models present an overall positive change in line with the one presented by the corresponding driving GCMs. CNRM-CM5, which is the driver of the ALADIN53 family, has higher values for the SSR mean change, as can be seen in figure 3.

The rest of the RCMs, from the first and second family, present a similar change in SSR among them, with a slight decrease in SSR with the exception of southern and western Europe, where a small increase is projected.

Changes in CLT are relatively weak for all GCMs and RCMs (European average absolute values below 1%, see table A1 in the appendix) and have a patchy spatial pattern. RACMO and ALADIN seem, however, to show spatial patterns closer to their respective driving GCMs with an increase in the north of Europe and a decrease in the south.

Figure 1. AOD summer change (2021–2050 minus 1971–2000) for (left) ALADIN53 and (right) RACMO22E models. In the four other simulations (driven by CCLM4-8-17 and RCA4) the evolution in AOD is 0 over the whole domain.
The value of the spatial correlation between SSR and CLT is included in table A1 for every simulation in the six-member ensemble. Negative high correlations for simulations without evolving aerosols are between around $-0.7$ and $-0.8$. On the other hand, for ALADIN53 and RACMO22E the spatial correlation between these variables is much smaller with $-0.2$ and $-0.3$ respectively. The same spatial correlation coefficient is calculated between SSR and AOD variables, obtaining a very high value for ALADIN53, $-0.9$, and $-0.6$ for RACMO22E. On the whole, the CLT spatial pattern explains well the SSR spatial pattern in RCMs without evolving aerosols, whereas both AOD and CLT are required to explain the SSR spatial pattern in GCMs and RCMs with evolving aerosols. AOD pattern is even the dominant signal for ALADIN53.

Evolving aerosols play a major (even sometimes dominating) role in explaining the mean SSR climate change response over Europe as well as its spatial pattern. In addition, RCMs with evolving aerosols simulate SSR changes similarly to their driving GCM. Not taking evolving aerosols into account may lead to the wrong sign in the SSR projected changes in RCMs, as is the case in most of the EURO-CORDEX and probably CORDEX RCMs to date.

4.3. Projected changes in PV production

The PV yearly productivity as well as the monthly productivity, defined as the ratio between the power output and the nominal power capacity, is calculated for each pixel of land in the domain. The annual European averaged values are shown in table 2. For the summer months, i.e. the most important season for solar energy supply, the results of the relative changes, with respect to the reference period (1971–2000) and averaged by country, are shown in figure 5 and table 2.

The geographical distribution of the PV change is largely explained by the pattern of change in SSR projected by ALADIN53 and RACMO22E, which in itself
is closely related to the evolution of AOD in central Europe. The most important result is that the PV output summer change is positive for both RCMs with evolving aerosols in countries where the other RCMs give the opposite signal.

The simulations that do not include evolving aerosols have similar values, close to zero in western and southern Europe and negative for the central and northern areas. On the other hand, ALADIN53 presents a strong change for Central European countries with summer maximum increases above +10%.

RACMO22E has positive values but smaller in magnitude than for ALADIN53, with the maximum values around the countries of south-eastern Europe with values between 3%–4%.

The annual values of PV changes for the models without aerosol evolution in the whole domain is in the same order of magnitude between −2 to −0.5%. ALADIN53 projects a positive annual mean change of 3.2% and RACMO22E close to zero, −0.6%, as can be seen in table 2.

At the country level, some representative examples have been included in table 2. For ALADIN53 values above 10% are found in Germany, Hungary, and the Czech Republic, whereas lower values are found for Spain (2.4%), Italy (6.4%), or Greece (4.6%), although
Figure 4. Changes in mean summer CLT (%) for the period 2021–2050 with respect to 1971–2000.

