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Delivering an Improved Framework for the New Generation of CMIP6-Driven EURO-CORDEX Regional Climate Simulations

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ABSTRACT: The Coordinated Regional Downscaling Experiment (CORDEX) is a coordinated international activity that has produced ensembles of regional climate simulations with domains that cover all land areas of the world. These ensembles are used by a wide range of practitioners that include the scientific community, policymakers, and stakeholders from the public and private sectors. They also provide the scientific basis for the Intergovernmental Panel on Climate Change-Assessment Reports. As its next phase now launches, the CMIP6-CORDEX datasets are expected to populate community repositories over the next couple of years, with updated state-of-the-art regional climate data that will further support national and regional communities and inform their climate adaptation and mitigation strategies. The protocol presented here focuses on the European domain (EURO-CORDEX). It takes the international CORDEX protocol covering all 14 global domains as its template. However, it expands on the international protocol in specific areas; incorporates historical and projected aerosol trends into the regional models in a consistent way with CMIP6 global climate models, to allow for a better comparison of global versus regional trends; produces more climate variables to better support sectorial climate impact assessments; and takes into account the recent scientific developments addressed in the CORDEX Flagship Pilot Studies, enabling a better assessment of processes and phenomena relevant to regional climate (e.g., land-use change, aerosol, convection, and urban environment). Here, we summarize the scientific analysis which led to the new simulation protocol and highlight the improvements we expect in the new generation regional climate ensemble.

SIGNIFICANCE STATEMENT: As climate change affects all aspects of human life, it is imperative to have access to high-quality state-of-the-art regional climate data in order to serve emergent societal needs. A high level of coordination and a design protocol are required, when large climate model datasets are produced, with the aim to be used by a broader community of scientists and stakeholders. In this work, we present the framework within which the next generation of regional climate model simulations over Europe will be produced. We provide the relevant scientific background, underlying the decisions taken to form the protocol and the improvements we expect in comparison with the previous data repository. This work aims to provide valuable information and guidance to the users of regional climate data produced within the European Coordinated Regional Downscaling Experiment (EURO-CORDEX).

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1. Introduction

As the impacts of climate change demonstrably result in costly damage to communities and ecosystems, climate scientists are deeply engaged in the coordination of climate modeling research. This endeavor aims to enhance the ability of climate models to accurately reproduce historical climate trends and in turn improve their ability to provide robust projections of future climate. There are two foundational climate modeling experiments currently operating under the auspices of the World Climate Research Program (WCRP): the Coupled Model Intercomparison Project (CMIP) for global scale and the Coordinated Regional Climate Downscaling Experiment (CORDEX) for regional scale (Giorgi et al. 2009). These two programs provide the scientific basis for the assessments of working group I of the Intergovernmental Panel on Climate Change (IPCC), an international body with the aim to provide policymakers with regular scientific updates on climate change and its implications.

The regional climate model simulations produced within EURO-CORDEX driven by CMIP5 global climate models (GCMs) (i.e., the global models provided the lateral boundary conditions for the regional models) were included in the recent release of the Sixth IPCC Assessment Report (IPCC 2021) and its interactive Atlas (Gutiérrez et al. 2021). They were also incorporated in the Copernicus Climate Change Climate Data Store facilitating their wider distribution and use (Diez-Sierra et al. 2022). Additionally, the CORDEX Coordinated Output for Regional Evaluations (CORDEX-CORE) EXP-I initiative provided worldwide downscaled information to increase understanding of processes relevant for regional climate change and impacts and to assess the added value of regional climate models (Giorgi et al. 2022).

The upcoming CMIP6-driven CORDEX dataset is expected to populate community repositories over the next couple of years, with data arising from updated state-of-the-art regional climate models nested into the latest generation of global climate models, that will further support national and regional communities and inform their climate adaptation and mitigation strategies.

Our focus is on EURO-CORDEX, which gathers CORDEX activities focusing over the European domain; we present the experiment design for the dynamical downscaling of CMIP6 global climate data, which is binding for the members contributing to the EURO-CORDEX ensemble. This new design aims to serve as a reference for regional climate modelers, wishing to contribute to the new EURO-CORDEX datasets, as well as regional climate data users, who are interested in using regional climate data for their downstream investigations and development of services. This new protocol for the European domain takes the international CORDEX-CMIP6 experimental design covering all 14 global domains as a basis and expands it in several specific areas, according to the priorities and capabilities of the European modeling community.

2. Preparation of a new protocol for the dynamical downscaling activities over Europe

Since 2009, the EURO-CORDEX community has coordinated the dynamical and more recently statistical downscaling and climate information distillation activities over Europe (Jacob et al. 2014, 2020). Together with several CORDEX Flagship Pilot Studies (FPSs), which cover a wide range of state-of-the-art research topics (convective permitting simulations, land-use change, aerosol, and urban climate), they have contributed to improved process understanding at local to regional scales and have produced open-access regional climate ensembles for climate change and impact study assessments.