Table 2. Relative change of annual PV and JJA PV with respect to the reference period for the whole domain and JJA PV relative change averaged by country. The first column is for the GCM model name, which includes the institute name and the GCM. The second column gives the RCM model names.

| CMIP5 GCM          | RCM      | ΔPV_{annual} | ΔPV_{JJA} | Spain  | Germany | Italy  | Greece | Hungary | Greece | Czech Republic |
|--------------------|----------|--------------|-----------|--------|---------|--------|--------|---------|--------|----------------|
| CNRM-CERFACS       | ALADIN5.3| 3.2%         | 2.7%      | 2.4%   | 10.9%   | 6.3%   | 4.6%   | 11.2%   | 12.0%  |                |
| CNRM-CM5           | CCLM4-8-17| −1.4%        | −0.8%     | −0.6%  | −2.2%   | −0.4%  | 0.3%   | −1.0%   | −1.6%  |                |
|                    | RCA4     | −1.5%        | −0.7%     | −0.8%  | −1.5%   | −0.4%  | −0.4%  | −0.5%   | −1.1%  |                |
| ICHEC-EC-EARTH     | RACMO    | −0.6%        | 0.6%      | 0.3%   | 1.4%    | 1.6%   | 2.3%   | 4.0%    | 2.5%   |                |
|                    | CCLM4-8-17| −2.3%        | −1.5%     | −0.6%  | −1.8%   | −0.6%  | −1.4%  | −1.8%   | −1.7%  |                |
|                    | RCA4     | −2.0%        | −0.7%     | −0.8%  | −0.3%   | −0.6%  | −0.9%  | −0.7%   | −0.4%  |                |
still positive. For the same countries, RACMO22E shows the highest increase in Hungary, 4%, and smaller values in the rest, from 0.4% in Spain to 2.5% in the Czech Republic.

These results suggest that for most parts of Europe, information from RCM projections might be misleading if a classical multi-model ensemble mean approach is used for this energy-related purpose.

5. Discussion and conclusion

One of the main issues in climate science is to determine the uncertainty in climate projections. Different RCM simulations, due to differences in their parameterization schemes and in their driving GCMs, can lead to a different response to the same socio-economic scenario forcing. For that reason, multi-model analysis has been largely considered to be the most accurate approach to study future projections [33].

Our study illustrates a case where model democracy [34] should be excluded. Indeed, a large majority of EURO-CORDEX simulations do not include evolving aerosols, which seems to be detrimental to the future climate information they can provide for SSR and PV potential in Europe. For that reason, this preliminary study is the first step towards illustrating the role of aerosols in RCM projections.

Uncertainties due to the different AOD datasets used as driving conditions in the two RCMs and in the representation of cloud–aerosol–radiation interactions make it difficult to provide a robust answer regarding the magnitude of the change in PV production. However, despite these limitations, the direct radiative forcing of aerosols had a dominating role in SSR trends over Europe [6, 35]. An ensemble with more simulations using evolving aerosols would also reinforce the robustness of our results.

For the mid-century, an increase in PV potential is projected over Europe when the evolution of aerosols over the area is considered. The magnitude of the change depends on the country, the most impacted areas being those in Central Europe, with an important potential increase of more than 10% in summer for some countries. That increase could lead to an increase in the amount of energy produced in the lifetime of a PV plant, as has been seen in previous studies [8]. However, there is also large uncertainty between RCMs. That uncertainty could be partly related to different cloud representation in the RCMs. We are aware that the chosen periods probably maximize the aerosol effect because (1) the reference period includes the 1980s, when the aerosol load was at its maximum over Europe, and (2) the GHG effect is still moderate during the chosen future period.

The study shows that results of RCMs with time-evolving aerosols in the scenario are completely different from those that have an aerosol climatology constant in time. The sign of the change in the mean summer SSR of these models reverses, in agreement with the positive signal projected by GCMs. In contrast, RCMs with a constant climatology for future
scenarios agree with previous studies on the solar resource and SSR. Thus, the study illustrates the key role of the often-neglected aerosol forcing evolution in RCMs. In previous studies, the ensemble approach has been considered to evaluate the impact of climate change in renewable resources [12–14]. However, due to the fact that a large number of RCMs do not consider aerosol evolution, their impact is masked by the ensemble mean approaches. Our results argue for the inclusion of evolving aerosols in the next generation of CORDEX simulations.