As the new global-scale simulations are available within the CMIP6 framework (Eyring et al. 2016), the CORDEX community is getting prepared to dynamically downscale these new global datasets. The EURO-CORDEX community took the decision to coordinate a new set of simulations driven by CMIP6 GCMs in their 2019 Annual Meeting. Task teams with the aim to work on different aspects of the new experiment protocol were set up in the 2020 Annual Meeting, especially for those not covered by existing FPSs. During the 2021 Annual Meeting, with the first common baseline CORDEX experiment design for the dynamical downscaling of CMIP6 (CORDEX 2021), the EURO-CORDEX community took the decision to boost the finalization of the experiment design of the European contribution to CMIP6-CORDEX by means of a series of workshops to be held during that year (Table 1). Below, we present the fundamental ideas behind the construction of this new experimental design; we present the rationale for our approach, highlighting the differences from the previous downscaling activities driven by CMIP5 GCMs and also the novelties with respect to the general CMIP6-CORDEX design. This work can serve as a guide for both the modeling community and the users of EURO-CORDEX data, in their effort to interpret properly the new datasets in due course.

3. Modeling aspects

a. Types of experiments. CORDEX considers three types of simulation experiments, namely, evaluation, historical, and scenario projections (Giorgi and Gutowski 2015). Evaluation experiments are forced by a state-of-the-art reanalysis dataset, providing a realistic boundary forcing to the regional climate simulations. The evaluation experiments in the EURO-CORDEX domain have been used extensively to provide assessments of the model performance (e.g., Katragkou et al. 2015; Kotlarski et al. 2014; Vautard et al. 2013). A new reanalysis product developed within the Copernicus Climate Service by ECMWF, ERA5 (Hersbach et al. 2020) will drive the CORDEX-CMIP6 evaluation experiments for the time period 1979–2021. In comparison with the ERA-Interim reanalysis, which drove the evaluation experiments of the previous CMIP phase, ERA5 has higher horizontal resolution (31 vs 80 km) and, therefore, provides more suitable boundary conditions for the new high-resolution regional climate modeling simulations. Moreover, ERA5 saves output with hourly frequency and shows better performance than ERA-Interim, as a result of developments in model physics, dynamical core, and data assimilation.

CORDEX-CMIP6 historical simulation experiments will be performed for the time period 1950–2014, with a minimum requirement from 1960 to 2014. From 2015 onward, projection simulations will extend up to 2100, following one of the Shared Socioeconomic Pathway (SSP) scenarios (Meinshausen et al. 2020). While each modeling group may select any CMIP6 GCM to dynamically downscale the European domain, the EURO-CORDEX community has prioritized several GCMs that fulfill specific criteria concerning availability,

Table 1. EURO-CORDEX workshop series for decision making on CMIP6-CORDEX simulations over the European domain.

Date	EURO-CORDEX workshop
10 Mar 2021	Aerosol and land-use forcing
19 Apr 2021	Prioritization of SSP forcing scenarios
28 Jun 2021	GCM evaluation and selection
8 Oct 2021	Convection permitting strategy

plausibility, future spread, and independence (Sobolowski et al. 2024, hereafter "Balanced Ensemble Design"). Driving this, effort was a recognition that a more robust and transparent assessment of driving GCMs will improve the final ensemble. Therefore, nine CMIP6 GCMs are suggested for downscaling in EURO-CORDEX (Table 2 in Sobolowski et al. 2024). Furthermore, taking into consideration issues like balance of the ensemble, physical consistency, and range of uncertainty, seven RCMs were suggested to fill the EURO-CORDEX balanced matrix (Table 3 of Sobolowski et al. 2024). This effort has a dual aim: 1) to improve the approach to ensemble construction in this next phase of simulations and 2) to promote the early availability of a balanced subset of simulations that can be used by downstream vulnerability, impacts, adaptation, and climate services practitioners. This latter point is meant to avoid choosing uninformed or poorly informed subsampling of the larger EURO-CORDEX ensemble.

In response to the increasing scientific and societal demand for detailed climate information, the EURO-CORDEX 0.44° domain (~50 km) is considered phased out in CORDEX-CMIP6, a resolution of 0.11° is required by all modeling groups, while the 0.22° domain (~25 km) (Fig. 1) can be used but will not be part of the EURO-CORDEX Balanced Ensemble Design.

Spectral nudging is not required. However, the lateral boundaries can be nudged if modeling teams so choose. Nudging in the interior of the domain is not allowed for any types of simulations. A 3-hourly update frequency of boundary conditions is requested from regional modeling teams, whereas a 6-hourly interval is not ruled out. At least 1 year of spinup time is mandatory for each modeling experiment; however, more years may be required depending on the specifications of the land surface model used and whether coupled components [e.g., surface/subsurface hydrology turning the model into a so-called Regional Earth System Model (RESM)] are included. Several years of spinup time have been shown to be necessary when higher-resolution simulations are performed (Mooney et al. 2020).

b. Scenarios. Scenarios are used in climate change research to evaluate climate change impacts and adaptation measures under various greenhouse gas emissions trajectories. All regional climate models referenced in the IPCC-AR6 reports used the representative

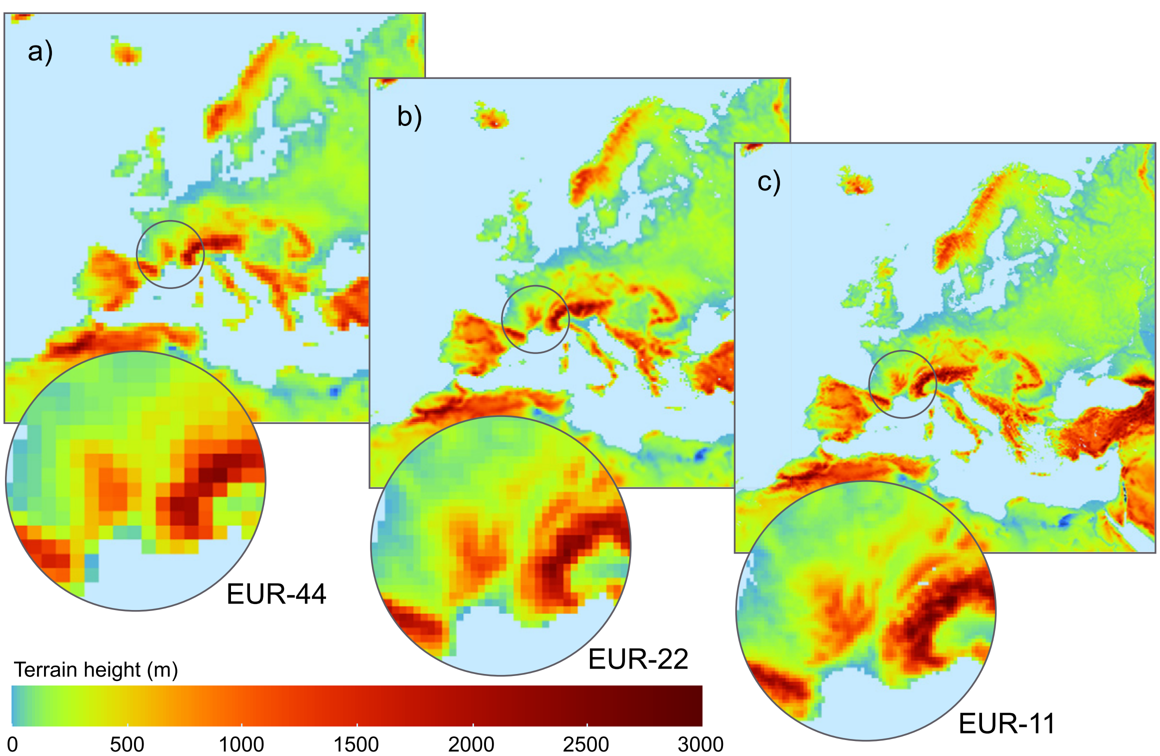

Fig. 1. Orography in the EURO-CORDEX domains: (a) 0.44°, domain size 106 × 103 grid cells, (b) 0.22°, domain size 225 × 201 grid cells, and (c) 0.11°, domain size 424 × 412 grid cells.

concentration pathways (RCPs), the four pathways that result in a radiative forcing between 2.6 and 8.5 W m^{-2} at the year 2100 (van Vuuren et al. 2011). Adoption of a scenario for an RCM implies that a specific scenario of the coupled GCM will force the regional model and that the necessary evolution of GHGs will be prescribed within the RCM to interact with the radiative scheme.

In the current protocol, all models will follow the greenhouse gas concentrations of the nine SSPs, which represent and evolution of the previous generation scenarios (RCPs) and cover a more policy-relevant scenario space (O'Neill et al. 2014). Briefly, the SSP1 family corresponds to "sustainability," SSP2 to the "middle-of-the-road" scenario, SSP3 to "regional rivalry," SSP4 to "inequality," and SSP5 to "fossil fuel development." In the long run, all scenarios should appear in the EURO-CORDEX ensemble, as all of them are plausible future and contribute to key questions addressed by climate services. However, due to resource demands (both computational and human), prioritization is required, and some scenarios have been prioritized in the simulation protocol and thus will appear sooner in the EURO-CORDEX archives. The discussion around scenario priorities was held during a EURO-CORDEX community workshop (Table 1) that aimed to align climate science user needs and CORDEX's desire to provide information across a range of outcomes, with the current best understanding of scenario likelihoods.

As first-priority scenarios for the EURO-CORDEX community were considered SSP1-2.6 and SSP3-7.0, the first is the "2°C scenario" of the SSP1 socioeconomic family, whose radiative forcing level is 2.6 W m^{-2} (roughly corresponds to RCP2.6). The second is a medium-high reference scenario within the SSP3 socioeconomic family, with the highest methane and air pollution precursor emissions and a radiative forcing of 7.0 W m^{-2}. As second and third priority scenarios were chosen SSP2-4.5 followed by SSP5-8.5; a middle-of-the-road scenario (roughly corresponding to RCP4.5) and a high-reference scenario corresponding to a world in which continued fossil fuel development is aggressively pursued. Priorities assigned within the EURO-CORDEX community by no means should be interpreted as a sign of likelihood. The prioritization will help regional modelers to build representative ensembles more quickly and efficiently so that the data can be easily taken up by users, instead of uncoordinated GCM-RCM-SSP combinations which cannot contribute to meaningful climate impact interpretations.