The impacts of missing evolving aerosols on other climate variables such as surface temperature, water cycle, or extremes are likely and should be further assessed [36].

Our study illustrates the European case but other regions in the world are also known to face strong AOD values such as South-East Asia, North America and Amazonia. Therefore, our main findings may apply to other CORDEX domains.

More generally, an effort should be made to check and understand GCM–RCM inconsistencies, if any, in order to enhance the credibility of RCM projections and to deliver more robust information for climate change impact and adaptation studies.

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**Data availability**

The data that support the findings of this study are available upon reasonable request from the authors. In addition, the data that support the findings from climate simulations from CMIP5 and EURO-CORDEX are available on the Portal Earth System Grid Federation (ESGF node); therefore, the input variables for the PV model can be downloaded from there. The PV model used in this study is an open source tool written in R language [31], which can be used freely and the code can be downloaded from github at https://github.com/oscarperpinan/solar.

**Appendix A. Mean changes**

Table A1. European spatial mean JJA changes (2021–2050) with respect to the reference period (1971–2000) for SSR, CLT, and AOD; and spatial correlation between SSR, CLT, and AOD maps (−15W, 45E, 30N, 65N; computed over land and sea).

| CMIP5 GCM | RCM      | ΔSSR (W m⁻²) | ΔCLT (%) | ΔAOD   | ρSSR,CLT | ρSSR,AOD |
|----------|----------|--------------|----------|--------|----------|----------|
| CNRM-CERFACS-CNRM-CM5 | ALADIN53 | 9.9          | 0.5      | −0.2   | −0.4     | −0.8     |
|          | CCLM4-8-17 | −2.4        | −0.8     | —      | −0.7     | —        |
|          | RCA4     | −2.6        | 0.2      | —      | −0.8     | —        |
| ICHEC-EC-EARTH | RACMO22E | 5.6          | −0.3     | −0.1   | −0.3     | −0.6     |
|          | CCLM4-8-17 | −2.7        | −0.9     | —      | −0.8     | —        |
|          | RCA4     | −2.1        | 0.1      | —      | −0.8     | —        |
### Appendix B. EURO-CORDEX ensemble

#### Table B1. RCMs from the EURO-CORDEX ensemble and aerosol description for the evaluation runs. The dashed line indicates that aerosols are not included.