In accordance with the general CORDEX-CMIP6 guidelines, all the above four scenarios are identified as high-priority (Tier 1) scenarios for IPCC-AR6. The IPCC-AR6 "Tier 2" scenarios within the socioeconomic context of an "unequal" world (SSP4-6.0 and SSP4-3.4) are not excluded in the EURO-CORDEX simulations; however, they are given a lower priority. They might eventually appear in the archives but at a later time.

c. Aerosol forcing. The CORDEX community has to date no specific recommendations on aerosol forcing in any of its three types of experiments (evaluation, historical, and projections). Aerosol implementation for each EURO-CORDEX modeling group was based on individual choice of available aerosol climatologies and model complexity, i.e., the ability of a model to include interactive aerosol and chemistry speciation and associated direct, indirect, and semidirect effects. In the CMIP5-driven EURO-CORDEX ensemble, the aerosol forcing was implemented with different degrees of sophistication; a few models did not incorporate aerosols in their simulations at all, while the majority included time-invariant aerosol climatologies without interannual variability [cf. Tables B1 and B2 in Gutierrez (2020)].

According to the findings of the CORDEX-FPS on aerosols, the evolution of anthropogenic aerosols explained a significant part of the observed inconsistency between GCMs and RCMs for temperature and radiation over Europe in the summer season. Specifically, an increase of 0.3°C/6.7 W m^{-2} is noted for every 0.1 decrease of aerosol optical depth over central Europe

(P. Nabat 2023, personal communication). Additionally, Gutiérrez et al. (2020) showed that the solar surface radiation mismatch between CMIP5-GCM and RCMs, as identified by Bartók et al. (2017), was alleviated when models incorporated the GCM aerosol forcings. Along the same lines, Nabat et al. (2014a,b), Boé et al. (2020), and Drugé et al. (2021) demonstrated the important role of evolving aerosols in climate projections on temperature, radiation, and the water cycle.

During a dedicated workshop (Table 1), the EURO-CORDEX community decided that for the CMIP6 downscaling production simulations, aerosol radiative forcing is mandatory and will include monthly and interannual variability. Models that are not able to incorporate aerosol forcing as requested will not be part of the official EURO-CORDEX Balanced Ensemble Design. To provide input for this new exercise, the CORDEX-FPS on aerosols prepared an evolving aerosol dataset to be implemented in the evaluation simulations. The dataset includes the 1980–2021 global 3D distributions of monthly spectrally resolved aerosol optical properties relevant to GCM and RCM radiative transfer schemes, including total and species-level aerosol optical depths, as well as aerosol extinction, single scattering albedo, and asymmetry parameter profiles. The aerosol fields were recalculated from the raw NASA MERRA-2 3-hourly aerosol reanalysis (Buchard et al. 2017; Randles et al. 2017), which has been chosen over CAMS reanalysis mostly due to a more extended temporal coverage. Specific aerosol mixing ratios (including five bins for dust and sea salt, two bins for fresh and aged organic and black carbon, and one bin for sulfates) and relative humidity (GMAO 2015) were combined with species-level aerosol optical properties, given for different humidity levels and spectral bands and consistent with the aerosol model used in MERRA-2 reanalysis (Chin et al. 2002; P. Colarco et al. 2010; P. R. Colarco et al. 2014; Gelaro et al. 2017). The spectral bands are based on the widely used RRTMG broadband radiative transfer scheme for shortwave and longwave and can be adapted to other radiative schemes used in RCMs. For limiting the size of generated files, dust and sea salt bin level optical properties have been lumped into a single dust and sea salt bin. The aerosol forcing of the spinup year (1979) which is not covered by MERRA-2 will be a replica of 1980.

The resulting effective optical property distributions are provided on the native MERRA-2 grid (0.5° latitude × 0.625° longitude × 72 hybrid levels, including the stratosphere) along with the monthly MERRA-2 surface pressure, pressure layer thickness, and layer air density fields, ensuring easy interpolation to RCM vertical coordinates, with the possibility to consider or not stratospheric aerosol optical properties variations. For the visible band, aerosol optical depths recalculated from extinction profiles are consistent with the official MERRA-2 monthly aerosol visible optical depth provided by Global Modeling and Assimilation Office (GMAO). This reconstructed dataset extends available information to additional optical properties (absorption/diffusion) as well as vertical and spectral distributions. Data are available for downloading on the AERIS (Data and Services for the Atmosphere) (Solmon 2022). Groups are free to select whether they will use the postprocessed MERRA-2 data or another product of their choice for aerosol forcing, provided it includes a realistic aerosol trend, which could be comparable to the reanalysis.

The implementation of the datasets in specific RCMs might require developments at the radiative scheme interface. Ideally, the monthly extinction, SSA, and asymmetry parameter should be interpolated at run time or through preprocessing on the RCM grid (including an eventual stratospheric hat) and feed the radiative scheme. As a minimum requirement is set the use of the visible aerosol optical depth (AOD) or AOD550 evolution in order to at least constrain the aerosol surface direct radiative forcing. At the EURO-CORDEX aerosol technical implementation meeting, held in September 2022, different options for the technical implementation were discussed among the involved parties. Since each modeling system requires different preprocessing and level of information on aerosol data, it was decided that it will be necessary for groups to provide detailed documentation on the methodology followed. Accounting for indirect aerosol effects would require the groups to use interactive aerosol schemes coupled to microphysics or using further assumptions [e.g., Max Planck Institute Aerosol Climatology, version 2, Simple Plume (MACv2-SP) approach; Stevens et al. 2017].

For the historical and projection simulations, each modeling group will use preferably the aerosol forcing of the driving GCM, to ensure maximum compatibility with the large-scale forcing or any product including the historical aerosol trend and the trend under a specific scenario, respectively. Since the aerosol information provided by the driving GCM is sometimes minimal (e.g., just the total AOD), adoption of several assumptions on composition, vertical distribution, and other optical properties might be necessary. Alternatively and similarly to a number of CMIP6 GCMs, the MACv2-SP approach can also be used in RCMs to get a representation of aerosol property evolution compatible with different SSP scenarios. For the EURO-CORDEX domain, preliminary results using a single regional model (WRF) showed that the total AOD is likely to be the first-order driving parameter; however, changes in composition and the absorption/diffusion profiles might also be important for subregional scales (Pavlidis et al. 2020) and for other CORDEX domains with significant trends in absorbing aerosol.

Figure 2 shows the comparison of AOD550 annual means between the MERRA-2 reanalysis (first column) and the aerosol of four out of nine CMIP6-GCMs identified in the Balanced Ensemble Design as provided in Table 2 in Sobolowski et al. (2024) (NorESM2-MM, MIROC6, MPI-ESM1-2-HR, CNRM-ESM2-1, CESM2, CMCC-CM2-SR5, IPSL-CM6A-LR, EC-Earth3-Veg, and UKESM1-0-LL) (next four columns) for the years 1980, 1990, 2000, 2010, and 2020 (rows). The differences can be large, as some models (MPI-ESM1-2-HR) incorporate stratospheric aerosol while others do not, or there may be differences in aerosol schemes and properties. To better understand the differences in the time evolution of aerosols between the different GCMs participating in the EURO-CORDEX Balanced Ensemble Design and the MERRA-2 reanalysis, we show (Fig. 3) the time evolution of AOD550 for four different SSPs, averaged over the European domain. MPI-ESM1-2-HR and MERRA are the only products that include the volcanic eruptions of El Chichón (1982) and Pinatubo (1991).

According to the EURO-CORDEX protocol, it is mandatory to provide aerosol metadata, to inform the users on potential differences in the forcing of different regional models, which affect the final downscaled product. A metadata table is already available for a quick view of model meta-information (EURO-CORDEX 2023); the long-term goal of the EURO-CORDEX community is to incorporate all model metadata and configuration information in the Earth-System Documentation (ES-Docs) documentation viewer.

d. Land-use forcing. Earth system models of CMIP6 take into account global land-use management and change for historical and projection periods under the SSP scenarios (Hurtt et al. 2020). Within the European regional climate modeling community, land-use and land-cover changes (LULCCs) have not been directly accounted for in the coordinated dynamically downscaled simulations (EURO-CORDEX driven by CMIP5). Therefore, to date, there is not a consistent estimate of the LULCC impact on the regional European climate.

Individual RCM studies explored different aspects of land-use and land-cover change impacts on the European climate mainly from agricultural practices (e.g., Huang et al. 2020; Davin et al. 2014). However, due to the lack of a common modeling protocol underlying these experiments, the results are highly model dependent and the robustness of the outcomes is difficult to assess. Coordinated experiments, on the other hand, can help the scientific community quantify uncertainties and draw more robust conclusions, when it comes to interpreting biogeophysical climate processes and responses to LULCC.