| Institute | RCM | Aerosol classes | Climatology | Spatial pattern | Temporal variability |
|-----------|-----|-----------------|-------------|-----------------|----------------------|
| AUTH-MC   | WRF-AUTH | Organic carbon, black carbon, sulfate, sea salt, dust | Tegen 1997 [37]; MACv1; MACC, GOCART (Pavlidis et al 2019 [38]) | 5° longitude and 4° latitude; 1°; 80 km; | Monthly variation |
| BCCR      | WRF1C2      | —                | —           | —               | —                    |
| CHMI      | ALADIN51     | Organic carbon, black carbon, sulfate, sea salt, dust | Szopa 2013 dataset [20] (LMDZ-OR-INCA GCM runs in ACCMIP) | 2D maps for each class; one vertical profile per class | Seasonal cycle for each class and trend for SU, OC, BC following HIST runs (no trend for SD and SS) |
|           | ALADIN52     | —                | —           | —               | —                    |
| CLMcom (BTU, DWD, ETHZ, UCD, WEGC) | CCLM4-8-17 CCLM5-0-6 | Sea, land, desert, urban | Tanré et al 1984 [18] | Hard-coded T10 coefficients for each of the four classes; prescribed vertical profiles | No seasonal cycle and no trends for AOD |
| CNRM      | ARPEGE51 ALADIN52 ALADIN53 | Organic carbon, black carbon, sulfate, sea salt, dust | Szopa 2013 dataset [20] (LMDZ-OR-INCA GCM runs in ACCMIP) | 2D maps for each class; one vertical profile per class | Seasonal cycle for each class and trend for SU, OC, BC following HIST runs (no trend for SD and SS) |
| CNRM      | ALADIN63     | Organic carbon, black carbon, sulfate, sea salt, dust | TACTIC aerosol dataset [39] | 2D maps for each class; one vertical profile per class | Seasonal cycle for each class and trend for SU, OC, BC following HIST runs (no trend for SD and SS) |
| CRP-GL    | WRF331A      | Organic carbon, black carbon, sulfate, sea salt, dust, volcanic | Collins et al 2001 [40] | Uniform background with vertical profile (29 levels) | Constant in time |
| CUNI      | RegCM4-2     | —                | —           | —               | —                    |
| DHMZ      | RegCM4-2     | —                | —           | —               | —                    |
| DMI       | HIRHAM5      | No info          | Climatology unknown | No info | No temporal evolution |
| ETH       | COSMO-crCLIM-v1.1 | Black carbon, POM, sulfate, sea salt, dust | AeroCom, Kinne et al 2006 [41] | 2D dataset of 1 x 1 spatial resolution for each class | Monthly mean values for the base year 2000 |
| GERICS    | REMO2009     | Sea, land, desert, urban | Tanré et al 1984 [18] | Low-resolution 2D map, prescribed vertical profiles | No seasonal cycle, no trend |
|           | REMO2015     | —                | —           | —               | —                    |
### Table B1. (Continued.)

| Institute       | RCM                | Evaluation                                                                 |
|-----------------|--------------------|-----------------------------------------------------------------------------|
| **HMS**         | **ALADIN52**       | Organic carbon, black carbon, sulfate, sea salt, dust                       | Szopa 2013 dataset [20] (LMDZ-OR-INCA GCM runs in ACCMIP) 2D maps for each class; one vertical profile per class Seasonal cycle for each class and trend for SU, OC, BC following HIST runs (no trend for SD and SS) |
| **ICTP**        | RegCM4-4 RegCM4-6  | —                             | —                                                                           |
| **IDL**         | WRF3.5             | Organic carbon, black carbon, sulfate, sea salt, dust, stratospheric aerosol | Tegen 1997 [37] With height and latitudinal (2.82°) Monthly variation |
| **IPSL–INERIS** | WRF361H WRF381P    | Continental, desert, volcanic, maritime urban, stratospheric background     | Hess et al 1998 (con., mar., des., urb.) [42], Bonnel et al (vol., str.) Probably no Constant in time |
| **KNMI**        | RACMO22E           | Sulfate, particulate organic matter black carbon, sea salt, desert dust stratospheric aerosols, volcanic aerosol | Inferred from CAM inventory (except volcanic) [21]; historical until 2005 RCP8.5 from 2006 [22] Spatial maps and vertical profiles per species Monthly variations and decadal trends |
| **MIUB**        | WRF361N            | —                             | —                                                                           |
| **MPI-CSC**     | REMO2009           | Sea, land, desert, urban                                                   | Tanré et al 1984 [18] Low-resolution 2D map, prescribed vertical profiles No seasonal cycle, no trend |
| **RMIB–UGent**  | ALARO-0            | Land, sea, soot, desert                                                    | —                                                                           |
| **SMHI**        | RCA4               | Single integrated class                                                    | Parametrized aerosol effect on radiation fluxes Uniform Constant in time |
| **UCAN**        | WRF3411            | Organic carbon, black carbon, sulfate, sea salt, dust, volcanic            | Collins et al 2001 [40] Uniform background with vertical profile (29 levels) Constant in time |
| **UCLM**        | PROMES             | Organic, black carbon, sulfate, sea salt, dust                            | Tegen 1997 [37] 2D maps for each class; one vertical profile per class Monthly variation |
| **UHOH**        | WRF331H WRF361H    | Organic, black carbon, sulfate, sea salt, dust                            | Collins et al 2004 [43] 3D distributions of aerosol mass Monthly variations |
| **UKMO**        | HadGEM3-GA7.01     | MACv2-SP dataset [44], total aerosol properties, nine bands                | Based on MACv2-SP [45] 3D maps Monthly variations |
| **UM**          | WRF361             | GOCART scheme: sulfate (SU), black carbon (BC), sea salt (SS), desert dust (DD), organic carbon (OC) | Aerosols are estimated online 3D distribution of aerosols. Emissions from HTAPv2.2 Online aerosols (hourly variation estimated every time step) |
Table B2. RCMs from EURO-CORDEX ensemble and aerosol description for the scenario runs. The RCMs marked * are those used in figure 2, while the RCMs in bold include time-evolving aerosols. The dashed line means that aerosols are not included.