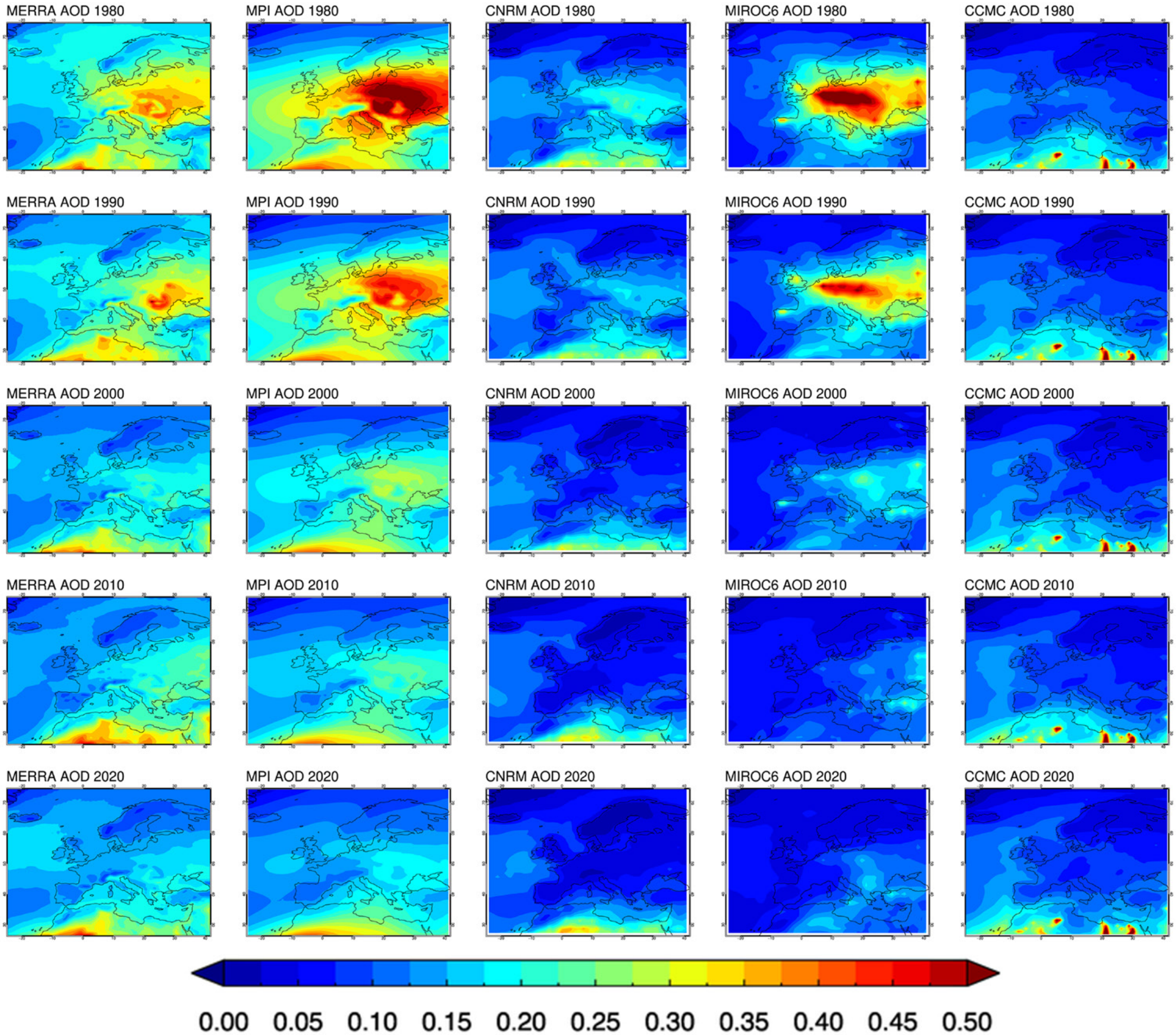

Fig. 2. Annual means for selected years of AOD550 over Europe for MERRA reanalysis and selected CMIP6 GCMs.

The CORDEX FPS-land use and climate across scales (LUCAS) is a European initiative that provides a common protocol for implementing land-use changes in coordinated RCM experiments (Rechid et al. 2017). Idealized experiments to investigate and intercompare model sensitivity to extreme land-use change forcings (LUCAS Phase I) have been performed for the European continent by more than 10 RCMs. FPS-LUCAS aims to provide a consistent framework for the RCM community to address land-use change forcing in CORDEX simulations (LUCAS Phase II, initializing June 2023).

Key findings based on LUCAS Phase I land-use change and evaluation experiments are as follows: the overall model agreement in winter temperature response to afforestation in Europe and a large intermodel spread in summer, due to different sensible and latent heat flux partitioning (Davin et al. 2020); the need for a careful selection of tailored metrics to interpret the complex biogeophysical processes occurring when land-use changes are implemented in RCMs (Breil et al. 2020); the relevance of soil processes especially in areas and seasons of strong land–atmospheric coupling (Sofiadis et al. 2022); and the importance of snow physics and the high uncertainty they impose especially during the ablation period, affecting considerably the regional climate of northern Europe (Daloz et al. 2022; Mooney et al. 2022).

Given the complex nature of LULCC implementation in regional climate models and the large associated uncertainties, the new EURO-CORDEX experiment design does not mandate LULCC forcings. So far, according to the meta-data table, no European modeling group has registered for the implementation of LULCC. However, if a modeling group wishes to implement LULCC in their transient simulations, it is given the opportunity to do so in a coordinated manner, within the framework of FPS-LUCAS. Following a dedicated LULCC protocol, the modelers may implement historical and future projection LULCC maps in their modeling systems, to investigate the impact of LULCC on regional climate. High-resolution LULCC datasets have been generated for use in CMIP6/EURO-CORDEX downscaling simulations (Reinhart et al. 2022, 2021; Hoffmann et al. 2021). Figure 4 illustrates, for example, the changes in urban fraction for the time period 1950–2015, when the urbanization rate is maximal in contrast to the far future time period 2050–2100, during which the urban areas decrease. Users of EURO-CORDEX data wishing to identify regional climate change attributed to regional LULCC should follow the FPS-LUCAS database and experiment protocol, as the EURO-CORDEX database will incorporate the LULCC forcing in, so far, all cases only through the GCM forcing.

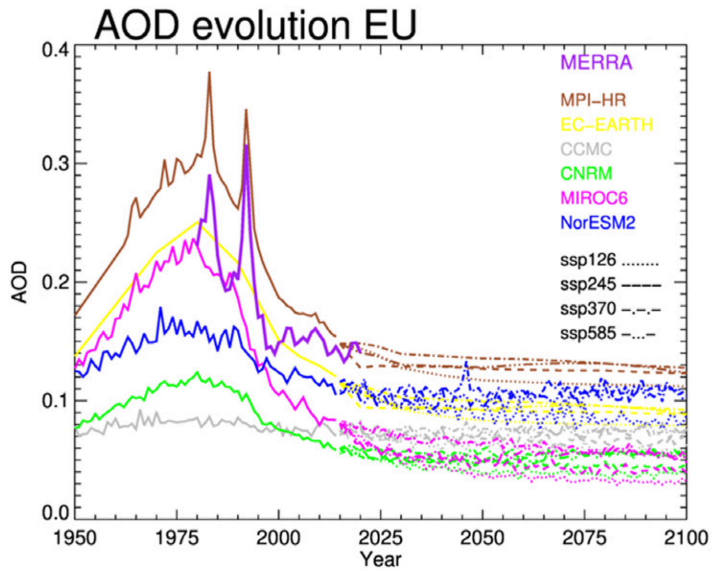

Fig. 3. AOD550 time series of GCMs selected as boundary conditions over Europe for different SSPs.

e. Model complexity. CMIP6-CORDEX requires as a minimum an atmospheric model coupled with a land surface model. The transition toward RESMs is encouraged, though, by using additional coupled components such as ocean, interactive aerosol, sea ice, dynamic vegetation, or urban schemes. Details on each model configuration are provided in the CMIP6/EURO-CORDEX RCM metadata table, maintained and updated by the EURO-CORDEX modelers (EURO-CORDEX 2023). Currently, only one modeling team will use interactive aerosols, four modeling groups will include to some degree explicit sea ice treatments, four groups indicate the use of lake models, three the use of urban parameterizations, and three include dynamic vegetation. Note that the configuration table is not yet final.

Urban climate is a focus of the CORDEX community, with the launch of the FPS on Urban Environments and Regional Climate Change (FPS-URB-RCC), which is a new coordinated study aiming to assess the effect of urban areas on regional climate and the impact of regional climate change on cities and their surroundings. The framework of this FPS, which is a joint effort of research groups from different continents and using different modeling tools (off- and online models), is designed to disentangle the urban versus large-scale effects on regional climate and improve the representation of urban environments in regional climate models. In the EURO-CORDEX experiment design, the use of an urban parameterization is recommended but not mandatory; every modeling group decides separately on the sophistication of the urban parameterization scheme and reports on the metadata table.

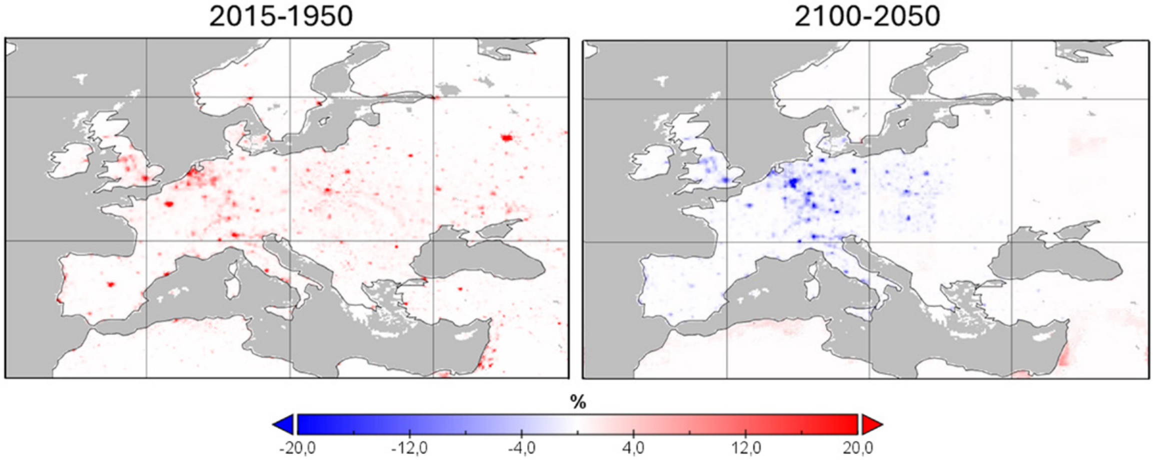

Fig. 4. Changes (%) in urban land use between (left) 1950 and 2015 and (right) 2050 and 2100 under the SSP3-7.0 based on the FPS-LUCAS high-resolution land-use and land-cover change data for regional climate modeling applications over Europe (Hoffmann et al. 2023).