| Institute          | RCM          | Aero classes                      | Climatology                                      | Spatial pattern         | Temporal variability |
|--------------------|--------------|-----------------------------------|--------------------------------------------------|-------------------------|----------------------|
| AUTH-MC            | WRF-AUTH     | Organic carbon, black carbon, sulfate, sea salt, dust | Based on MACC reanalysis (Innes et al, 2013) [46] | 80 km resolution       | Monthly variation    |
| BCCR               | WRF1C2       | —                                 | —                                                | —                       | —                    |
| CHMI               | ALADIN51     | Organic carbon, black carbon, sulfate, sea salt, dust | Forcing dataset as the driving GCM (Szopa 2013 [20] for CNRM-CM5) | 2D maps for each class, one vertical profile per class | Same forcing dataset as the driving GCM following RCP scenarios (Szopa 2013 [20] for CNRM-CM5) |
|                    | ALADIN52     |                                    |                                                  |                         |                       |
| CLMcom (BTU, DWD, ETHZ, UCD, WEGC) | CCLM4-8-17’/ CCLM5 – 0-6 | Sea, land, desert, urban | Tanré et al 1984 [18] | Hard-coded T10 coefficients for each of the four classes; prescribed vertical profiles | No seasonal cycle and no trends for AOD |
| CNRM               | ARPEGE51     | Organic carbon, black carbon, sulfate, sea salt, dust | Forcing dataset as the driving GCM (Szopa 2013 [20] for CNRM-CM5) | 2D maps for each class, one vertical profile per class | Same forcing dataset as the driving GCM following RCP scenarios (Szopa 2013 [20] for CNRM-CM5) |
|                    | ALADIN53’    |                                    |                                                  |                         |                       |
| CNRM               | ALADIN63’    | Organic carbon, black carbon, sulfate, sea salt, dust | Forcing dataset as the driving GCM (Szopa 2013 [20] for CNRM-CM5) | 2D maps for each class, one vertical profile per class | Same forcing dataset as the driving GCM following RCP scenarios (Szopa 2013 [20] for CNRM-CM5) |
| CRP-GL             | WRF331A      | Organic carbon, black carbon, sulfate, sea salt, dust, volcanic | Collins et al 2001 [40] | Uniform background with vertical profile (29 levels) | Constant in time |
| CUNI               | RegCM4-2     | —                                 | —                                                | —                       | —                    |
| DHMZ               | RegCM4-2     | —                                 | —                                                | —                       | —                    |
| DMI                | HIRHAM5’     | No info                           | Climatology unknown                              | No info                 | No temporal evolution |
| ETH                | COSMO-crCLIM-v1.1 | Same as evaluation runs          | Same as evaluation runs                          | Same as evaluation runs | Same as evaluation runs |
| GERICS             | REMO2009’/ REMO2015’ | Sea, land, desert, urban         | Tanré et al 1984 [18] | Low-resolution 2D map, prescribed vertical profiles | No seasonal cycle, no trend |
| HMS                | ALADIN52     | —                                 | —                                                | —                       | —                    |
Table B2. (Continued.)

| Institute     | RCM                  | Scenarios                                                                 |
|---------------|----------------------|---------------------------------------------------------------------------|
| ICTP          | RegCM4-4 RegCM4-6    | 2D maps for each class; one vertical profile per class                    |
|               |                      | Same forcing dataset as the driving GCM following RCP scenarios (Szopa 2013 [20] for CNRM-CM5) |
| IDL           | WRF3.5               | Organic carbon, black carbon, sulfate, sea salt, dust                    |
|               |                      | Tegen 1997 [37]                                                          |
|               |                      | With height and latitudinal (2.82°)                                     |
|               |                      | Following RCP8.5 scenario                                                |
| IPSL-INERIS   | WRF361H* WRF381P*    | Continental, desert, volcanic, maritime urban, strato background         |
|               |                      | Hess et al. 1998 (con., mar., des., urb.), Bonnel et al. (vol., str.)    |
|               |                      | Probably no                                                             |
|               |                      | Constant in time                                                        |
| KNMI          | RACMO22E*            | Sulfate, particulate organic matter black carbon, sea salt, desert dust stratospheric aerosols, volcanic aerosol |
|               |                      | RCP-prescription (2006–onwards) based on Van Vuuren et al. 2011 [47] and Lamarque 2011 [22] |
|               |                      | Spatial maps and vertical profiles per species                           |
|               |                      | Monthly variations and decadal trends                                   |
| MIUB          | WRF361N              | —                                                                         |
|               |                      | —                                                                         |
|               |                      | —                                                                         |
| MPI-CSC       | REMO2009*            | Sea, land, desert, urban                                                 |
|               |                      | Tanré et al. 1984 [18]                                                  |
|               |                      | Low-resolution 2D map, prescribed vertical profiles                      |
|               |                      | No seasonal cycle, no trend                                              |
| RMIB-UGent    | ALARO-0              | Same as evaluation runs                                                  |
|               |                      | No info                                                                  |
|               |                      | Same as evaluation runs                                                  |
| SMHI          | RCA4*                | Single integrated class                                                  |
|               |                      | Parametrized aerosol effect on radiation fluxes                          |
|               |                      | Uniform                                                                  |
|               |                      | Constant in time                                                         |
| UCAN          | WRF3411              | Same as evaluation runs                                                  |
|               |                      | Same as evaluation runs                                                  |
|               |                      | Same as evaluation runs                                                  |
|               |                      | Constant in time                                                         |
| UHOH          | WRF361H*             | Organic, black carbon, sulfate, sea salt, dust                          |
|               |                      | Collins et al. 2004 [43]                                                 |
|               |                      | 3D distributions of aerosol mass                                         |
|               |                      | Monthly variations                                                       |
| UKMO          | HadGEM3-GA7.01       | Historical period as eval., EasyAerosol (Voigt et al. 2014) [48] RCP scenarios |
|               |                      | Based on MAC [45]                                                       |
|               |                      | 3D maps                                                                  |
|               |                      | Time-varying aerosol following RCPs                                      |
| UM            | WRF331               | Same as evaluation runs                                                  |
|               |                      | Same as evaluation runs                                                  |
|               |                      | Same as evaluation runs                                                  |
|               |                      | Same as evaluation runs                                                  |
ORCID iDs
C Gutiérrez DOI: https://orcid.org/0000-0002-6747-6850
S Somot DOI: https://orcid.org/0000-0002-5066-2921
O Perpiñán DOI: https://orcid.org/0000-0002-4134-7196
M A Gaertner DOI: https://orcid.org/0000-0001-9909-8826

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