f. Documentation and archiving. All EURO-CORDEX output variables will have open access and be retrievable by the broader scientific and stakeholder communities through the Earth System Grid Federation (ESGF). Modeling groups should choose a license (terms of use) for their CMIP6-driven simulations depending on institutional and funding agency policies. This information is necessary to register an RCM in the CORDEX RCM list. It is strongly recommended to use the Creative Commons Attribution 4.0 International (CC BY 4.0) license, similar to the CMIP6 terms of use. Preferably, noncommercial license terms should be avoided in order to promote the use of these data in downstream climate mitigation and adaptation applications. The use of EURO-CORDEX data should be properly acknowledged.

The variable naming conventions and output frequencies for the European domain are collected and grouped in atmospheric Core, Tier 1, and Tier 2 tables (EURO-CORDEX 2022). Next to the 17 atmospheric core variables which are the mandatory output for all contributing modeling teams, there are optional Tier 1 and Tier 2 variables requested by modelers. The latter list has been distributed by the CORDEX-Scientific Advisory Team (SAT) in spring 2022 to the EURO-CORDEX modeling community and has been finalized after having considered the comments of the European modeling community. This procedure ensured that the basic requirements originating from the modeling and impact communities are addressed adequately.

In comparison with the previous EURO-CORDEX specifications, the Tier 1 group includes more detailed three-dimensional information: more vertical pressure levels (1000, 925, 850, 700, 600, 500, 400, 300, 250, and 200 mb; 1 mb = 1 hPa), all available soil layers, and new heights for wind speed (50, 100, and 150 m) to better serve the wind energy community. Several optional variables are requested in Tier 2, including additional radiation components or convective instability indices. Moreover, the output frequency for most variables has been set to 1 h, even for the Core variable set. This new set of additional variables aims to support better interpretation of model results and better services toward the sectoral impact community.

4. Summary and future outlook

The CMIP5-driven EURO-CORDEX ensemble continues to be a valuable asset that enables scientists to pursue both fundamental and applied research on regional climate. Further, it provides a foundation on which stakeholders and researchers build downstream climate information products and services [e.g., CH2018 2018; Norwegian Centre for Climate Services (NCCS) 2017] in several sectors (agriculture, energy, water management, biodiversity, etc.).

The new dynamical downscaling protocol along with rigorous assessment of driving GCMs and the design of a balanced GCM-RCM matrix establishes a more robust EURO-CORDEX ensemble versus as compared to the previously available ensemble.

The key features underlying the CMIP6/EURO-CORDEX protocol compared to its predecessor CMIP5/EURO-CORDEX are listed below:

- Mandatory high-spatial-resolution: 0.11° versus 0.44°.
- RCM GHG forcing based on the SSP versus the RCP scenarios.
- Evaluation experiments driven by an improved reanalysis product, namely, ERA5 versus ERA-Interim.
- Consistent space- and time-varying aerosol forcing, following the MERRA-2 reanalysis aerosol evolution for evaluation simulations and the CMIP6 aerosol evolution of historical/projection experiments versus no aerosol or space/time invariable aerosol forcing.
- Availability of a complementary detailed protocol for implementing consistently land-use and land-cover changes over the European domain, for modelers wishing to include them in their production simulations.
- Revised archiving of model data, including more key variables tailored to scientific and impact community needs.

Despite the advancements in CMIP6/EURO-CORDEX, there are still several issues that must be addressed by the regional modeling community in the coming years. First and foremost is the gradual transition from RCMs into RESMs, which couple key climate processes to the land–atmosphere core of RCMs. Implementation of oceans, chemistry, ice, vegetation, and urban or hydrology models is necessary to improve model realism and increase confidence in simulated changes at local-to-regional scales. Second is the pressing demand for ever higher-resolution simulations, pushing strongly toward convective permitting (CP) scales (<5 km). Within the FPS-convection framework, a coordinated multimodel ensemble of time-slice CP simulations over the greater Alpine region has been completed (Ban et al. 2021; Coppola et al. 2018). These simulations exhibit an improved representation of precipitation statistics (Ban et al. 2021) and are now available via the ESGF. A major task for the EURO-CORDEX community is to establish a strategy and a protocol for CP simulations, combining dynamical and statistical methods. Additional links with flagship European Projects (e.g., destination Earth) and WCRP Lighthouse Activities will be sought to ensure codevelopment of the European regional climate modeling community within the European directives.

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Data availability statement. Aerosol Optical Properties data analyzed in this study were a reanalysis of existing data, which are openly available at locations cited in the text and in the reference section. Further documentation about data processing is available in Solmon (2022): Aerosol Optical Properties from MERRA-2-Reanalysis at https://doi.org/10.25326/383.

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